Littoral Sediment Budget and Beach Morphodynamics, Pukehina Beach to Matata, Bay of Plenty

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"....preservation of the natural character of the coastal environment...." (section 6, R.M.A., 1991)

Abstract

The Pukehina-Matata coastal sector is one of the least studied parts of the Bay of Plenty coastline. Currently this section of coast is in a stable, tending towards erosive, condition, with historical erosion of 0-0.2 m/year.

Sediment mineralogy reflects the high input of quartzo-feldspathic material into the beach-dune-nearshore system. For the Otamarakau-Matata sector much of the sediment is provided from fluvial sources, predominantly the Waitahanui, Pikowai, and Herepuru streams, although the total stream input in this area is only 3,000 to 7,000 m^3 per year. The sources of beach sand from Town Point to Otamarakau includes some erosion of catchment material, supplemented by littoral drift, erosion of submarine rock outcrops in the Town Point-Otamarakau region, and possible onshore reworking of pre-Holocene sediments.

The greywacke gravels present within the littoral system, especially between Rodgers Road and Pukehina, are relict deposits, which are presently active within the beach-dune-nearshore system due to the small volume transfers of sandy sediments. Their original source, is suggested as from marine erosion of Castlecliffian sediments, such as exposed in the coastal cliffs at Matata.

Net littoral drift is suggested as bi-directional from a centre-point near Otamarakau, to both the north-east along Pukehina Spit, and to the south-west towards Matata. Some counter-drift occurs between the Tarawera River mouth and Matata, and along the tip of Pukehina Spit, with nourishment of this area by the Waihi estuary.

Nearshore sedimentary-morphodynamic units show that the nearshore and inner-shelf at Town Point, and from southern Pukehina Beach to Otamarakau, is characterised by the presence of numerous rock outcrops, which are responsible for the coarse sands and relatively higher carbonate abundances in this area.

Sediment volumes within the beach-nearshore system, and alongshore transfers between sectors of the coast are small, with annual net littoral drift estimated as 15,000 m^3 at Matata. Diabathic processes are considered to dominate, with the limit of significant onshore-offshore sediment transport no more than 12 m, and a parabathic limit of less than 6 m.

The net change in sediment volume for the entire beach system within the Pukehina-Matata coastal sector between 1989 and 1993, produced a calculated deficit of sediment of 90,570 m^3. In comparison a longer-term change, between 1978 and 1993, showed a sediment surplus of 218, 560 m^3. Over the Pukehina-Matata coastal sector these volume changes are reasonably small and their variability reflects both the dynamic nature, and the delicate state of equilibrium, of the beach-dune-nearshore system. The derived littoral sediment budget shows that in order to balance the inputs and outputs within the system approximately 27,400 m^3 of annual onshore sediment transport must occur.

Current sand extraction at Otamarakau has resulted in a decline in the beach sediment volumes between Otamarakau and Pikowai, with this sector in a sediment deficit. Although natural processes mask the true impacts, the increased sand extraction rate of 36,000 m^3 per year is liable to further deplete the beach-dune-nearshore system. However, in the short-term these effects are unlikely to be immediately noticeable.

Acknowledgements

Having read a few theses in the course of making up my own, it appears that the two most enjoyable pages to read are the frontispiece and the acknowledgements page, which in some small way convey what doing a thesis has actually meant to the author involved. So let the awards begin.

Top of the list comes me. Cos, I wrote this little thing, and experienced an array of emotions in doing so. So I'd officially like to thank myself. So cheers, it was hard but I got there (ignore the errors, O.K).

Other than that, first and foremost (since everyone else does it this way and you can't afford to upset your chief supervisor....not worthy, not worthy) I would like to thank my supervisor Professor Terry Healy, who initiated the project, managed to con the Regional Council out of some ratepayers money, and no doubt (the one time I can say those two words) enjoyed using his stamps to great (psychological) effect on my draft chapters. So, thank you very much. Thanks also to Dr Willem de Lange for his vast knowledge on equally vast fortran programs, and knowing heaps when asked, and asked.

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word of advice to budding coastal scientists, chose an accessible field area!, 3 hour boat trips back from your study area is zero fun after the fifth day.

Finally, I worked out one day that I had about five different circles of friends or mates (who for various reasons let me join in, and attend weddings, engagement parties, flat warmings, 21sts, and no reason at all parties, and gave me someone to drink with and/or hangout on the streets with. So hello, goodbye, and you can't get rid of me that easily to Glen & Lissa, Brendan & Helen, Derrick, Nickee (Spik), Mary, Anthonie, the entire Bishop clan, Mark, Shane, Malcolm, Anna-Lee, Jed, Darryl, Baz, Mongrel, Peewee, Pizzle, Wellsey, Shandley, Mac, Corky, Earl, the Easter Tourney Boys.... Also, for the sporting times at varsity which gave me a reason to stay at uni during the week and in Hamilton during summer (which is miles from the beach). Cheers to Hamilton-Star University Cricket Club (and Greg F.) for the days in the sun, and to one of the oldest rugby clubs in New Zealand, Pirongia Rugby Football Club, thanks for the days in the mud, and the times at the pub.

See ya round.

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Introduction

CHAPTER ONE: INTRODUCTION

1.0 Introduction

Of the Bay of Plenty coast, 192 km (74%) consists of sandy shores and 66.5 km (26%) is rocky (BOPRC, 1991). The stretch of coast from Pukehina Beach to Matata can be classified as a leeshore long, straight, moderate to low-energy sandy beach, which possesses a slight concave seaward shoreline and a NNE aspect (Figure 1.1). It is located on the Bay of Plenty coast some 28km south-east of Tauranga Harbour, and comprises 31km of barrier beach, of which the sediments are predominantly volcanic, interspersed with greywacke material.

1.1 Problem Background

There is currently a complete lack of knowledge concerning the sediment budget and beach dynamics within the thesis study area. While work has been undertaken at Maketu and further north in and around Tauranga Harbour, as well as to the south along the Rangitaiki plains extending to Ohiwa Harbour, this particular part of the Bay of Plenty has not been studied previously in any depth.

The sediment budget along the entire Bay of Plenty coast is poorly understood, with only approximate estimates on the amount of littoral drift passing along the coast known. Estimates range from 50,000 m^3 to 100,000 m^3 of sediment per year (Healy, 1980; BOPRC, 1991; Healy *et al.*, 1991; Hume and Herdendorf, 1992), with volumes of littoral drift tending to be greatest near Tauranga and decreasing towards Ohiwa Harbour. Further to this, while some work has been done on the direction of littoral drift along the coast, the direction of sediment movement within the Pukehina Beach to Matata section is not really known. For example, Gibb (1983) suggests that sediment in the area moves in a north-westerly direction towards Town Point, while other sources cite evidence for littoral drift continuing to the south-east, with the Bay of Plenty coast acting as a straight stretch of coastline, in which the littoral drift system is essentially uninterrupted from Waihi Beach to Ohiwa Harbour (Burton, 1987; Healy *et al.*, 1977; Healy, 1978; Healy, 1980).

Currently the area is subject to development pressure in terms of both housing and commercial interests, with for example, the recent advent of a crayfish farm at Nanric Road, Pukehina, and sandmining at Otamarakau. Coupled with these continued developments it has been noted that the more populated areas of Pukehina, Otamarakau, Pikowai and Matata, are affected to some degree by erosion and sediment loss.

In the past sand extraction has occurred on a fairly limited scale at both Otamarakau and Matata. Such activity has had a definite impact on the sediment budget in these areas (Healy *et al.*, 1977). Healy (1980), stated that sand extraction from the littoral system has in most cases had a harmful

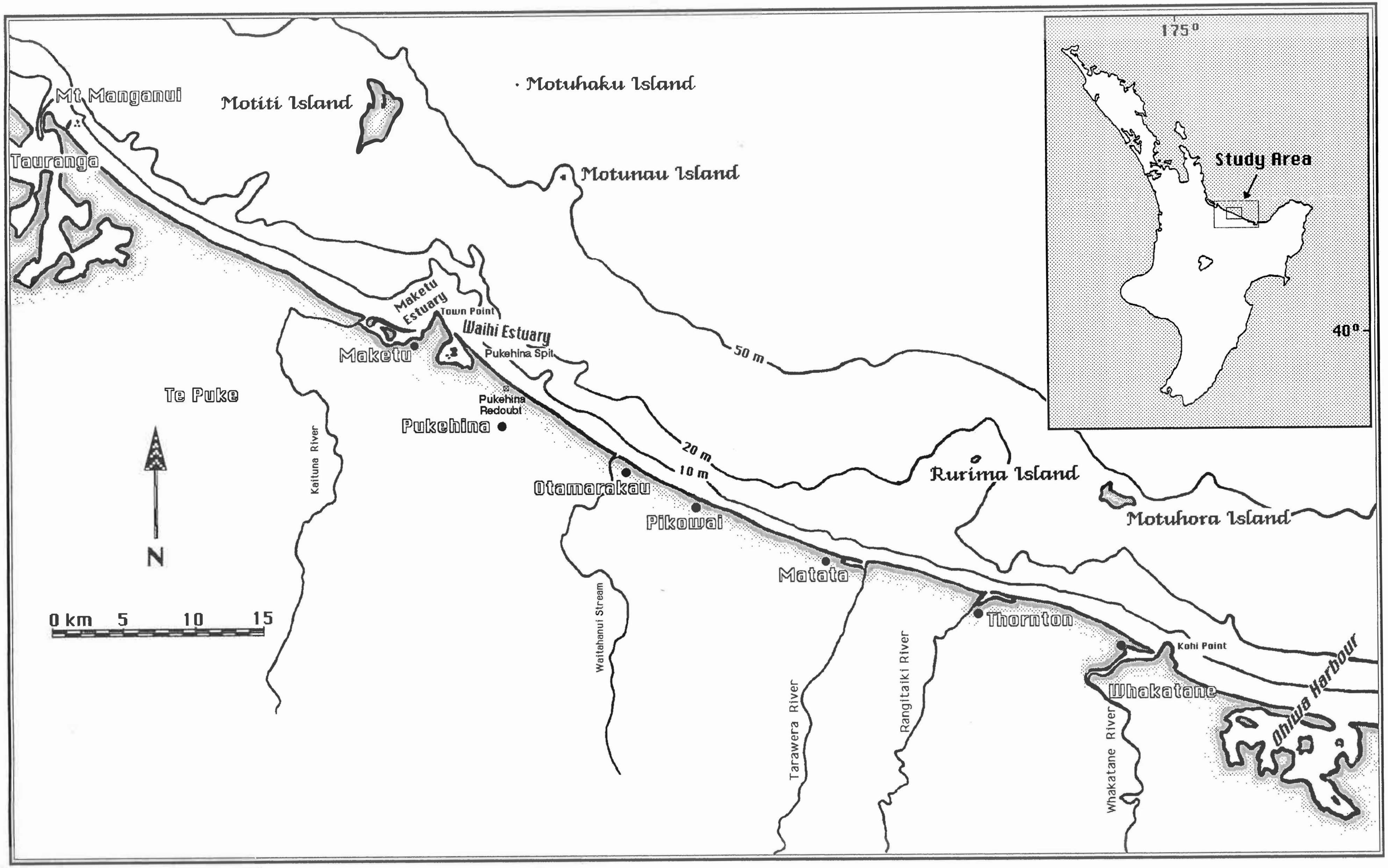


Figure 1.1 Location map of the Pukehina-Matata coastal sector.

effect on the nearshore-beach-dune system, with localised dune recession at Otamarakau and Matata.

Sand extraction at Matata ceased in 1986. At Otamarakau sand extraction has occurred for more than 35 years mainly by the Railways Department, along a 2km coastal strip from Otamarakau to Hauone, which has resulted in major destruction of the frontal dune and the only dune ridge. At present J.W. Patterson and Sons remove some 15,000 m^3 of sand from the beach annually, with a recent granting (May, 1993) of a coastal permit to remove 36,000 m^3 of sand annually from the beach over a four kilometer stretch of coast.

Hence, a greater understanding of the beach processes in the area would be beneficial to existing and future resource use, particularly relating to sand extraction and continued subdivision expansions. There is also a need to know the sediment provenance for this particular area of the coast, in order to properly assess the littoral sediment budget.

1.2 *Implications under the Resource Management Act (1991)*

> *"An understanding of the Bay of Plenty beach dynamics is essential for planning and resource management purposes."* (BOPRC, 1991)

Knowledge obtained on the coastal sector proposed in this study, is of importance in the development and implementation of the Bay of Plenty Regional Coastal Plan and related aspects covered under the Resource Management Act (1991). The purpose of this act is to promote the sustainable management of natural and physical resources while:

(a) sustaining the potential of natural and physical resources to meet the reasonably forseeable needs of future generations; and
(b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and
(c) avoiding, remedying, or mitigating any adverse effects of activities on the environment.

In order to achieve the purpose of the Act, Regional Councils are required under section 6, to "recognise and provide for the following matters of national importance:

(a) the preservation of the natural character of the coastal environment (including the coastal marine area, wetlands, and lakes and rivers and their margins, and the protection of them from inappropriate subdivision, use, and development;
(b) the protection of outstanding natural features and landscapes from inappropriate subdivision, use, and development;
(c) the protection of areas of significant indigenous vegetation and significant habitats of indigenous fauna;
(d) the maintenance and enhancement of public access to and along the coastal marine area, lakes, and rivers;
(e) the relationship of Maori and their culture and traditions with their ancestral lands, water, sites, waahi tapu, and other taonga"

Hence, the Act is of extreme importance to the coastal marine area, defined in Part I, section 2. Further to this, Part IV, section 35 (1) of the Resource Management Act (1991) directs local authorities (Regional Councils) to "...gather such information, and undertake or commission such research, as is necessary to carry out effectively its functions under this Act". With section 35 (2a) stating "Every local authority (Regional Councils) shall monitor the state of the whole or any part of the environment of its region or district to the extent that is appropriate to enable the local authority to effectively carry out its functions under this Act..."

Since little is known about the littoral sediment budget and beach morphodynamics of the Pukehina-Matata coastal sector which is currently under jurisdiction of the Bay of Plenty Regional Council, the results of this study are also of importance in fulfilling requirements under the Resource Management Act. This is particularly relevant concerning the sand extraction at Otamarakau. The Coastal Overview Report (BOPRC, 1991) states in summarising current research activity that "Investigations which would provide further essential and informative data on the coastal dynamic processes includes the quantification of littoral drift rates, sediment sinks and sources and the movement of offshore bar systems".

1.3 Research Objectives

The principal objectives of this study are therefore to:-

(i) Investigate the origin of the beach sediments and their mineralogy, in particular the terrigeneous fraction of greywacke present in the sediment which may be derived from: erosion of the Town Point conglomerate; sources offshore; fluvial sources; or from erosion of the Whakatane Heads.

(ii) Investigate the beach morpho-sedimentary units, in terms of texture and morphology, to determine possible sediment transport pathways, and areas of long-term change in the Pukehina-Matata coastal sector.

(iii) Assess the nature of the nearshore zone sedimentary- morphodynamic pattern, to provide information on sediment sinks and sources particularly in comparison to the beach, as well as general background data.

(iv) Produce information on the nearshore oceanography and currents using S4 current meters to monitor the interaction of the beach and nearshore in terms of sediment transport.

(v) From available survey data, including beach profile records, and calculations of source and sink volumes, attempt to refine a sediment budget for the Pukehina-Matata coastal sector.

1.4 Previous Work

While work has been undertaken on beach processes, littoral drift and sediment budgets in numerous localities both in New Zealand and overseas, nothing of any great extent has been published or written on the Pukehina-Matata coastal section. The Bay of Plenty Regional Council's Coastal Overview Report, in summarising available knowledge on coastal processes within the Bay of Plenty, sites the need for more work to be undertaken on beach processes and littoral drift in the Pukehina-Matata area (BOPRC, 1991).

The BOPRC Overview Report provides a useful summary of the current state of knowledge on the Bay of Plenty coastal resources and environment (BOPRC, 1991). The main previous work within the Pukehina-Matata sector is included in the Coastal Erosion Survey (Healy *et al.*, 1977), carried out in 1976/77. The DSIR have carried out routine erosion/accretion monitoring of the area, particularly at Otamarakau, as well as work under contract to the Department of Conservation and J.W. Patterson and Sons on sandmining and sand resources in the region (Smith, 1989; Smith, 1990a; Smith, 1990b, Smith *et al.*, 1992). Additionally, the BOP Regional Council have a large data set on beach profiles and beach volume changes, and presently survey some 44 monitoring sites along the coast, with the profile sites between Waihi and the Tarawera River mouth surveyed four times a year.

The Bay of Plenty Coastal Resources Inventory (CRI, 1990) is also of some relevance in providing background data on conservation and wildlife values in the area, although this is of limited use in relation to beach processes. Other information of some relevance is various publications to the Whakatane District Council associated with subdivision development at Matata (Healy, 1976; Healy, 1977b; Healy, 1989).

1.5 Thesis Outline and Approach

The organisational structure and interaction of this investigation is illustrated in Figure 1.2. Following the introductory chapter, chapter 2 provides background information relevant to this study, and includes physiographical, geological, and mineralogical characteristics of the Pukehina Beach-Matata region. Chapter 3 is a literature review on beaches, littoral drift, sediment transport, and the beach sediment budget, relating as much as possible to New Zealand and Bay of Plenty beaches.

Chapter 4 details the beach morphology and geomorphology, and includes analysis of historical aerial photographs, as well as repeated beach profiling and cut & fill cycles, as indicators of beach changes with time and the volumes involved in sediment transport.

Chapter 5 deals with the sedimentology and morphodynamic units present, following detailed analysis of the textural characteristics of the beach and nearshore sediments, and attempts to determine sediment sources and sinks, beach-nearshore interaction, and applies three sediment textural transport models.

The importance of the minerals present in the sediments along this stretch of coastline is discussed

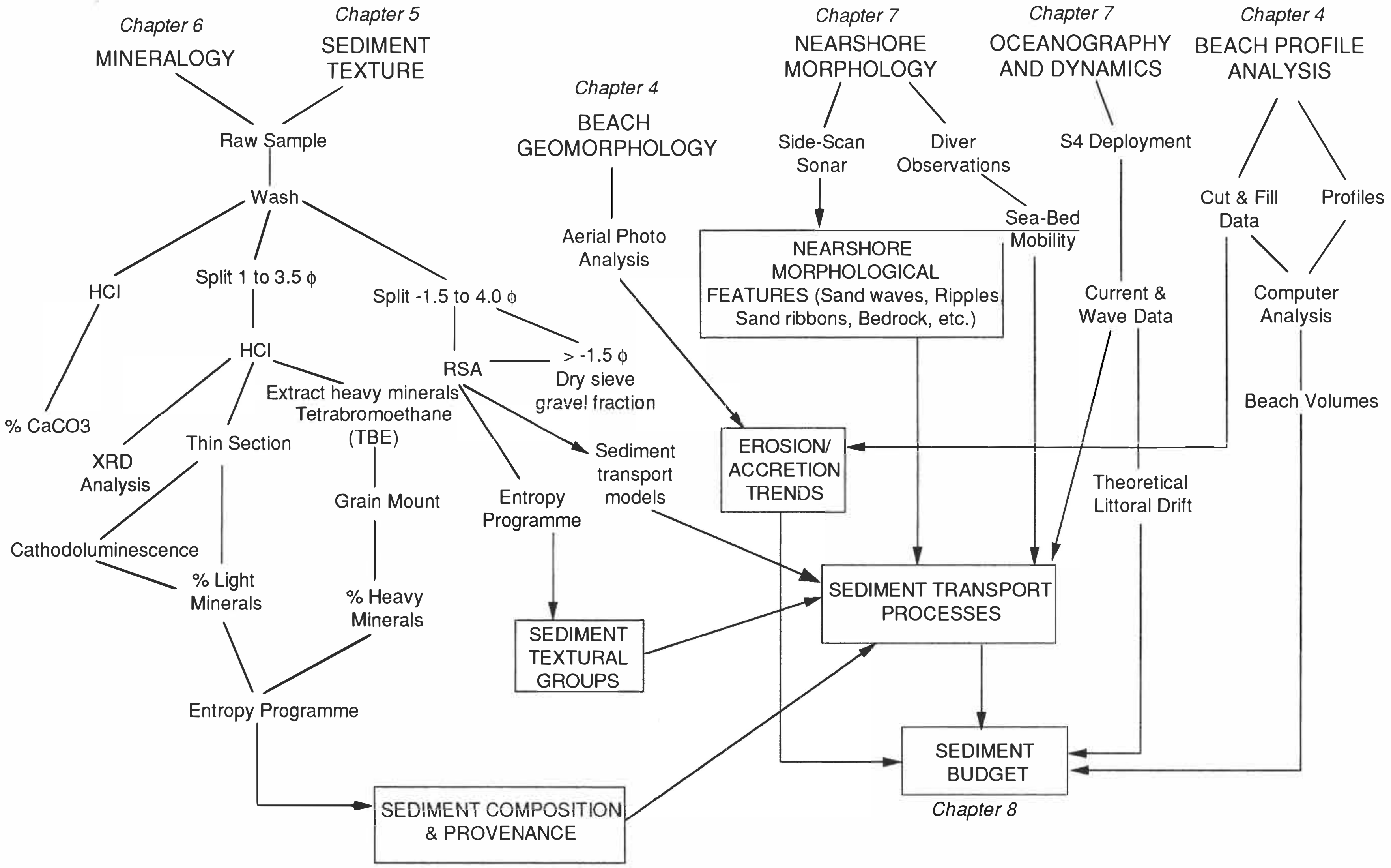


Figure 1.2 Thesis organisational structure, showing the data presented and results expected, based on the main objectives of this study.

in Chapter 6, in relation to the sediment budget and sediment sources, and includes mineralogical investigations of sediment samples obtained.

Chapter 7 discusses the nearshore morphology, using side-scan sonar analysis, wave and current data, and diver observations.

Chapter 8 integrates the sediment budget for the Pukehina Beach to Matata coastline calculating sediments inputs, outputs and transfers within the dune-beach-nearshore system, with the major findings and conclusions summarised in Chapter 9.

CHAPTER TWO:

Regional Setting

CHAPTER TWO:
REGIONAL SETTING

2.0 Introduction

Exposed sandy beaches are usually very dynamic with either short or long-term variations in morphology, relating to accretion and erosion patterns. This chapter discusses the regional setting of the study area, as it relates to the dune-beach-nearshore system, sediment transport, and the littoral sediment budget.

2.1 Geological History and Physiographic Evolution

The Pukehina-Matata coastal sector borders the Maketu Basin, which includes the Maketu and Waihi estuaries, and Kaharoa Plateau of poorly consolidated pumiceous material. The Kaharoa Plateau is terminated in the east of the study area by fault scarps on the western side of the Whakatane Graben, which include the Bramar, Rotoitipakau, and Matata Faults (Wright, 1990). Pumice ash-flow deposits of Rotoiti Breccia north of the Rotorua lakes form gentle slopes into the Maketu Basin (Healy et *al.*, 1964).

The broadly curved coastal outline of the Bay of Plenty is the result of a combination of several factors and processes.

Primary factors:
(i) Tectonic Warping
(ii) Regional and local geology
(iii) Faulting
(iv) Pleistocene sea-level fluctuations
(v) Rapid sedimentation
Secondary factors:
(vi) Wave refraction
(vii) Available sediment
(viii) Wind

The Opotiki, Maketu, and Tauranga Basins were formed by downwarping during the middle to late Pleistocene (Shaw and Healy, 1962), influencing the formation of the harbours that these basins now contain. Warping has also resulted in the inclination of the coastal terraces in the area (Chappell, 1975). Glacio-eustatic sea-level fluctuations occurred throughout the Pleistocene, with the last major retreat some 70,000 to 20,000 years B.P. At times of maximum glaciation the streams and rivers dissected the coastal hinterland and terraces, cutting down to a base level 100 to 150m below the present sea level. The last transgression that followed, resulted in the infilling of incised valleys and basins, the formation of new terrace surfaces, and the formation of harbours and estuaries that front the Bay of Plenty coastline. During this time events were further complicated between Maketu and Whakatane by faulting and further warping. Collapse of the Whakatane Graben brought the sea inland as far as Te Teko and Kawerau. The western wall of the Whakatane

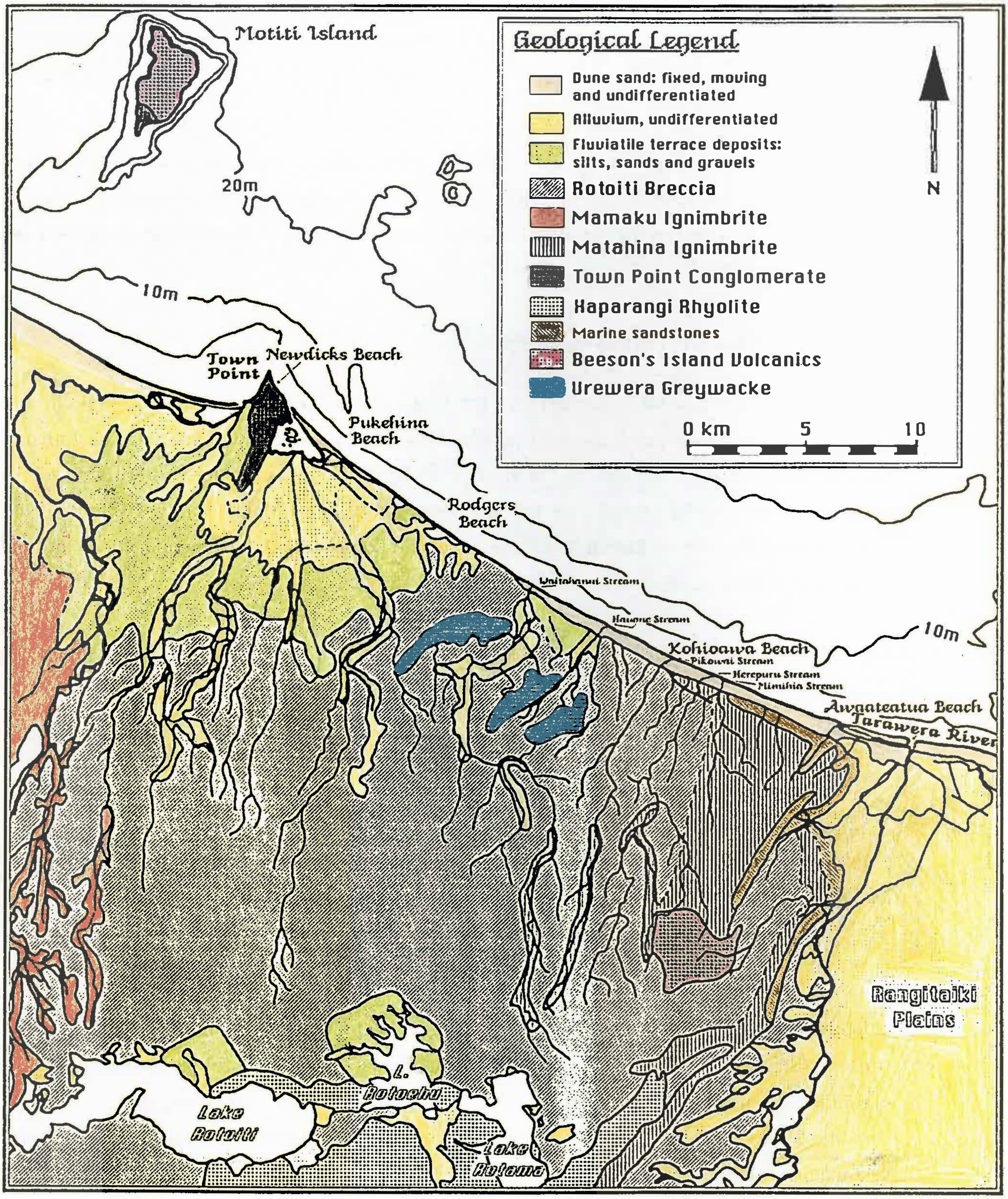


Figure 2.1 Regional geology of the central Bay of Plenty incorporating the Pukehina-Matata coastal sector. *(source: modified after Healy et al., 1964)*

Graben formerly extended out to the Rurima Rocks as a ridge of bedrock, sand and boulders, but has since been worn away by marine erosion and cliffed back to Matata.

A more comprehensive geological history of the Pukehina-Matata area is included in Healy (1967) as part of the Whakatane District.

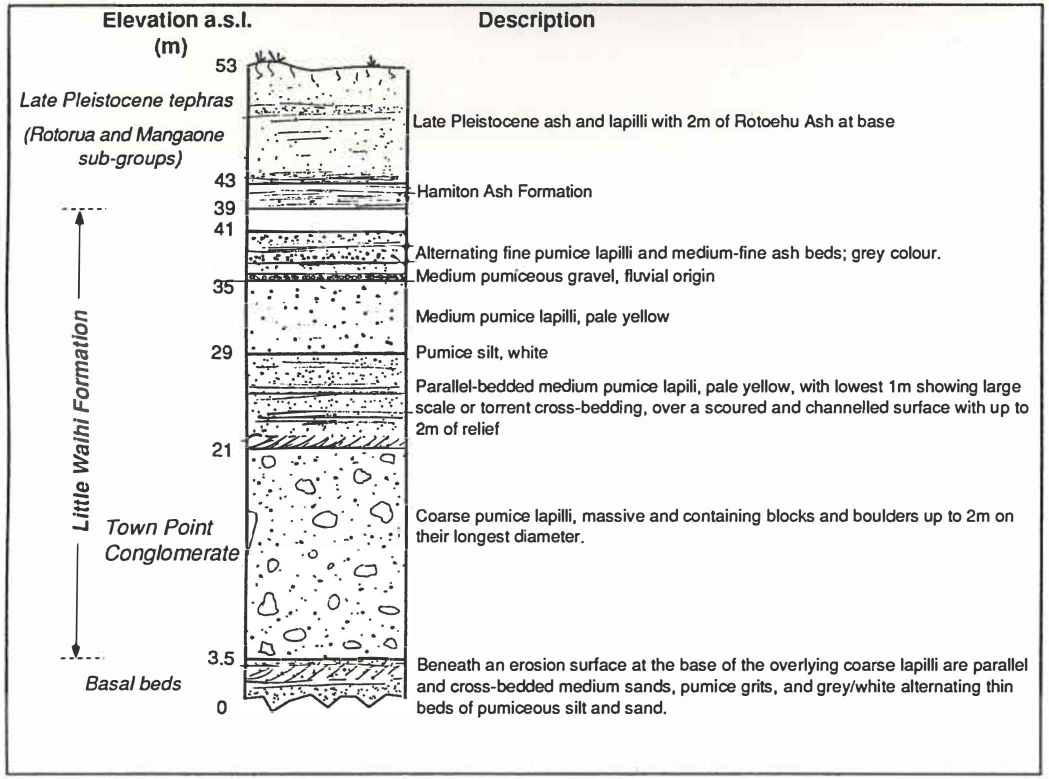
2.1.1 Local Geology

Nearly all the lithologies exposed within the hinterland bounding Pukehina Beach to Matata are of volcanic origin, in the form of primary or redeposited accumulations. The exceptions to this are the isolated outcrops of Urewera Greywacke inland from Otamarakau, which underlie the entire region, and the occurrence of marine sandstones along the NE-SW bounding fault near Matata. The geology of the region is given in Figure 2.1.

Pyroclastic deposits from volcanic eruptions between c.55,000 to 107 yrs B.P. mantle the Pukehina to Matata region, contributing to the past and present sediment loads of the streams and rivers. The most erodible lithologies exposed within this area are the weakly compacted volcanic breccias, terrace and fan deposits. These include the Rotoiti Breccia, Town Point Conglomerate Formation, and undifferentiated terrace deposits. The more stable lithologies tend to be the rhyolites and welded ignimbrites, such as the Matahina Ignimbrite.

The main direct fluvial contributors to the sediment budget, apart from sources updrift from the main direction of littoral drift, are the major catchments streams such as the Waitahanui, Pongakawa, and Pikowai Streams. These streams all have relatively small catchments compared to the neighbouring Tarawera and Kaituna rivers, and between Pukehina and Matata there are at least eighteen, although some of these do not appear to discharge at the coast, or are small seasonal streams which operate only during periods of high rainfall and runoff. The majority of these streams drain into the beach between Otamarakau and Matata (Figure 2.2). Smith estimates the total drainage area as 218 km2. The three largest catchments within this sector; Waitahanui, Herepuru, and Pikowai, all rise in the high country of the Kaharoa Plateau, with headwater elevations of approximately 300 m, rising in places to nearly 400 m. These streams, due to the loosely consolidated nature of the local geology, are deeply incised into the volcanic material forming the plateau.

There are several more unusual lithologies present in the study area. The Town Point Conglomerate Formation referred to in Figure 2.1, is described more accurately as including the Little Waihi Formation Chappell (1975). The Little Waihi Formation is a Late Pleistocene pumiceous tephra formation, some 40m in height at its seaward extension, which underlies the Hamilton Ash Formation, and is responsible for the morphological characteristics of Town Point (Figure 2.2). At the base of the Little Waihi Formation lies the Town Point conglomerate and undifferentiated pumice deposits, with numerous boulders littering the backbeach. Henry (1991) in a study of the



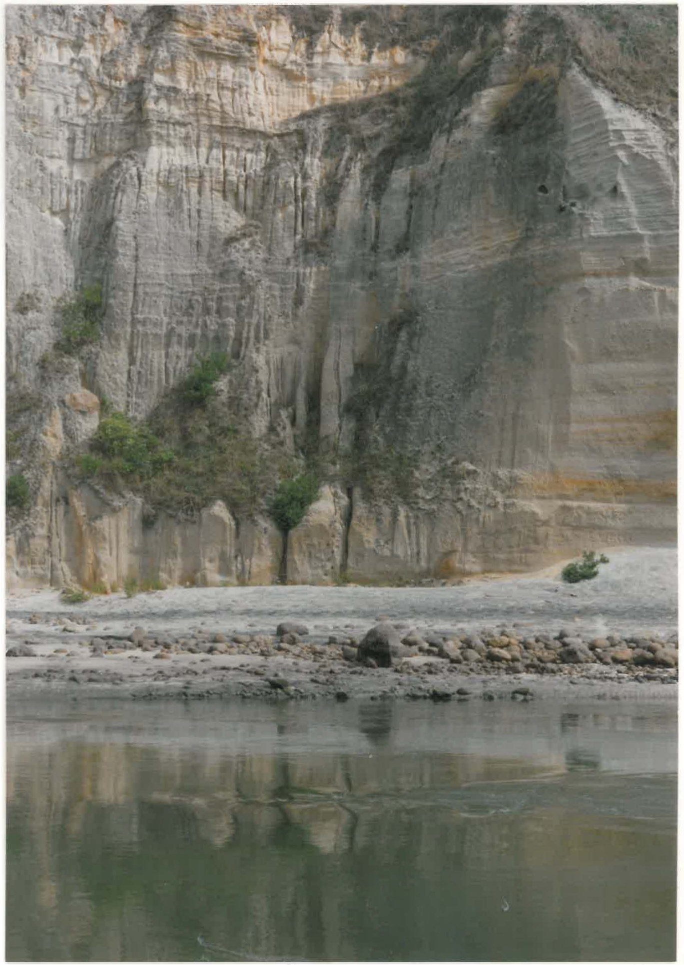


Figure 2.2 Cliff section at southern Town Point on the northern side of the Waihi estuary, which is composed of various ignimbrite, conglomerate and reworked volcanogenic material deposited during the late Pleistocene at some time between 280,000 and 50,000 yrs B.P. Note the blocks and boulders at the base, which are a mixture of rhyolites, conglomerate and welded ignimbrites derived from erosion of the above cliff strata. *(source: in part Chappell, 1975)*

geology of nearby Motiti Island notes that similar outcrops of Quaternary sediments occur at the southern tip of Motiti Island. If the two deposits are similar, which appears to be the case, then based on tephrochronology the Town Point Conglomerate Formation was deposited pre-50,000 years B.P. (Henry, 1991).

The only notable work published on the geology of the Pukehina-Matata region is a generalised description of the geology and geological history of the Whakatane District (Healy, 1967) and a brief description of the coastal cliffs between Otamarakau and Matata (Healy and Ewart, 1965), which appear to contain lithologies similar to those at Town Point. The coastal section from Otamarakau to Matata, is dominated by steep cliffs, which are the result of cliffing from marine erosion during the late Pleistocene, exposing upper marine strata and overlying volcanic deposits erupted from vents within the Okataina Volcanic Centre (Figure 2.3 and 2.4). These include the Matahina Ignimbrite, the Rotoiti Breccia Formation, and in parts the Little Waihi Formation, as well as numerous tephra formations. The appearance of the Little Waihi Formation especially at Herepuru/Mimihia roads is of a lesser extent than at Town Point and Little Waihi where these deposits are thickest. The formation at Town Point shows within its main unit (18m coarse lapilli deposit) boulders up to 2m in diameter suggesting that the eruptive centre was nearby (Chappell, 1975), whereas within the Otamarakau-Matata cliffs these occur as only occasional blocks up to 0.2m in diameter. A modified stratigraphic column of the Matata-Otamarakau cliffs is shown in Figure 2.4.

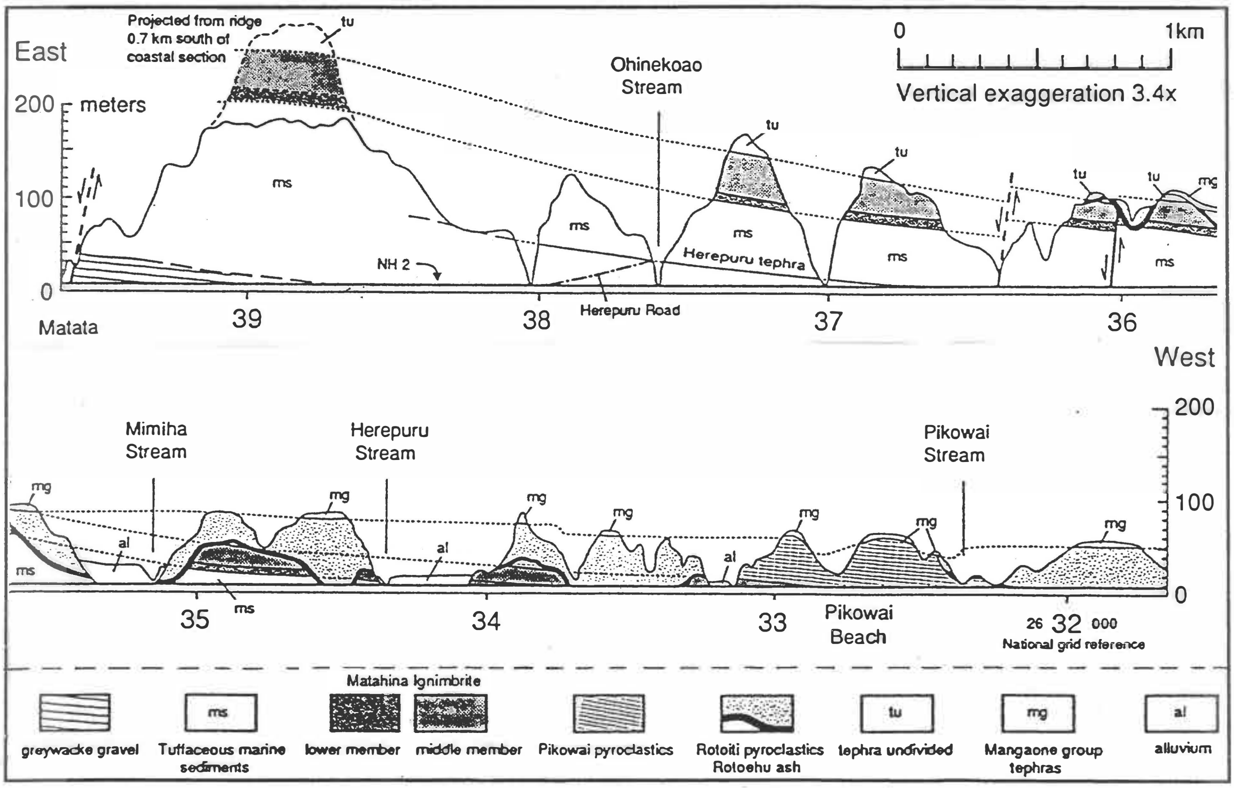
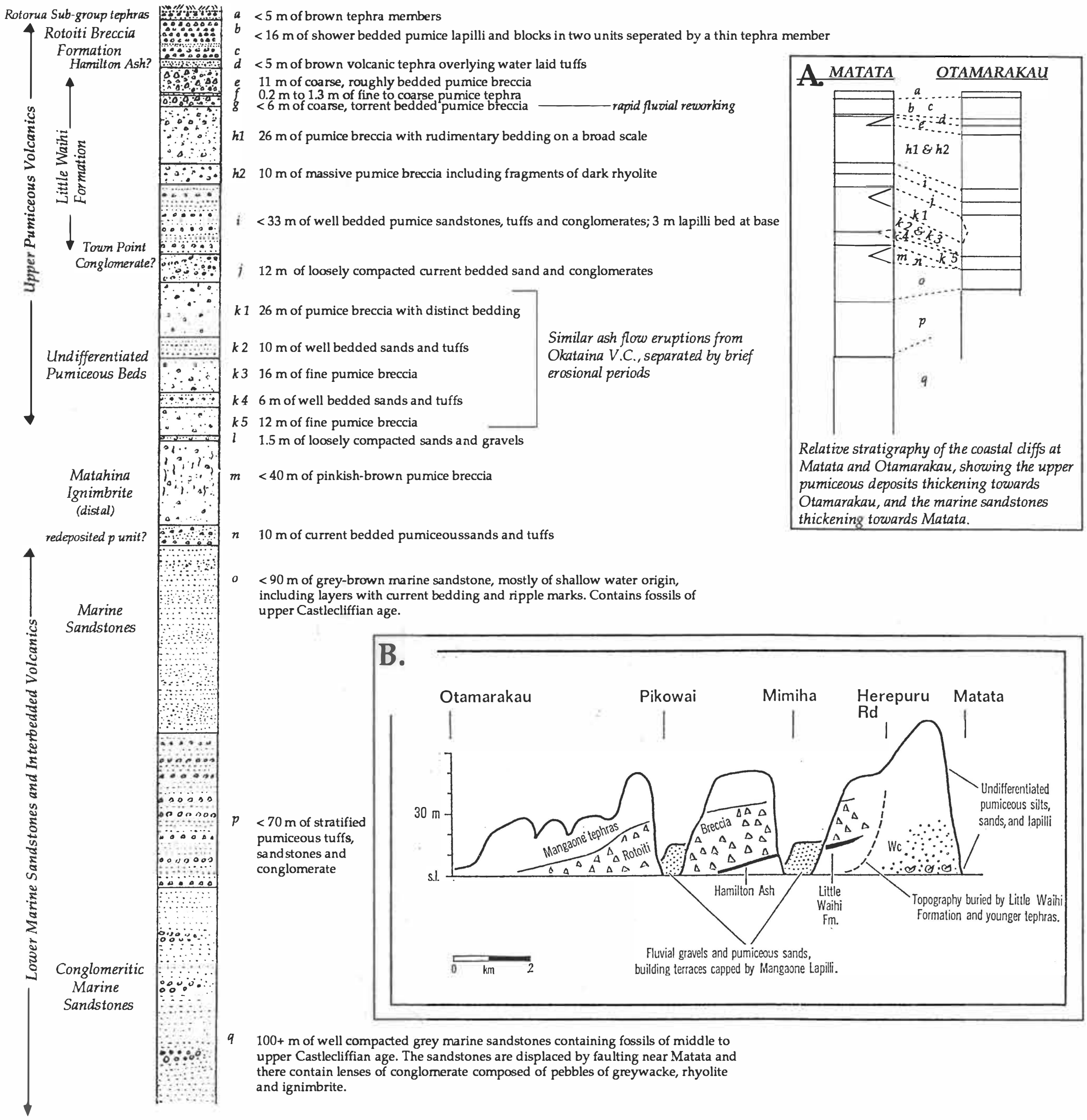


Figure 2.3 East-west cross section of cliff exposures along the Bay of Plenty coast between Matata and Pikowai. Showing the erosional unconformity separating Pikowai pyroclastics (Little Waihi Formation and/or undifferentiated pumice deposits) and Matahina Ignimbrite from Rotoehu Ash and Rotoiti Pyroclastics. Gradual eastward rise of Matahina due to post-depositional structural uplift on margin of Whakatane graben. *(source: Bailey and Carr, in prep.)*



Relative stratigraphy of the coastal cliffs at Matata and Otamarakau, showing the upper pumiceous deposits thickening towards Otamarakau, and the marine sandstones thickening towards Matata.

Figure 2.4 Generalised section of the geology exposed along the Matata-Otamarakau coast, including the Matahina Ignimbrite and pumice breccias of the Rotoiti Breccia Formation *(source: modified after Healy and Ewart, 1965)*. Inset *A)* schematic representation of the relative stratigraphy showing the differences in strata thickness between Matata and Otamarakau *(from information in Healy and Ewart, 1965)*, and *B)* sketch of the coastal cliff exposures *(Chappell, 1975)*.

The tephra formations exposed in the coastal cliffs and surrounding hinterland contribute a large amount of erodible material which is removed to the beach-dune-nearshore system as fluvial additions and cliff erosion. Pullar (1972), presents several maps depicting the extent and approximate thicknesses of various erupted tephras, from the Taupo Volcanic Zone eruptive centres. For example, the rhyolitic Rotorua Ash formation dated at 13,800 yr BP, is some 20-30 cm thick at its coastal extent between Otamarakau and Matata (Nairn, 1980). Contributions to the sediments of the region from tephra deposits may be fairly substantial, with approximately 10 metres (Pukehina Spit) to 30 metres (Pikowai-Otamarakau area) of material deposited during the late Quarternary within the catchment and coastal areas of the Pukehina-Matata area (Pullar, 1970).

The Whakatane Graben which forms the north-east end of the Taupo Volcanic Zone where it crosses the coastline in the Bay of Plenty, is bounded on the north-western side by a prominent fault scarp which meets the coast at Matata (Figure 2.5). To the west of Matata the upthrown block is tilted gently to the north-west, a trend which is also observed in the upper pumiceous volcanics which thicken in the direction of Otamarakau (Healy and Ewart, 1965).

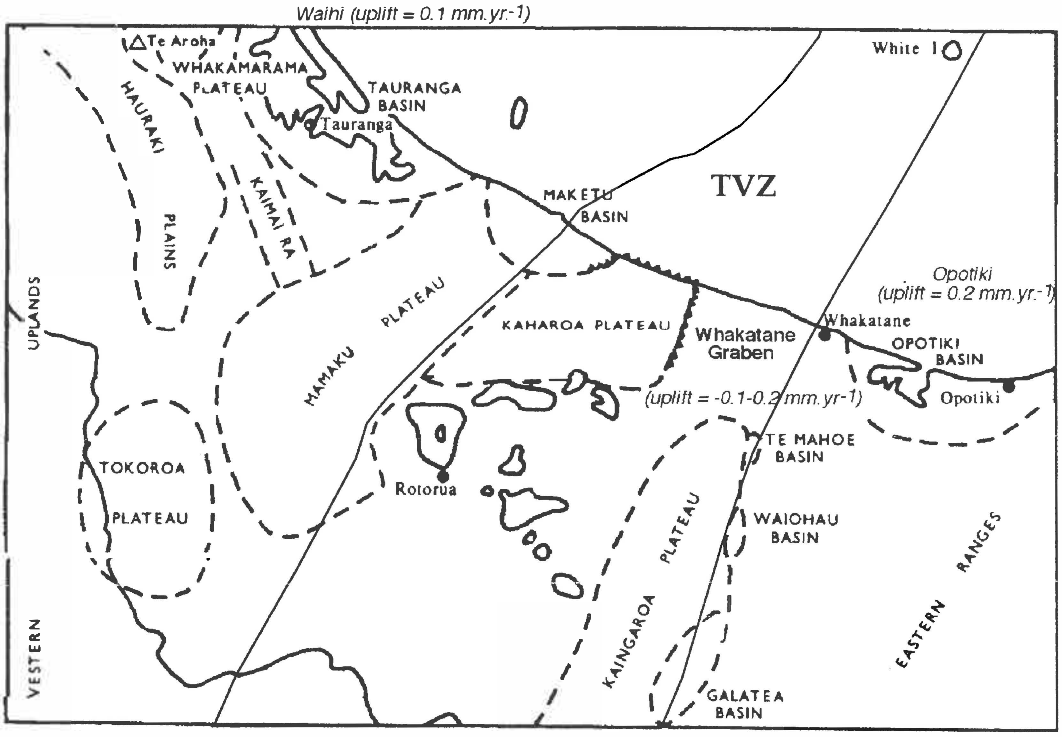


Figure 2.5 General Structural Characteristics of the Bay of Plenty. *(source: Healy et al.,,1964, Pillans, 1990, Wright, 1990)*

Uplift rates for the Maketu Basin are suggested to be very minimal or zero, based on the examination of coastal terraces in the Bay of Plenty (Chappell, 1975), with Pillans (1990) suggesting that for the Bay of Plenty rates vary between 0.1 and 0.2 mm.yr^{-1}. Hence, in the short term this factor should not attribute to any significant erosion or accretion in the study area. The Whakatane Graben which incorporates the Rangitaiki Plains is actively subsiding at the coast at a rate of 1-2 mm.yr^{-1} (Nairn and Beanland, 1989). Added to this are faulting movements. The

Rotoitipakau, Edgecumbe and Matata Fault zones have all been active in the past 100 yrs (Wright, 1990), with the most recent movements from the 1987 Edgecumbe earthquake resulting in the Rangitaiki Plains being downlifted 0.5m. By applying the Bruun rule for sea level rise (Bruun, 1983) it is expected that this would result in approximately 35m of horizontal erosion to the area (Smith, pers. comm., 1992). Conversely at Matata the area was uplifted by 0.1m, leading to a marked increased in sediment volume along the Matata section of beach (Smith, 1990a; Smith pers. comm., 1992).

2.1.2 Beach Sediments and Mineralogy

Regional and local geology, along with sediment additions via littoral drift and onshore shelf transport, has a strong bearing on the mineralogy of the beach sands and nearshore sediments of the region. Sediments of the Bay of Plenty may therefore originate from three sources: (1) Local catchment rocks (Figure 2.6); (2) volcanic sediment from the TVZ; and (3) tephras covering the hinterland. In turn this should be reflected in the mineralogy.

A brief petrological description of the major rock types in the region is given below:

Town Point Conglomerate Formation
Fluviatile silts, sands, gravels and interbedded pumiceous tuffs, underlying terraces at 100ft, and 200ft above base level; large rhyolite, greywacke, basalt, and welded ignimbrite boulders are present at base. Is a mixture of primary, and reworked and redeposited lithologies. Contains the Little Waihi Formation, Town Point Conglomerate, and undifferentiated pumiceous deposits (Figure 2.2).

Marine Sandstones
Marine sandstones with fossils, conglomerates, and interbedded pumiceous tuffs in upper part. Occurs in cliff section near Matata and along the Whakatane Fault graben.

Rotoiti Breccia
Poorly compacted white pumice breccias and basal siltstone. The pumices are generally cobble to granule in size and can have a high crystal content. Extensive in volume covering much of the Kaharoa Plateau, and is exposed in most cliff sections, particularly between the Pukehina Redoubt-Otamarakau area. Ewart and Healy (1965) describe the Rotoiti Breccia as *"a series of pumice breccias laid down as hot avalanche deposits"*, with Thompson (1968) including all airfall breccias and tuffaceous siltstones overlying the Mamaku Ignimbrite and beneath the Holocene volcanic ashes, as Rotoiti Breccia.

Mamaku Ignimbrite
Pale pink to grey ignimbrite containing plagioclase and minor quartz; poorly welded. Contributions to the beach sediments appears to be minimal since the lithology appears mainly north of Pukehina, although its sediments may be carried to the south by littoral drift.

Matahina Ignimbrite
Pale pink to grey ignimbrite containing abundant plagioclase and minor quartz; upper part poorly compacted and pumice recrystallised; lower part fine grained, welded lenticulite. Present near Matata and Pikowai in cliff section, may also contribute to beach sediments via fluvial inputs from upper catchment areas.

Beeson's Island Volcanics
Hornblende and pyroxene andesites. Present in only one place in the study area, some 10km inland from Matata, possible fluvial contributions.

Urewera Greywacke
Banded argillite, alternating siltstones and sandstones, conglomerates, and in places fine grained basic volcanic rocks. Located in part in three outcrops near Otamarakau. Found extensively in the eastern Bay of Plenty.

Figure 2.6 Typical rock types found along the Pukehina and Redoubt section of the study area. 1= pumice, derived from localised cliff erosion of the Rotoiti Breccia; 2= greywacke; 3= weathered fluvial and tephra deposits from the base of the Rotoiti Breccia; 4= grey ignimbrites (possibly Matahina Ign.); 5= beach gravels of mixed origin, abundant with greywacke material; 6= rhyolites.

The greywacke material present in the beach sands of the Pukehina-Matata segment of coast, is unique in that it is only found in any abundance along this section of coast, with little to none occurring further north or south. Several sources are possible, and will be discussed in later chapters:

1). Erosion of greywacke boulders present in the basal section of the Town Point Conglomerate; and subsequent longshore transportation to beaches to the south.

2). Fluvial sources. This includes local streams whose catchments contain greywacke outcrops, such as those near Otamarakau (Waitahanui and Hauone); also the Whakatane river, and basement greywacke since covered by volcanic materials. The greywacke outcrops near Otamarakau which are enclosed by a local positive gravity anomaly (Stern, 1986) have two possible origins. Firstly the outcrop may represent the surface expression of basement structure for the region. Alternately the outcrop represents the surface expression of an allochthonous block, rifted sometime in the past from the eastern edge of the Central Volcanic Region (Calheim, 1973; Evison *et al.*, 1976). From geophysical evidence Stern (1986) suggests the second reason, in that the outcrops are isolated blocks rather than surface manifestations of basement rocks.

3). Submarine offshore outcrops of greywacke, which have been weathered by wave and water action and brought onshore.

4). Erosion of the Whakatane Heads, which consist entirely of greywacke.

Generally the beach sands of the Bay of Plenty between Pukehina and Matata, are composed of predominantly quartz and feldspars, although volcanic glass is a significant contributor to the beach sands, as a result of the volcanic nature of much of the surrounding catchments. In terms of heavy minerals, the relative abundance of a particular mineral species depends on the exact additions from sources. Healy (1978) found that three major heavy mineral groups occurred in the beach sands of the eastern Bay of Plenty: (i) pyroxenes (*hypersthene* and *augite*); (ii) amphiboles (*hornblende* and *cummingtonite*); and (iii) opaques (mainly *titanomagnetite*). All these minerals are representative of a volcanic source origin, and exhibit a limited number of heavy mineral species compared with areas with more unique mineral assemblages, such as south Otago (Bardsley, 1977).

The Coastal Erosion Survey (Healy *et al.*, 1977), indicated from sedimentological analyses that for beaches west of Whakatane (thereby including the Pukehina-Matata section), the major sources for the Bay of Plenty littoral sands were likely to be the Mamaku & Kaharoa Plateaus and the Okataina Volcanic Centre.

2.1.3 *Offshore Sediments*

The sediments found in the nearshore and offshore zones of the Pukehina-Matata region, have been generalised by Doyle *et al.* (1979) in a broad-scale map of the Bay of Plenty sediments, shown in part in Figure 2.7 overleaf. This shows predominantly sand sized sediments in the nearshore zone extending out to 30-35 m water depth. Beyond this the sediments become increasingly finer as the silt content increases. This is related to the concept of the size-graded shelf, which states that sediment size will decrease across the shelf in a seaward direction as an indirect function of depth and a direct function of the amount of wave energy penetrating to the bottom (Swift, 1970). Although the pattern does appear to be a complex distribution of sediment types, rather than a simple progression. In the nearshore zone several variations on the sediment pattern are apparent. Offshore from the Tarawera River mouth in approximately 10m water depth is a patch of gravel and calc-gravelly sand. Other calc-gravelly sand patches occur offshore from Matata (20-25m), in the entire nearshore zone from the Pokare Trig to the Waitahanui Stream mouth (to ~30m water depth), and in the area surrounding Town Point and Maketu.

An unpublished report by the Bioresearches (1984), details the biology and levels of pollution of the coastal environment near the Tarawera River mouth, with a few grain size measurements taken, showing the area to contain medium to fine grained sands.

2.2 Geomorphology

The 34km coastline from southern Town Point to the Tarawera River can be sub-divided into three basic physiographic units.

1). Town Point:- a rock strewn promontory bounded by Waihi and Maketu estuaries, with Newdicks Beach at its south-eastern extent. The crest of the peninsular is a well formed fan surface some 60-66 metres above sea level, composed of Pleistocene reworked volcanogenic and fluvially derived material, underlain by marine beds of Castlecliffian age (Healy *et al.*, 1964).

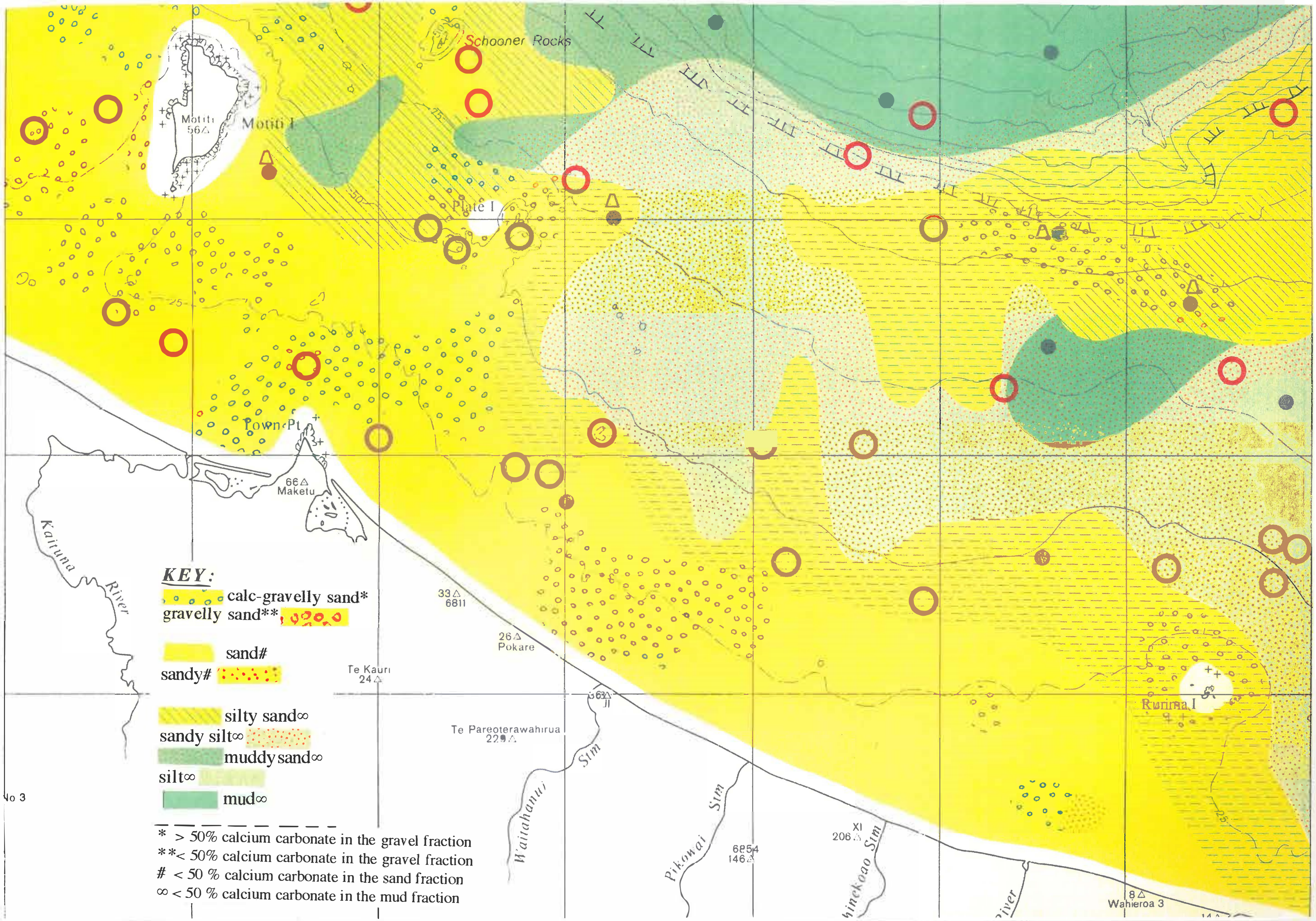


Figure 2.7 Generalised sediments of the Bay of Plenty in the vicinity of the Pukehina-Matata coastal sector. Red circles are representative notation for consolidated rocks of unknown age. Scale is 1:200, 000. *(source: Doyle et al., 1979)*

2). *Pukehina Beach:-* a narrow barrier spit consisting of late Holocene sands, fronting the Waihi estuary.

3). *The coast from Pukehina Redoubt to Matata:-* consisting of a narrow sandy strip backed by cliffs cut into Pleistocene terraces, composed predominantly of Rotoiti Breccia, Matahina Ignimbrite, and marine sandstones in the Matata area. Between the Pukehina Redoubt and Otamarakau there is no frontal dune and the cliff is actively eroding in parts, which may contribute locally to the sediment budget. In contrast, from Otamarakau to Matata a broad dune ridge separates the beach from the cliffs, in which a narrow lagoon or coastal swamp commonly backs the dune (Healy *et al.*, 1977).

2.2.1 *Pukehina Beach*

Pukehina beach is an open, ocean sandy beach (6.5km long) south-east of Town Point. At its north-west end Pukehina Spit encloses the Waihi Estuary. The beach is backed by residential development behind the foredune. The Coastal Resource Inventory (1990) notes that Pukehina Beach and the sand spit are susceptible to erosion, and that residential development is beginning to encroach along the foredunes.

The Holocene barrier spit of Pukehina Beach, separating the Waihi Estuary from the ocean is similar to the dune ridge features existing along the Bay of Plenty-Coromandel coastline, such as Pauanui and Ohope spits. These barrier spits developed soon after the recent post-glacial transgression (c.6000 yr B.P.), as a direct result of the rapid onshore flux of sediment associated with sea level rise (Healy and Kirk, 1982). Apart from the rise in sea-level contributing to rapid sedimentation, non-periodic phenomena have also had a marked effect. Perhaps the most important of these are volcanic eruptions. Large-scale rhyolitic and pumiceous eruptions have continued throughout the late Quaternary and Holocene, centred in the Rotorua-Taupo region. The main effect has been to provide a massive amount of sandy sediment to the littoral system which has assisted in forming progradational features, such as the Pukehina Spit (Healy and Kirk, 1982). Additionally tectonic events have further modified the region. Examples being the Quaternary uplift of the Maketu Basin which led to the formation of the Maketu and Waihi estuaries, and the fault bounding the Whakatane Graben, near Matata.

2.2.2 *Pukehina Redoubt-Otamarakau-Matata*

This area extends from the Pukehina Beach Road, near the Redoubt, and continues south-east past Rodgers Road Beach and Otamarakau, to Matata. The beach frontage from the western boundary of the Tarawera River mouth to the Waitahanui stream at Otamarakau is 18 km long, and is dissected by six major streams. In the south where local development is minimal the dune system is largely intact. Adjacent to the Matata Lagoon, near Matata township, moderate modification has occurred as a result of sand extraction prior to 1986. Closer to Otamarakau the dune system is well vegetated and generally in a healthy condition. The area is subject to investigation by the DSIR for baseline monitoring of coastal erosion/accretion trends (Smith, 1989).

2.3 Coastal Inlets

Within the Bay of Plenty estuaries may be categorised into two main groups (BOPRC, 1991), both of which are represented within the Pukehina-Matata region:

(a) barrier enclosed estuaries with sand supplied by onshore transport of shelf sand and/or littoral drift. These estuaries often have either intermittent connection with the sea or direct exchange with the ocean only near high tide. *For example, (Little)Waihi Estuary.*

(b) river mouth estuaries with large fluvial input and river dominated hydrology. The lower reaches of the rivers are stratified, or there is a tidal backwater effect on flows. *For example, the Tarawera River.*

The main estuary within the study boundaries is the Little Waihi estuary (Figure 2.8), with most other 'estuaries' consisting of fairly small streams and rivers discharging at the coast. Nevertheless they are important to the beach processes of the region, and are classified in Table 2.1.

The Waihi Estuary is separated from the Maketu Estuary by Town Point, and is a large, shallow, bar bound estuary with fresh water inflow via a number of channelised streams. The estuary contains a number of low-lying islands, with 9.5 km of coastal perimeter and an overall area of 2.4 km^2 (CRI, 1990), of which more than 70% is aerially exposed (Healy, pers. comm.). The Coastal Resources Inventory (1990) note that subdivision on the coastal spit has resulted in damage to the coastal dunes and the natural shoreline of the Waihi Estuary. Stopbanking has been necessary around the margins of the estuary which in turn has significantly reduced the tidal prism.

2.4 Sand Mining Activity

One of the aspects that prompted this study, is the present and future effects that sand mining may have on the beach-dune-nearshore system, particularly at Otamarakau. Bay of Plenty beaches have been the source of industrial sand for many years, with the principal extraction sites at Matakana Bank, Papamoa, Otamarakau, Matata, and Hukuwai Beach-Snells Road (Figure 2.9). In nearly all cases sand mining has had a destructive affect on the beach system, leading to erosion problems as the littoral reservoir of sand is depleted.

Smith (1986) states that ideally a beach mining location should have the following characteristics, rarely found in nature:

- The area needs to be in a location which has few severe storms, and is a predominantly low energy wave environment to maintain the beach in a well nourished condition year round.
- The wind regime should be predominantly offshore or parallel to the shore.

Table 2.1 Classification of estuaries within the Pukehina-Matata sector after Hume and Herdendorf (1988), together with approximate shoreline perimeter and area. *(source: modified after Table 3.1, BOPRC (1991))*

Inlet	*Classification*	*Shoreline Perimeter (km)*	*Area (km²)*
Waihi Estuary	4, single spit	9.5	2.4
Tarawera Estuary	8, straight banked[1]	2.1	0.09
Herepuru Stream	7, beach impounded	1.8	0.03
Otamarakau	7, beach impounded	1.5	0.02
Pikowai Stream	7, beach impounded	1.0	0.01

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[1] the current classification of the Tarawera Estuary is due to diversion and modification for flood prevention. Floodgating of secondary side channels has reduced the estuarine area which was initially a spit lagoon. Prior to 1913 the Tarawera River discharged at Matata at the present day locality of the old Matata sand extraction site.

A

Figure 2.8a) Oblique aerial photograph of the (Little) Waihi estuary mouth during mid-tide (April 23rd, 1992), and *b)* Town Point viewed to the south-east along the Pukehina-Matata coastal sector showing barrier enclosure by the 6km long Pukehina Spit. Note also the rock strewn nature of the Town Point littoral zone. *(photo: T.R. Healy)*

B

- The site should have a well defined sediment source and preferably a well documented history of accretion.
- Accretion rates need to be moderate rather than high, as high input of new material will not allow sufficient time for wave action to remove the weaker material from the deposit.
- Not be located in environmentally sensitive areas, such as wildlife nesting areas, camping grounds, or areas of developed housing.

Hence, suitable sites are often difficult to find, although such operations are lucrative with good quality sand in high demand, for example current extraction from the Otamarakau sand mining site is estimated to be worth annually in excess of 2 million dollars (Brett O'Shaunessy pers. comm.). Within the Pukehina-Matata coastal sector, two sand extraction operations have occurred over a number of years, although currently only the beach from Otamarakau to Pikowai is subject to sand mining activity.

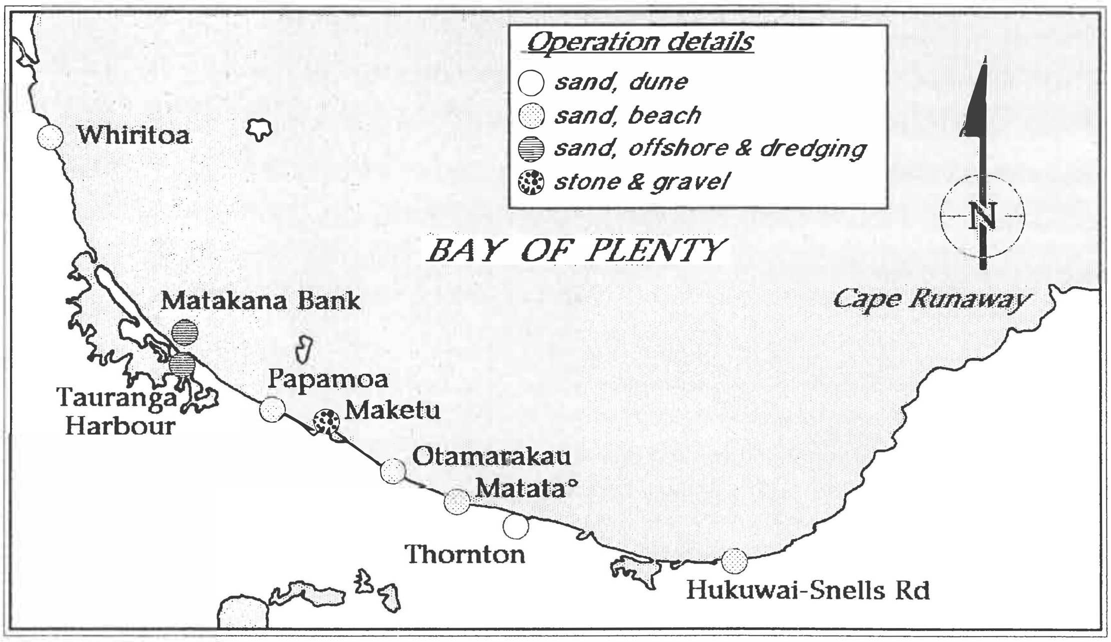


Figure 2.9 Locations of previous (Papamoa, Maketu, Matata), present (Whiritoa, Matakana Bank, Otamarakau, Hukuwai-Snells Road) or proposed (Tauranga Harbour) coastal mining sites within the confines of the Bay of Plenty. With the exception of Maketu and Hukuwai-Snells Road all sites have extracted sand. *(source: modified after Smith, 1986)*

Sand extraction at Matata ceased in 1986, with 6,700m^3 per year licensed for extraction since the late 1960's (Healy *et al.*, 1977). While the dune has receded considerably in the immediate vicinity of the extraction site, Healy et al. (1977), note that the offshore bar is apparently not noticeably depleted, since littoral drift from the southeast and the Tarawera River contribute to replenishing the beach-dune-nearshore system. Although, with the cessation of mining the beach and dune have recovered somewhat, with rapid accretion in the back beach and beach face regions (Smith, 1989).

At Otamarakau sand extraction has occurred for more than 35 years mainly by the Railways Department, along a 2.4 km coastal strip from Otamarakau to Hauone. Approximately 4,000 m^3 was

Figure 2.10a & b Sand extraction at Otamarakau, where sand is mined from between the berm and dune. This activity over 35 years has resulted in complete decapitation of the dune and only dune ridge. Figure a) shows the site in April 1992, and b), a year later in April 1993 with a noticeable stockpiling of sand estimated at 12,000 m^3 or 90% of the operators annual limit (Brett O'Shaunessy *pers. comm.*)

removed per year in the late 70's and early 80's, although extraction rates in the 60's and early 70's were much greater. The current licence to extract sand is held by J.W. Patterson and Sons, who previously mined at Matata, and is subject to monitoring by NIWAR for the Department of Conservation (Smith, 1990a, 1990b) and the BOPRC. At present the licence is for of 15,000 m^3 of sand to be removed annually, with the operator recently granted a coastal permit to increase this amount to 36,000 m^3 along a four kilometre stretch of coast between Otamarakau and Pikowai (BOPRC, 1993). Apart from major destruction of the frontal dune and the only dune ridge shown in Figure 2.10a and b, the beach system appears to have been able to cope with present extraction rates, with the nearby Waitahanui Stream probably helping to replenish extracted sand losses (Smith, 1992). The subject of the Otamarakau sand mining is examined in subsequent chapters.

2.5 Bay of Plenty Beaches and the Coastal Erosion Survey

The Bay of Plenty Coastal Erosion Survey (Healy *et al.*, 1977), is one of the few publications which deal with the Pukehina-Matata coastline, and is therefore important in providing comparative data for this study. The Coastal Erosion Survey is somewhat deficient in detail since only sparse data was collected along a large sector of coastline. This is most apparent in the mineralogical analyses of the beach sands along the Bay of Plenty, where conclusions were based on an extremely limited number of samples.

> *"For this project we have made bulk mineralogical analyses only and it will be necessary to undertake the detailed heavy mineral analyses as given in Judge (1970) of the beach sands, and of the river sediments being transported to the system." (Healy et al., 1977)*

From the Coastal Erosion Survey and companion reports on beach profiles and nearshore beach bars (Healy, 1978b; Healy, 1978c) several findings and conclusions were reached concerning the Pukehina-Matata section of the Bay of Plenty coast:-

1). West of Matata (where steep cliffs back a narrow coastal zone) dune change in the past 31 years to 1974 has been minor except near the river mouths. Erosion was noted where there is sand mining activity, and erosion/accretion cycles were evident on Pukehina Spit.

2). The frontal dune for the majority of this section was noted as either actively scarped or in a state of recent cut. Of particular hazard was the subdivsion at Pukehina, which the authors noted as poorly planned in the 1940's on an unstable area.

3). At Pukehina, both Healy *et al.* (1977) and Healy (1978c) on separate occasions found that offshore profiles (BOPCES site 27) showed an absence of an offshore bar, and instead a horizontal sub-tidal platform existed. The reason stated for the sub-tidal platform was that the bar was not being replenished either by sand off the beach or from littoral drift. At Pukehina this was suggested as possibly partly due to Town Point blocking the southerly littoral drift. In addition, Little Waihi estuary, immediately north of the beach acts as a sediment 'sink'.

4). The two apparent worse locations for erosion within the study area were Pukehina Spit and Matata. One conclusion the Coastal Erosion Survey noted in relation to coastal subdivision was that,

"Ohiwa was doomed, Waihi looked bad, but Pukehina showed the biggest potential for disaster".

Other areas of relevance connected with the Coastal Erosion Survey are mentioned in the relevant chapters.

2.6 Wind Climate

The Bay of Plenty (BOP) weather is controlled by wind direction (Quayle, 1984). The BOP is exposed to the north and north-east, and sheltered to the west by the North Island. The prevailing winds are from the west which induce wind-forced westerly waves, while longer period waves from the north are caused by the passage of cold fronts and slow moving depressions across the North Island from the west, and by tropical cyclone activity north of New Zealand.

Although the prevailing wind-flow over northern New Zealand is west to south-west, winds over the Bay of Plenty region are modified by local topography, which acts to reduce the effects of this predominant wind flow.

Quayle (1984) notes that the wind climate in the Bay of Plenty region is influenced by:

a) North to north-east airstreams;
b) Disturbed west to south-west air flows;
c) South to south-east airstreams;
d) West to north-west air flows;
e) Tropical cyclones from the north-east.

Most winds affecting the Bay of Plenty result from the first two groups (Figure 2.11), but with respect to the generation of significant waves, north to north-east airstreams and tropical cyclones from the north-east are of major importance (Harray, 1977). At Whakatane to the south-east of the study area (eastern Bay of Plenty), the wind roses show a much more predominant north-easterly component (Harris *et al.*, 1983).

Local storms are a dominant influence on the wave energy of the northeast coast of New Zealand, with winds blowing from an easterly quadrant over only short distances resulting in fetch-limited conditions, and the mobile nature of these storms also causing duration-limited conditions (Harris, 1985). The frequency of occurrence for different scale storm events has been extensively studied on the western Bay of Plenty coastline by Hay (1991) for the period between 1873 and 1990. This has shown that most storm events occur from an easterly quadrant (74%), with moderate scale events of Force 7 Beaufont Scale winds (13.9 to 17.1 $m.s^{-1}$) occurring on average once every 0.71 years, and extreme winds of Force 8 and 9 Beaufont Scale (17.2 to 20.7 m.s^{-1} and 20.8 to 24.4 m.s^{-1}) every 14 and 30 years respectively. These storm events are usually of limited duration, ranging from 6 to 39 hours, with an extreme value of 92 hours.

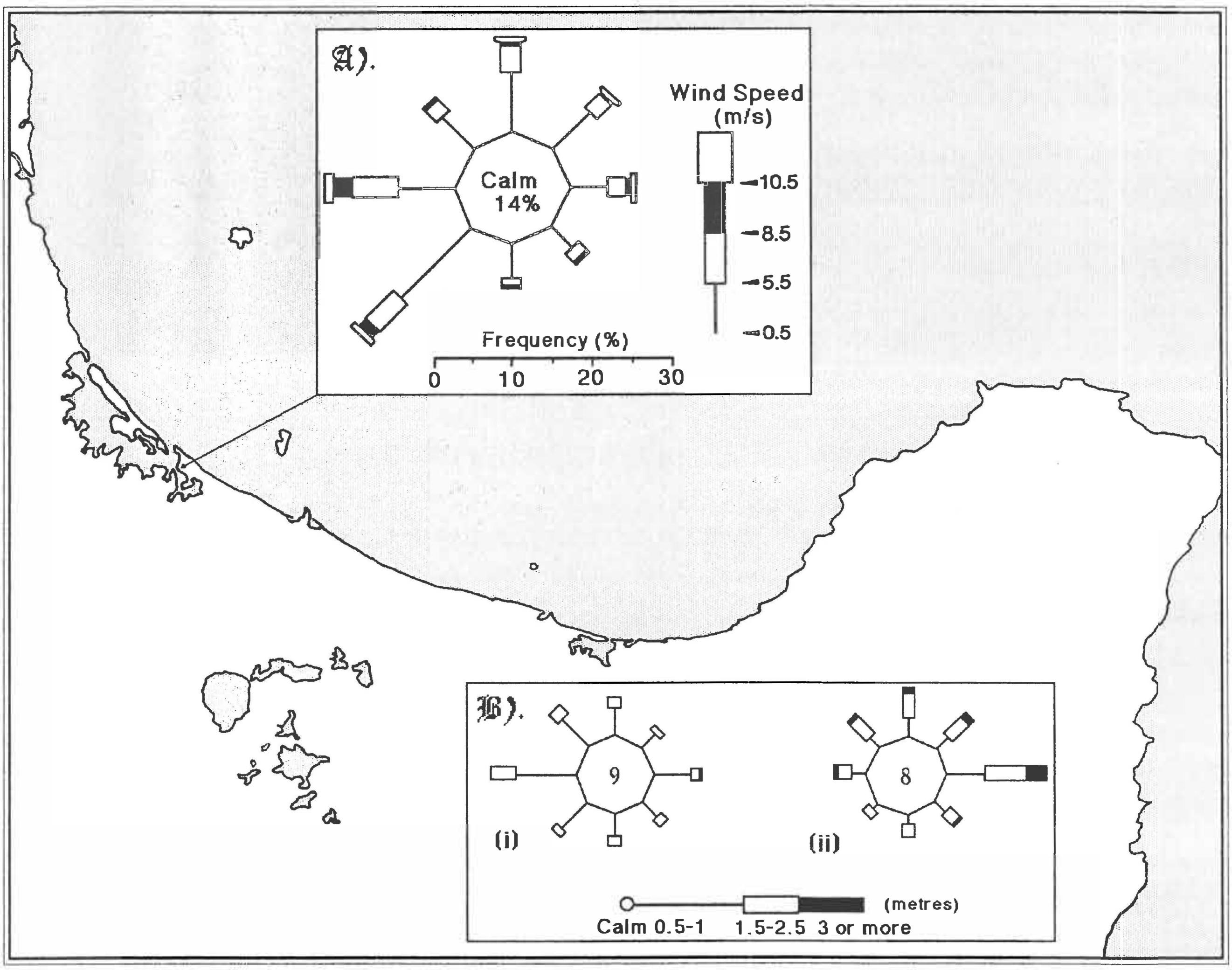


Figure 2.11 *A).* Mean annual frequency of wind speed and direction for Tauranga Airport for records from 1970-1979. *B). (i)* Wind wave, and *(ii)* Swell roses based on ship reports in a two-degree square centred on 37°S, 177°E. *(source: Quayle, 1984)*

2.7 Wave Climate

The wave climate of New Zealand has been characterised by Pickrill and Mitchell (1979) using all wave data available up to 1978. They found that the wave environment is dominated by swell originating from the west and south-west of New Zealand and storm waves generated to the north. The northern coast between North and East Capes is not exposed to the high energy swells of southern origin. The prevailing waves are from the northeast and have a height of 0.5-1.5 m and a period of 5-7 seconds (Pickrill and Mitchell, 1979).

Sea and swell wave characteristics in the Bay of Plenty are determined by the area's exposure to the prevailing winds and by the sheltering effect of the North Island. Waves are predominantly either wind-forced, developed under westerly wind conditions, or swell waves from the east to north-east, due to their longer fetches. The study area is open to locally generated waves arriving directly from 345° to 100°.

Healy *et al.* (1977) included data from Harray (1977) and Davies-Colley (1976) to describe the Bay of Plenty wave climate as (abridged): *"A mild meso-energy swell environment with an offshore significant wave height of approximately 1.5 m and a nearshore significant wave height of 0.6m. Refraction over the twenty kilometre continental shelf tends to modify the wave angle approach so that the waves become aligned near normal to the shoreline, with some refraction also occurring around offshore islands"*.

Observations summarised from ship reports between 1975-1980 are shown in Figure 2.9B. Further observations have been made at Tauranga (Davies-Colley, 1976; Davies-Colley and Healy, 1978; Dahm and Healy, 1980; de Lange, 1991) and at Waihi Beach (Harray, 1977), with a large study undertaken by NIWAR including detailing the wave climate over a three year period from 1992-1994, offshore from the northern Tauranga Harbour inlet in 34 m water depth, which will be of significant future use. The most recent assessment by de Lange (1991) of the offshore wave climate at 'A Beacon' offshore from Tauranga Harbour in 11 m of water, shows that from the period September 1989 to February, 1990, the average significant wave height was 0.7 m with a 9 s period. Studies of local storm wave conditions on the Bay of Plenty coastline by Hay (1991) have shown that heights range from 1.01m to 5.00 m, with a mean storm wave height of 2.97 m, and periods from 4.34 s to 10.42 s, with a mean of 7.65 s.

Pullar (1976) notes for the Matata-Otamarakau coastline that *"this part of the coast takes a battering from heavy seas generated by northerly and north easterly winds and suffers a fairly high incidence of cut and fill"*. In terms of the volumes of sediment eroded during storm events the largest known for the Bay of Plenty resulted in approximately 130-150 m^3/m of beach being eroded (Healy, 1989).

Large-scale storms such as the April 1968 Wahine storm and July 1978 (H_S= 9.0 m, T= 12 s) (Frisby and Goldberg, 1981) storm cause significant coastal erosion along the BOP coast. Pullar (1978) notes that such a storm or Marangai-noui (squalls from the nor' nor' east) occurred on 16th Feb. 1827, noted by the French explorer Dumont D'Urville who was nearly wrecked on the Astrolabe Reefs offshore from Whakatane. Within the Pukehina-Matata coastal sector the 1968 storm produced (Pullar, 1978):

- *storm surges of 1.98 to 2.68 m above m.s.l. ;*
- *erosion of the foredune at Pukehina and Otamarakau;*
- *seawater flooding in swales behind the foredune at Matata;*
- *seawater flooding of the stream and river estuaries;*
- *seawater over topping of foredunes along Pukehina Spit and at Matata, which has been known to have occurred previously in 1906 and 1926; and*
- *encroachment of seawater on the railway line between Otamarakau and Matata.*

Seasonal changes to the wave climate have also been observed to result in associated annual cycles of erosion and accretion at Waiotahi on the eastern Bay of Plenty (Smith, 1986). The sediment grain size also shows a corresponding annual cycle on beaches from Pukehina to Matata (BOPRC, 1991).

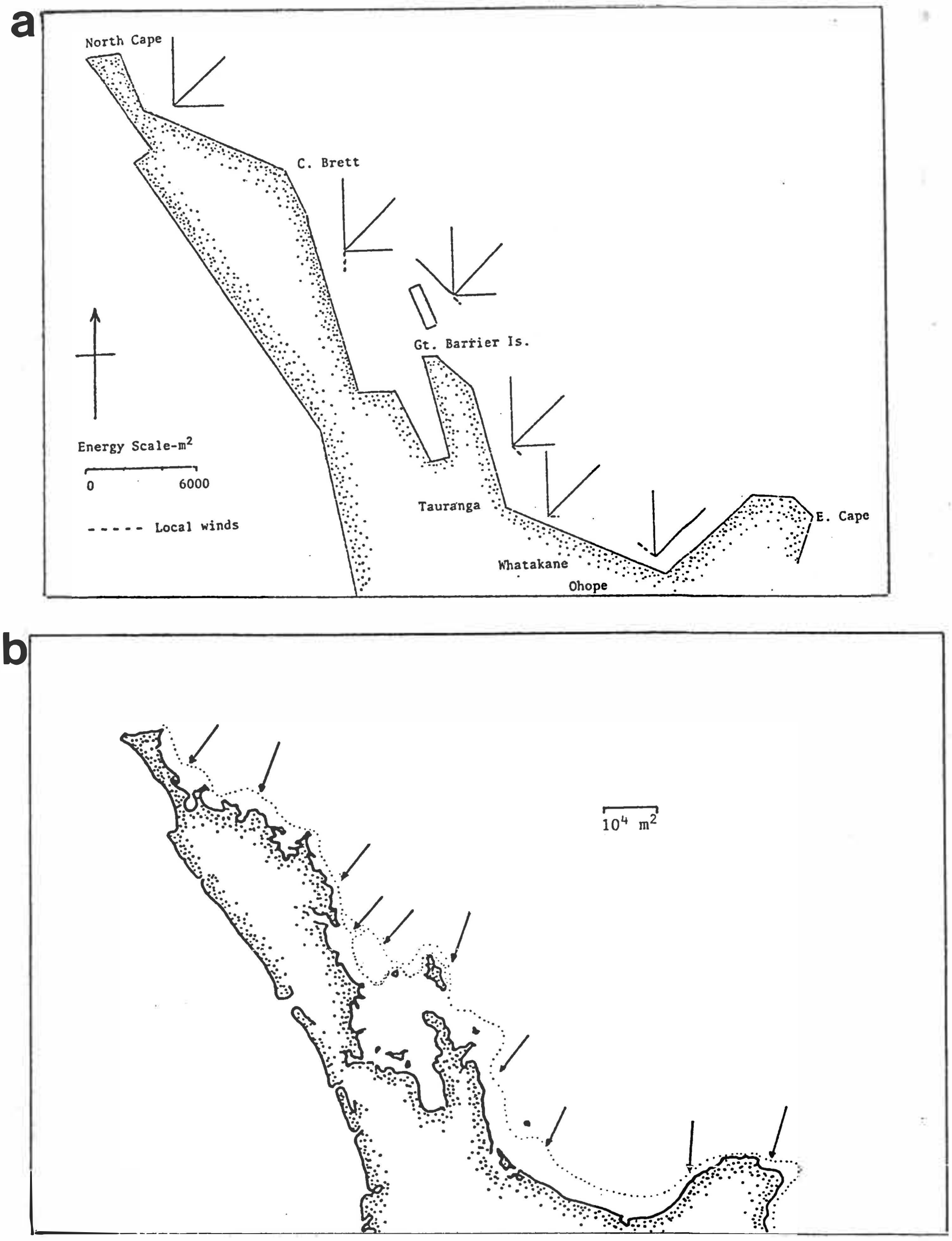


Figure 2.12a) Inferred energy roses; and ***b***) Magnitude and direction of net deep water wave energy approach, for the Bay of Plenty. *(source: modified after Harris et al. 1983)*

Harris *et al.* (1983) used results from Hicks Bay to infer deepwater (50 m) energy roses and extrapolate the directions of net wave energy approach for the Bay of Plenty coastline (Figure 2.12). These directions are usually approximately normal to the mean coastline and longshore transport of sediments is unlikely to be large, except on the two sides of the Bay of Plenty, which are subject to waves of significant obliquity. The wave energy impinging on the Bay of Plenty beaches appears to be fairly evenly balanced, with waves generated over local fetches probably determining the net longshore transport (Harris *et al.*, 1983).

2.8 Summary of the Study Area Setting

Important aspects of Pukehina-Matata regional setting include:

- The formation of the study area by downwarping of the Maketu Basin during the Pleistocene, faulting and collapse of the Whakatane Graben, and glacio-eustatic sea-level fluctuations forming coastal terraces along the entire area. Rapid sedimentation during the late Pleistocene and Holocene formed Pukehina Spit and the beaches fronting the coastal cliffs between Otamarakau and Matata. Hence, the Pukehina-Matata coast can be considered to consist of a veneer sand beach over a shore platform cut into a cliffed Pleistocene terrace.

- The main physiographic units of Town Point, Pukehina Spit, and between Pukehina Redoubt and Matata the continuous long narrow sandy beach backed by cliffs cut into Pleistocene terraces and feed by streams originating on the Kaharoa Plateau.

- The ultimate derivation of the beach sediments from the Taupo Volcanic Zone, and in particular Okataina Volcanic Centre, via fluvial inputs and cliff erosion of poorly consolidated volcanogenic catchment material. The mineralogy reflects these origins, with quartz, feldspar and volcanic glass major contributors to the bulk mineralogy, and hypersthene, augite, hornblende, cummingtonite, and titanomagnetite in the heavy mineral fraction.

- The occurrence of numerous greywacke pebbles limited to the Pukehina-Matata coastal sector.

- A micro-tidal, low to moderate wave energy coastal setting dominated by westerly winds, which are disrupted by storm conditions from the north to north-east associated with occluded mid latitude cyclones, sub-tropical Tasman Depressions, and decaying tropical cyclones.

- A mixed storm and swell wave environment, characterised by either low wave (H_S= 1 to 1.5 m, T= 4 to 9 s) or longer period swell wave conditions (H_S= 0.91 to 1.73 m, T= 8.3 to 13 s) during fair weather periods, with higher waves produced during storms (H_S= 1.0 to 5.0 m, T= 4.3 to 10.4 s), and rare storm conditions of up to H_S=9.0 m and T=12 s. This mixed wave environment producing characteristic 'cut and fill cycles' along much of the study area.

- Recent granting of a coastal permit in May 1993 to extract up to 36,000 m3 of sand from a four kilometre mining strip between Otamarakau and Pikowai. Previous sand mining at Otamarakau by Patterson and Sons Ltd. between 1987 and 1993 allowed for the removal of approximately 15,000 m3 per year over a 2.4 kilometre mining strip from Otamarakau to Hauone. Sand extraction within the study area has occurred since the 1960's at both Matata, prior to 1986, and presently at Otamarakau, and while the effect on the dune-beach-nearshore system is mostly unknown the frontal dune in both these areas has been largely destroyed.

CHAPTER THREE:

Beaches and Budgets

CHAPTER THREE:
BEACHES AND BUDGETS

3.0 Introduction

This chapter attempts to present a general review of existing literature, ideas and concepts dealing with beaches, sediment transport, littoral drift, and the use of heavy minerals tracers. Central to all topics is the beach sediment budget, which by definition is:

> *"a sediment transport volume balance for a selected segment of the coast.... based on quantification of sediment transportation, erosion, and deposition for a given control volume" (CERC, 1984).*

The sediment budget of any beach is governed by its morphological response to short term, seasonal, and long term variations in the wave environment and littoral drift. Essentially, when additions to the beach-dune-nearshore system are greater than losses from it, accretion occurs. Similarly, if losses from the system are greater than the additions, then erosion results. Overall, the volume of sediment gained or lost from the beach-dune-nearshore system during short term variations from the processes listed above is termed the *sediment budget* (Healy, 1974).

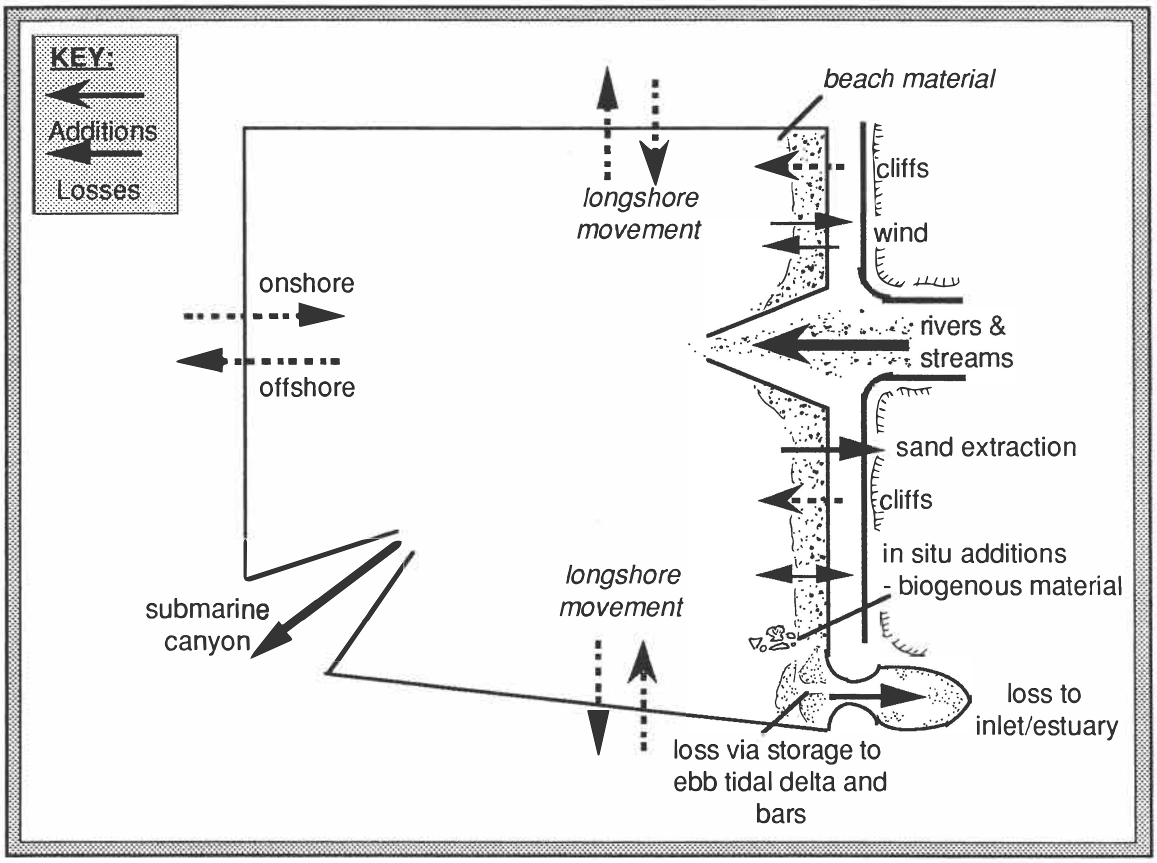


Figure 3.1 Schematic Sediment Budget. *(source: modified after CERC, 1977; Kirk and Hewson, 1978)*

From (Figure 3.1) sediment accumulation in the beach-dune-nearshore system may arise from: (1) littoral drift; (2) onshore movement from the continental shelf; (3) sediment discharge from streams or rivers flowing into the system; (4) artificial beach nourishment; (5) blowing sand from landward of the frontal dune; and (6) nearby cliff erosion (Bascom, 1960; Healy, 1974; CERC, 1984).

In terms of the beach from Pukehina to Matata, factors (1), (2), and (3) appear to be the main contributors to the sediment budget (Smith, 1986). Sediment additions to the beach-dune-nearshore system may also include erosion of the Town Point promontory and the Pleistocene cliffs fronting the section of coast between the Pukehina Redoubt and Otamarakau.

Conversely sediment depletion from the beach system occurs from: (1) littoral drift; (2) offshore movement of sand onto the continental shelf; (3) wind-blown sand from onshore winds and deflation of the frontal dune; (4) sand mining and quarrying; and (5) deposition of littoral sand in adjacent estuaries which are recognised sediment traps (Russell, 1968; Healy, 1974).

Littoral drift is shown in the sediment budget model as capable of transporting beach materials both into and out of either end of the defined limits of the beach. Consequently it is often the major component of the sediment budget of open-ended beach systems. Thus, after initially discussing the basic concepts associated with beaches and sediment transport, the importance of littoral drift to the beach sediment budget is detailed.

3.1 Nearshore Processes and Sediment Transport

The nearshore region is a zone of active bedload movement controlled by the height of waves, fluid shear stresses, and a complex pattern of bottom boundary layer currents (Niedoroda *et al.*, 1984). Sediment transport, either diabathic (onshore-offshore) or parabathic (longshore), occurs as two distinct types: (i) suspended load, and (ii) bedload. Suspended load exists when the moving grains are supported mainly by the surrounding fluid. Conversely bedload occurs when the grains are supported mainly by grain to grain forces (Neilsen, 1983). In reality this is difficult to define, particularly in discerning sediment budget estimations, since the proportions of each type of transport vary greatly within the dynamic littoral system. Hence, often this is loosely defined by grain size limits, typically gravel and very coarse sand is considered bedload, and all else suspended load (Murray, 1976).

It is important to recognise the distinction between bedload transport and suspended load transport, which amongst other things depends on the effects of wave power, wave motion and surface bedforms. Horikawa (1988, pp. 172-185), differentiates the various sediment transport modes into four main types and two sub-types in the second and third main types: 1) Bed Load (BL); 2) Bed Load-Suspended Load Intermediate (BSI); 3) Suspended Load (SL); and 4) Sheet Flow (SF).

The morphological characteristics of the nearshore zone which are of paramount importance in defining the extent of the littoral sediment budget are shown in Figure 3.2.

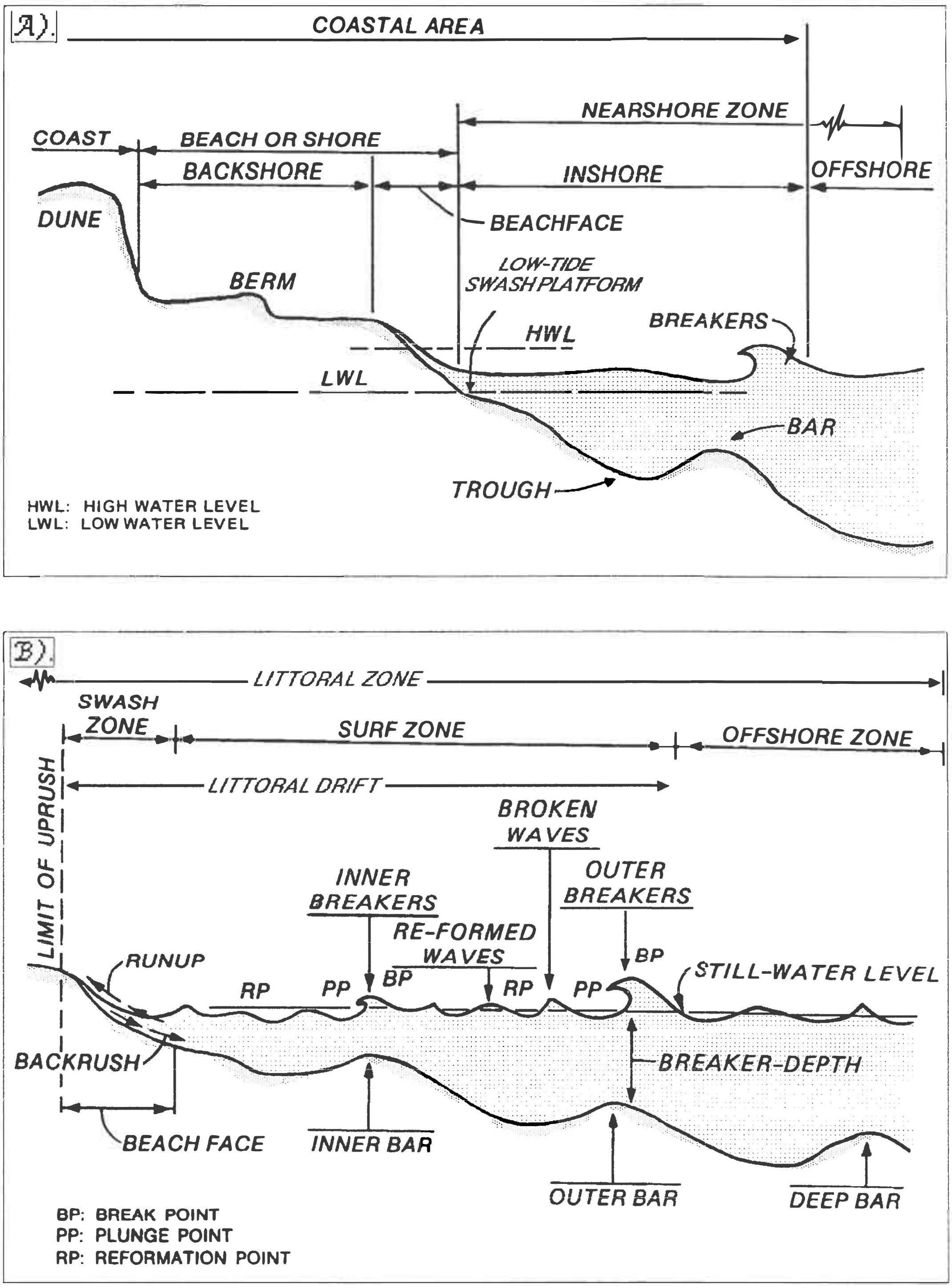


Figure 3.2 a) Morphology and b) dynamics of the nearshore zone illustrating profile characteristics. *(source: adapted after Larson and Kraus, 1989)*

Gradual shoaling of waves as they approach the shoreline leads to an increase in wave height with waves breaking when the ratio of the height of the breaking wave (H_b) to the water depth at breaking (h_z)is equal to 0.78. Seaward of this break point is the offshore region, and landward is the surf and swash zones. Within the surf zone wave bores propagate and dissipate their energy through turbulence, which initiates and maintains sand suspension. At the beach face the remaining wave energy is expended by a run-up bore as the water rushes up the profile before percolating into the sand or returning down the berm face as a backwash.

The width of the various morphological zones and the extent to which sediment transport occurs in each is dependant on numerous factors, such as wave energy, sediment characteristics, tide and wind conditions, and the antecedent beach state, all of which are related to the beach-dune-nearshore system morphology.

3.1.1 Surf Zone Transport

Sediment agitation by wave breaking and any subsequent reformation and secondary breaking is the principal factor affecting both longshore and cross-shore transport in the surf zone. Two other factors of importance to sediment transport in the surf zone are water level change associated with the tide, and mean currents, such as longshore current and the cross-shore return flow from the swash zone.

The variation in longshore sediment transport across the littoral zone is confined nearly exclusively to the swash and surf zones (Figure 3.3), as wave shoaling and subsequent breaking causes wave orbital velocities to increase at the nearshore bed surface, and entrain sediment.

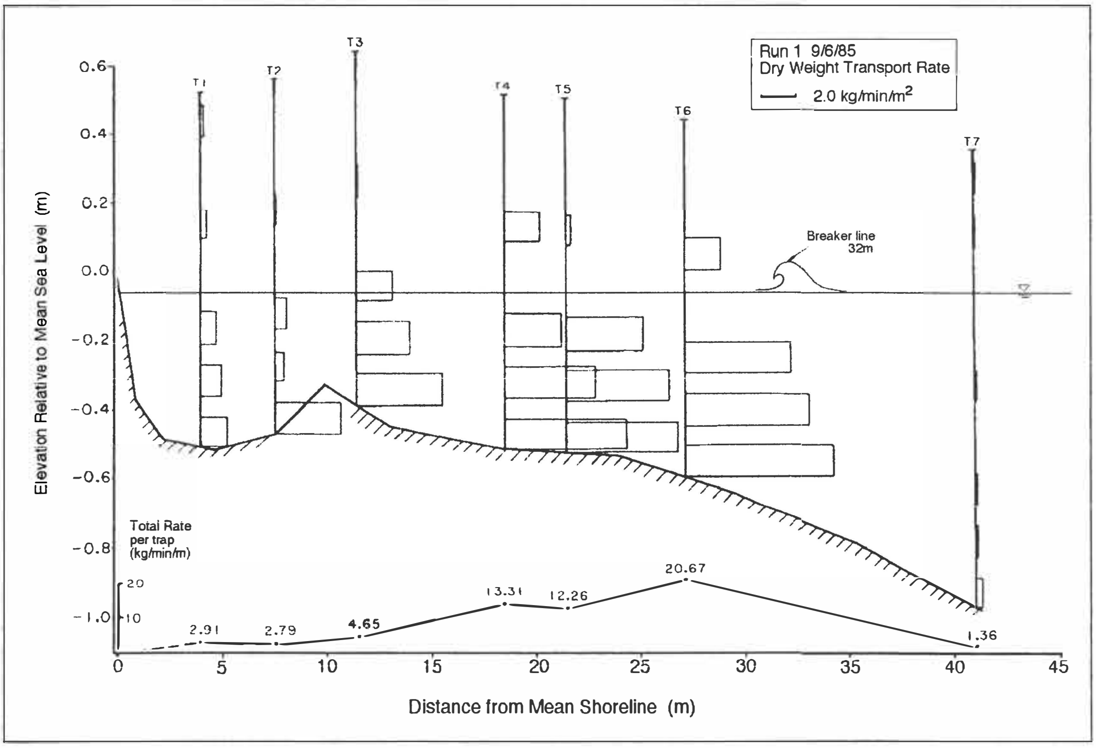


Figure 3.3 Measured vertical and cross-shore longshore transport rates, using streamer type traps. The bottom most peak represents bedload and some bedload-suspended load intermediate transported sediment, while the other vertical peaks are mainly suspended load. The diagram also shows that very little sediment is transported in the area seaward of the breaker zone. *(source: Kraus, 1987)*

3.1.2 Swash Zone Transport

The swash zone is the subaerial beach landward of the surf zone where waves rush up and down (Figure 3.2). Sediment transported across the shoreline by swash ultimately governs the long-term stability of the coastline (Hegge *et al.*, 1991). The swash zone has been shown for beaches in the

Bay of Plenty to be the area where the most significant accretion and erosion changes occur (Hay, 1991), and hence can be considered to be one of the most dynamic components of the beach system.

The beachface is subject to swash motion in two components, uprush and backwash. Uprush immediately follows the final breaking of the wave at the base of the beach and is distinguished by the rapid landward translation of a bore-like mass. Backwash follows the maximum uprush excursion (run-up) and is recognised by the gradual thinning and seaward movement of the swash mass (Emery and Gale, 1951).

When swell waves are long and low, the beach infiltration rate is high in relation to the volume of swash, and as a consequence, the backwash discharge is low. Sediment carried by the swash is deposited under these conditions. The reverse applies under high, short swell or sea waves. The backwash discharge is greater and entrains the sediments. Swash interactions, in which swashes either enhance or inhibit one another, inevitably lead to increased turbulence and thus increase the sediment potential at the shoreline. Hegge et al. (1991), recognised four distinct swash interaction modes, suggesting that the prevailing mode of swash interaction may be used as a convenient indicator of the morphodynamic state of a sandy beach.

3.1.3 Wave and Current Interaction

Niedoroda *et al.* (1984) have shown that the shoreface region of wave-dominated sandy coasts is a zone of active bedload sediment transport. The rate of sediment transport on the shoreface is strongly controlled by the height of waves which serve to entrain the bottom sediments. Sediment on the upper shoreface is entrained by relatively small waves and generally shifted landward during non-storm conditions. As a result of the asymmetrical wave orbital fluid stresses caused by non-linear nearshore waves, accretion of the shoreface sand reservoir occurs. The pattern of sediment transport on the shoreface during storm events is controlled by the fluid shear stresses and transport of water in the bottom boundary layer of the coastal ocean (Niedoroda *et al.*, 1984) .

Based on boundary-layer processes four distinctive hydraulic regimes can be recognised, of which two, the *inner shelf* and *shoreface*, are important to this study. The inner-shelf zone is characterised by storm-generated flows where friction is the most important dissipating factor. The boundary layers are thick and sediment transport is shear driven. The bedforms are generally more complex and the gradient steeper than in the mid-shelf zone. The shoreface zone is characterised by thin boundary-layers associated with wind-generated gravity waves, which dominate sediment transport. Typically the shoreface morphology is concave upwards (Bradshaw, 1991), with either barred or non-barred regions of coarse sediment at the shoreward boundary, grading seaward into relatively planar, finer sediments (Niedoroda *et al.*, 1985). The shoreface zone is very similar to the nearshore zone, which is defined mainly by morphology and sediment textural changes (Figure 3.2).

The dominant effects of storm conditions in the coastal boundary layer are usually to cause significant shore-parallel bedload transport, with an important shore-normal secondary component (Vincent *et al.*, 1981). However, the complex nature of wave-current interactions must always be considered, as depending on factors such as bed roughness and the horizontal angle between wave incidence and the mean current, the vector resultant of sediment flux may be opposite to the current and need not parallel either the wave incident angle or the mean current (Wright, 1987).

Understanding nearshore morphodynamics and sediment transport on the north-east coast of New Zealand has been furthered by Bradshaw (1991) for the east Coromandel shelf, who proposed a conceptual model for inner shelf dynamics and sediment transport during calm weather periods and episodic storm periods (Figure 3.4b), similar to Hilton's (1990) model for Pakiri (Figure 3.4a). Bradshaw (1991) found that the east Coromandel regional shelf current pattern which extends into the Bay of Plenty, is dominated by two mutually exclusive shore-parallel bottom currents which flow to the north and south.

3.2 The Beach-Dune-Nearshore System

The beach-dune-nearshore system is extremely important in dealing with littoral sediment budgets, since there is a definite need to understand the processes occurring within the whole system, in terms of an holistic approach, rather than concentrating on what is occurring in only one region.

The equilibrium beach is an open system easily modified by changes in the sediment budget and hence it is pertinent to briefly discuss the equilibrium beach concept. The equilibrium beach concept involves the interaction of all morphological components coupled with short term, seasonal, or long term variations in the wave climate and overall sediment budget.

The beach system consists of various morphological components which interact as a single dynamic system. Hence, for example, erosion of the foredune will result in sediment accumulation in the nearshore zone, in response to the *equilibrium beach* concept first suggested by Tanner (1958) (Figure 3.5). Over a period of time the beach outline tends to become moulded to an equilibrium shape dependant on the longshore sediment supply and the resultant wave regime, especially wave refraction. Under these conditions the beach is basically stable. However this stability is often masked by short term changes in beach morphology resulting from variations in the intensity of storms, swell direction and the rate of sediment supply. Such short term variation in beach morphology primarily results from the process of cut and fill, which has been found to be a common component of Bay of Plenty beaches (Christopherson, 1977; Harray, 1977; Hay, 1991), with accretion during summer months associated with settled weather patterns, and erosion during winter months resulting from episodic storm events and unsettled weather patterns. Beaches within the study area have been shown to typically be well nourished during the summer and autumn months (January to April) and reach maximum depletion in the late winter-early spring (August to October)

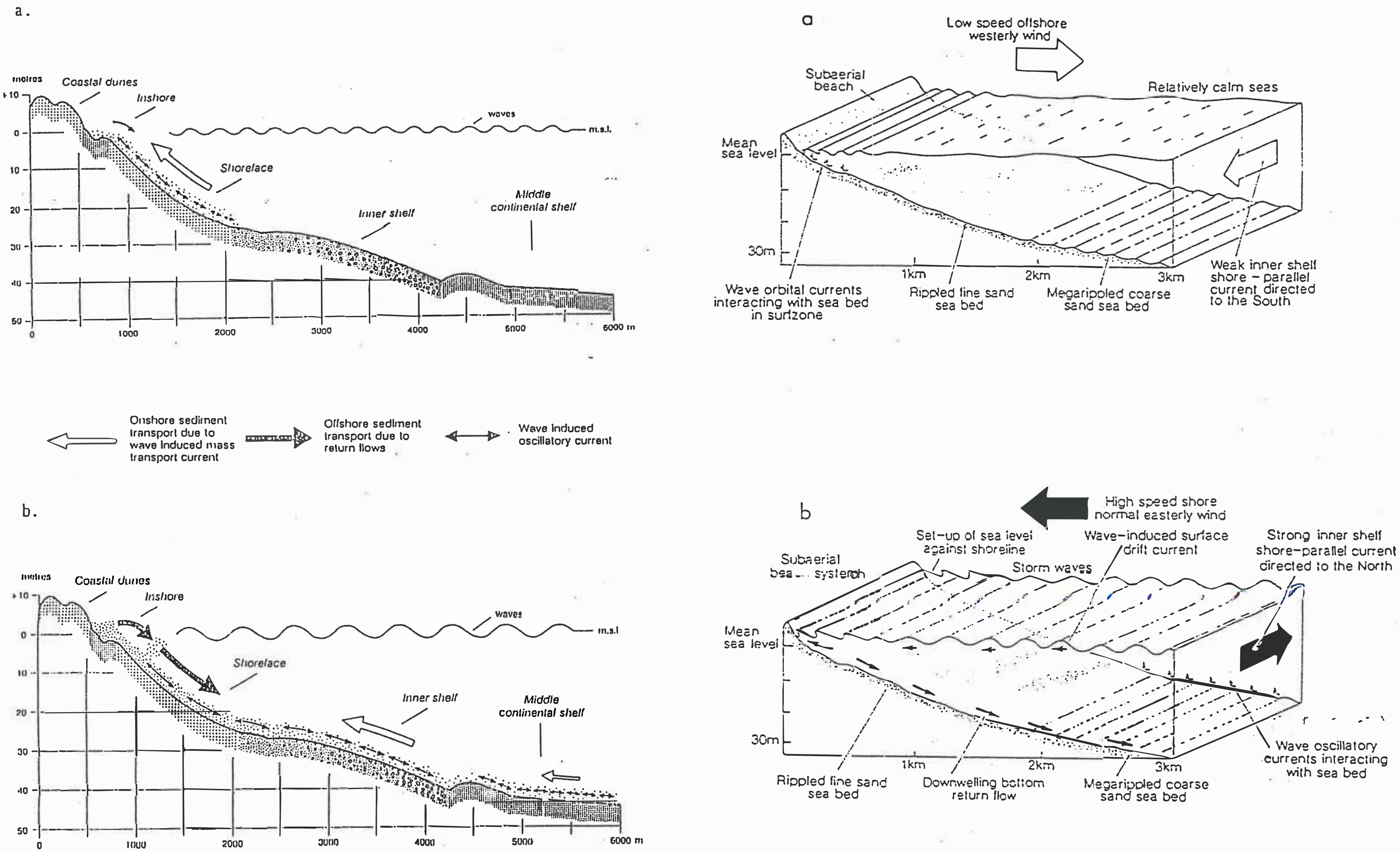


Figure 3.4 Conceptual models for inner shelf dynamics and sediment transport at **A)** Pakiri *(Hilton, 1990)* and **B)** East Coromandel shelf *(Bradshaw, 1991)*, during: *a)* calm weather conditions; and *b)* storm conditions.

(Smith, 1989). The period October to January appears to be the usual time for the landward migration of sediment to nourish the depleted beach deposits, in accordance with the equilibrium beach concept.

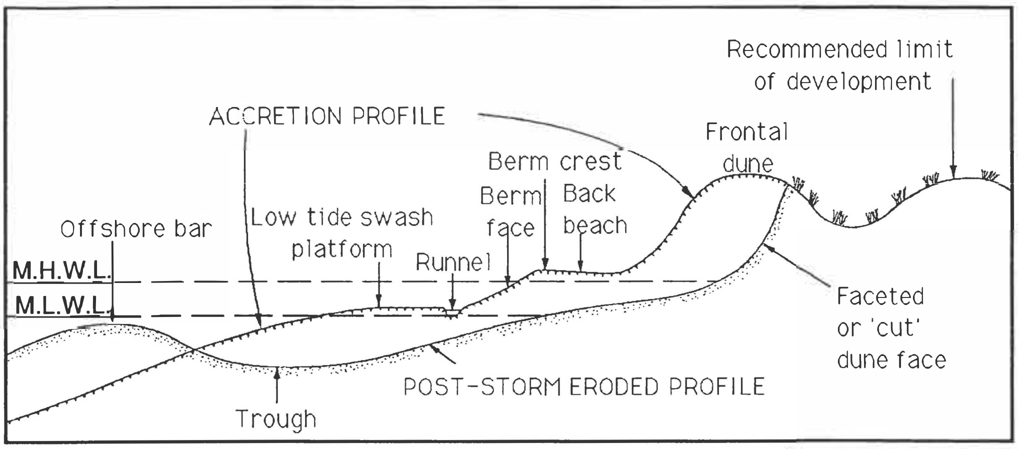


Figure 3.5 The model of the 'Equilibrium' Beach. *(source: Healy et al., 1977)*

Long period swell waves, in excess of 8-10 seconds, in which the ratio of wave height to wave length (steepness) is small tend to build up the beach, leading to accretion of the beachface and berm development characteristic of an accreting beach system. The constructive characteristics of these long period waves is determined by the large horizontal energy release as the surf is washed up the beachface. The long period spilling waves travel up the beachface carrying beach material in the swash, percolation of some of the water through the beach material reduces the power of the backwash and a significant proportion of the material is deposited on the beach face with each arriving wave. By contrast the shorter period and steeper waves tend to tumble on breaking and expend all their energy over a narrow width of the beachface. The near vertical water movement generates a bottom current seawards carrying beach material out to beyond the break point of the waves (King, 1972). The short period between breaking waves and the narrow stretch of beach affected does not allow sufficient time for water to drain out of the beach deposit before the next wave arrives. Thus the sediment is partly buoyant and less cohesive than normal and is easily transported seawards.

Wind conditions can also effect the beach response to wave conditions. King and Williams (1949) first demonstrated that onshore winds cause erosion while offshore winds cause accretion on the beachface. The onshore winds tend to push the wave crest over itself upon breaking, causing similar conditions on the beachface as those caused by steep waves. The wind driven surface mass of water escapes seawards along the sea floor after the wave has broken and carries beach sediment to beyond the break point. Offshore winds conversely hold up the wave crest and also create a surface driven current seawards. The combined effect of the surface current and wind pressure cause the wave to wash up the beach carrying sediment with it and building up the beach. During storms (such as the Wahine 1968 storm and July 1978 storm) the combined effect of large, steep waves and persistent onshore winds causes significant erosion to the sediment stored within the beach-dune system. This material is taken offshore to form bars, which under accretionary conditions are brought back onshore to accrete the beach.

The factors which influence periodic episodes of erosion, given by the post-storm eroded profile, are detailed in Table 3.1, illustrating how erosion can be more or less severe depending on the coastal environment at any given time. Storm surge has a large determinative effect on beach erosion, since the sea level elevation during a storm event is determined by a combination of tidal level and storm surge. Storm surge is described by Heath (1979) as the change in mean sea-level under storm conditions that results from the re-adjustment of the sea-surface to atmospheric pressure, alongshore wind transport of water onto or away from the coast, and the direct wind set-up due to winds blowing perpendicular to the coast. This elevation is therefore a major determinant of the extent of foreshore inundation and wave induced erosion. During a storm with higher sea-level elevation, beach erosion takes place in order to provide sediments to the nearshore so that the nearshore bottom can be elevated by an amount equal to the rise in water level (Hay, 1991).

Table 3.1 Factors influencing erosion on clastic beaches. *(source: Kana, 1977)*

Main factors	*Sub-factors*	*Increased tendency toward erosion with (high/low) values**
Storm Processes	Wind velocity	High
	Wind direction	Variable
	Wave height	High
	Wave period	Low
	Wave steepness	High
	Longshore current	High
	Storm duration	High
Beach	Sediment size	Low (to silt size)
	Degree of lithification	Low
	Morphology	
	slope	High
	rhythmic topography	Variable
Water Level	Tide surge	High
	Storm surge	High

* For example, erosion tends to increase when wave height is *high*, wave period is *low*, and beach slope is *high*, *etc.*

Storm damage may be increased when storms with low pressure systems and high onshore winds coincide with tidal extremes. If storms occur during periods of spring tides, the still water level will be elevated to a greater extent and storm waves will break further up the beach profile.

3.3 Onshore-Offshore Sediment Supply

Onshore transport of sediment from the marine environment can arise in two distinctly different ways. Firstly, in the long-term there may be a net gain of sediment to the beach resulting from the onshore movement of sediment from the continental shelf. Secondly in the shorter term, sediment may move onshore following seasonal or storm-induced beach profile changes, especially during occasions of long period swell waves. However, such onshore movements in the second case can be considered to 'average out' in the long term, with any sediment that migrates onshore and offshore in the immediate nearshore zone as a result of seasonal changes still contained in the sediment budget boundaries, governed by the depth to active sediment movement.

The role of sediment supply outside of budget boundaries, from the inner continental shelf, is difficult to determine accurately and is generally an unknown component of the littoral sediment budget (Bowen and Inman, 1966; Smith, 1986). Although the relative contribution of sediment from the continental shelf to the sediment budget is small compared to other components of the budget, it has been shown nevertheless to occur (Saville, 1961; Bowen and Inman, 1966; Pierce, 1969). Several such examples exist from work carried out in New Zealand:

- Dingwall (1974) studied the bay-head sand beaches of Banks Peninsula. Evidence from sediment textures and mineralogy suggested that some of the beaches that were accreting derived a portion of their sand from longshore-drifted sediment on the adjacent continental shelf.
- Thoms (1981), analysed sediment texture and rollability to help determine sedimentation patterns in the New River estuary, Southland. Results from the analysis identified the adjacent continental shelf as the dominant external source of medium-fine sand, therefore indicating onshore movement.
- Four rapidly prograding sand beaches on along the north-eastern flank of the Otago Peninsula were studied by Nicholson (1979). He found that the entire sand sequence could have accumulated within the last 200-500 years. Because the beaches were isolated from active river sources the author concluded that the sand must be derived from the continental shelf.
- O'Brien and Associates (1992, p. 30) in studying the littoral system between Pakiri and Mangawhai, estimated that in order to balance the sediment budget, onshore sediment transport was about 160,000 m^3 annually, or 46 % of the total budget.
- At Mt. Maunganui sediments dumped offshore since the early 1960's, in 20-30m water depth, have moved onshore onto the beach, based on long-term beach accretion, and evidence from shell species and sediments found on the beach which are associated only with the harbour environment (Healy *et al.*, 1991).
- Foster (1991) from a sediment dye tracing experiment and repeated nearshore profiling at Mt. Maunganui Beach similarly found significant onshore movement of dumped material.
- Smith (1986) determined that onshore drift within the Otamarakau-Matata coast was a common source of beach material concluding that *"too little information is available about both the material and the wave environment to estimate the potential supply from this source"*.

Movement of sediment offshore, out of the littoral budget boundaries, and onto to the inner continental shelf is mainly restricted to suspended load. Carter (1986) in devising a Holocene sediment budget for the South Otago continental shelf, found that suspended load (v. fine sand and mud) accounts for over half of the sediment input and is nearly all transported from the area to accumulate in north-easterly shelf and slope depocentres. Since the majority of suspended load is transported offshore it has less long-term effect on the sediment budget of the littoral zone in comparison with bedload material of sand and gravel size.

3.4 Littoral Drift

Coastal sediments record the long-term average result of near-coastal water movements; as summarised by Carter (1980) and Heath (1981, 1982), these movements contain many independent elements and are very complex, however, near to shore wave-induced littoral drift tends to dominate. The open coast beach system of the study area is exposed and subjected through a 180° arc to the energy inputs of the offshore wave environment. Consequently it is characterised by a movement of the constituent materials in both directions along an axis parallel to the shoreline. This longshore component of movement caused by the interaction of coastal processes is commonly termed 'longshore sediment transport', 'parabathic transport', or 'littoral drift', and is a major factor in the dynamics of coastal environments, exerting a strong influence on the littoral sediment budget. Net littoral drift is most often used in coastal studies, as this is the combined effect of the gross littoral drift in the two alongshore directions within a beach system over a year period negating seasonal variations when littoral drift may vary in direction.

Littoral drift is the main mechanism by which sediment is supplied to the beach, with 80-90% of the littoral drift occurring within the breaking wave zone, i.e. between the offshore bar and the MHWM (King, 1972; Komar, 1976; Kraus and Dean, 1987).

Direct measurements of littoral drift have been extremely difficult to make, so normally indirect methods are employed, although in recent years work on using sediment traps and ultrasonic flux meters have proved relatively successful (e.g. Kraus *et al.*, 1982; Kraus, 1987; Horikawa *et al.*, 1988; Seymour, 1989). Accordingly three main methods have been used: 1) Measuring the rates of accretion or by-passing of sand at a littoral barrier such as a jetty or breakwater: 2) Computing the littoral drift from statistical wave data utilising an equation which relates the two; and 3) measuring the rate of dilution of heavy minerals within the beach sands (Komar, 1976).

Various equations have been formulated to calculate both the longshore current and the rate of sediment transport (Komar and Inman, 1970; Longuet-Higgens, 1970; Komar, 1976; CERC, 1984). Most quantitative calculations of littoral drift consider sediment to be moved as a progressive conveyor belt of sand, subject to the dominant wave direction and power. However it is fairly well established that sandy beaches possess at least three distinctively different kinds of nearshore circulations (Figure 3.6) under different conditions of energy and slope (Komar and Inman, 1970). In each case it is known that the circulation pattern is the dominant control on the pattern of sediment movement, with the angle of wave approach determining the circulation which occurs. Within the study area it is likely that all three types of longshore transport may occur.

In the rip cell circulation concept there is no overall net unidirectional transport, due to the low to zero angles of incidence creating only rip currents flowing seaward which are feed from feeder currents flowing parallel to the shore. More moderate angles of incidence tend to produce progressive rip cells that are feed from only one direction, and migrate alongshore with the direction of wave approach. Littoral drift in this case (Fig. 3.6b), may arise from both cell migration and interactive flow. The final circulation pattern is the simplest, and is essentially a one-dimensional, uni-directional flow that transports material as a river or conveyor belt of sand along an axis parallel to the shoreline. This situation arises in conditions of high angles of wave approach and the main sediment transfers are alongshore (Neale, 1987; Komar and Inman, 1970).

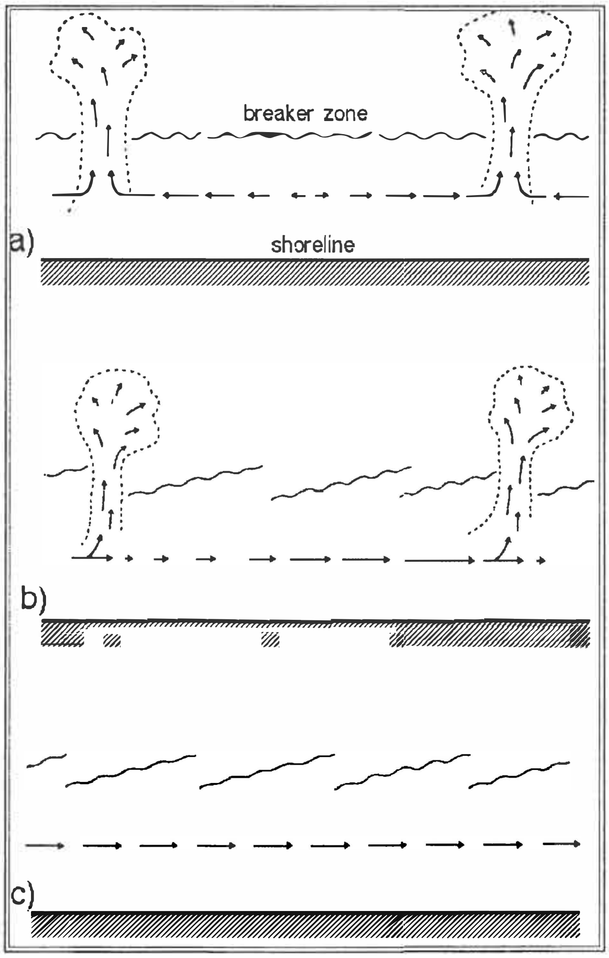


Figure 3.6 Circulation types due to different wave angles on a sandy beach. ***(a)*** rip cell circulation, resulting from the interaction of incident waves with edge waves. ***(b)*** progressive rip cells, a combination of a & c. ***(c)*** river of sand approach. *(source: Komar and Inman, 1970)*

The 'river of sand' circulation type causing littoral drift is often that envisaged to occur on sandy beaches and is usually the basis of littoral drift models, due to its one-dimensional simplicity. However, the circulation type depends a great deal on the angle of wave approach, which due to wave refraction is often perpendicular to the shore and hence little alongshore transport results. Most circulation patterns, are associated with rip currents of one form or another, although this depends on the beach state, which significantly effects the littoral drift regime.

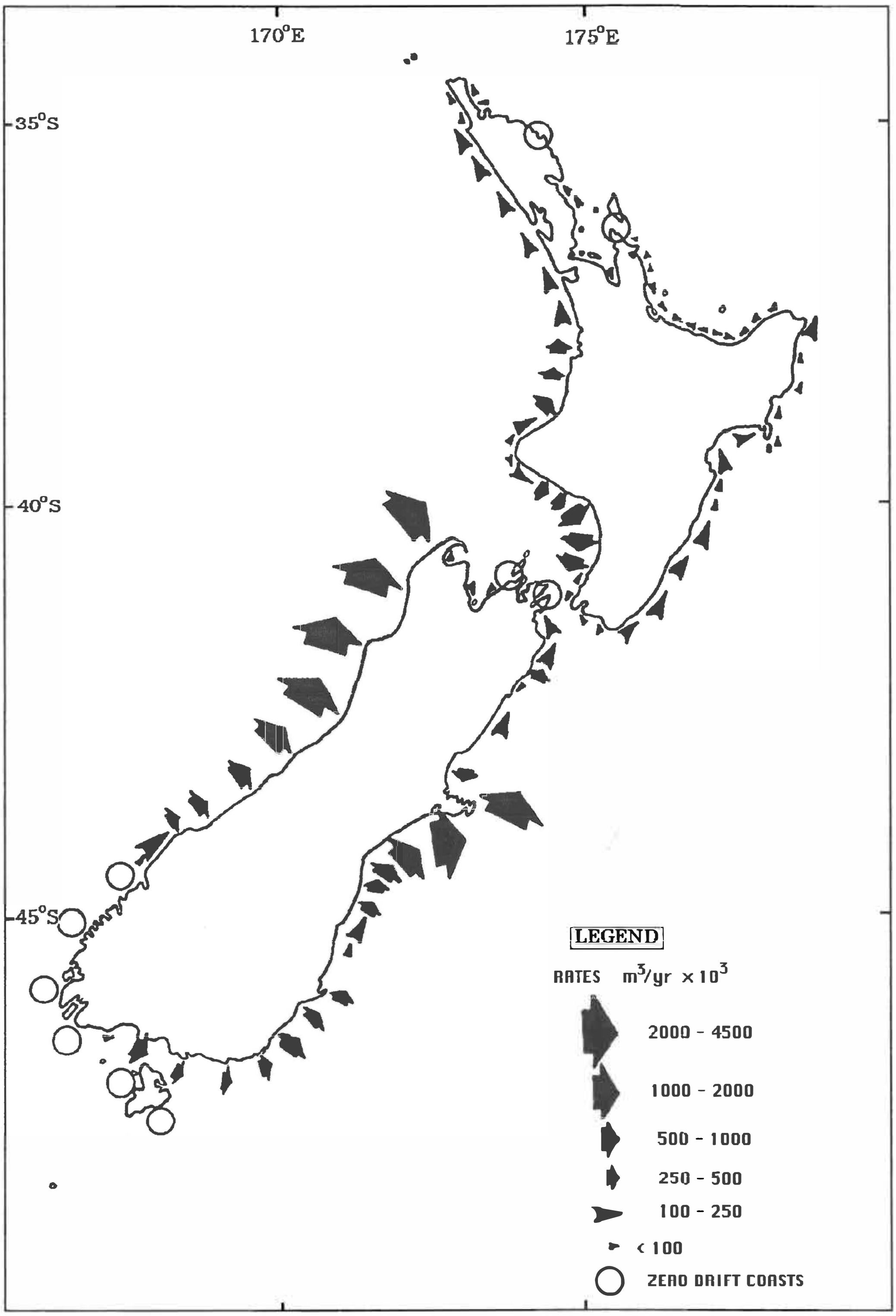


Figure 3.7 Sketch of inferred net littoral drift directions and estimated approximate volumes of sand and gravel transported, for the New Zealand coastline. Note that transport directions are based primarily on geomorphic evidence. *(source: Gibb, 1983)*

The differences in beach state, as shown for example in the Wright-Short model (Wright and Short, 1983), which govern beach slope, grain size etc., in turn influence the littoral sediment transport that occurs, and may vary along a beach, seasonally, and with variations in the tide. For example, on a steep, coarse sandy beach, in a reflective beach state in which the incoming waves break at the beach face, the main parabathic sediment transport is confined to the swash zone, and is the result of swash interactions. In contrast on a low angled, fine sandy beach, in a dissipative beach state, in which waves break on the offshore bar, littoral transport occurs in the breaking wave zone.

3.4.1 Littoral Drift Estimates

Gibb (1983), produced a map depicting relative net littoral drift rates and directions for the entire New Zealand coastline based on collated evidence and estimates (Figure 3.7). Much of this is speculative as very few investigations on littoral drift have been carried out, and the majority of drift estimates are based on geomorphic evidence (Gibb, 1979). The direction of littoral drift for the Pukehina-Matata coastal sector for example is based solely on the morphological indications provided by the orientation of Pukehina Spit. Most semi-quantitative estimates are derived from port and harbour dredging records, such as for Timaru and Tauranga.

While the general net littoral drift in the Bay of Plenty is evidently considered south-eastward at present, during the Pleistocene it may have been in a north-west direction, since much of the Coromandel coastal sediments are derived from the Taupo Volcanic Zone, which suggests that the sediments would have been discharged at the Bay of Plenty coast and transported northwards. Such a north trending littoral drift was probably the result of different wind and current regimes which operated during the Pleistocene glacial maximum, particularly greater southerly generated winds (Harray and Healy, 1978).

For the Pukehina-Matata section of the Bay of Plenty coast the littoral drift rate is estimated at between 50,000 m^3 to 100,000 m^3, based on studies centred in and around the Tauranga Harbour entrance with littoral drift considered greatest near Tauranga Harbour and decreasing towards Ohiwa Harbour. For example, Hicks and Hume (1991) give a littoral drift estimate of 70,000 m^3 at both Ohiwa and Tauranga Harbours, thereby assuming a constant rate of sediment transport along the entire section of coast. From harbour maintenance dredging at Tauranga the net littoral drift is estimated at about 50,000 to 70,000 m^3/yr (Hume and Herdendorf, 1992). The inferred directions of littoral drift for the Bay of Plenty are shown in Figure 3.9.

3.4.2 Direction of Littoral Drift

The actual littoral drift direction for the Pukehina-Matata section of the Bay of Plenty coast is not known with any degree of certainty. One of the main reasons for this is the orientation of the Maketu and Pukehina Spits in opposing directions. Jacobsen and Schwartz (1981) suggest that the downdrift orientation of the axes of coastal spits is *"one of the most reliable indicators of net shore-drift direction"*. Normally, spits orientate themselves in the direction of the net littoral drift, which would imply that longshore transport should result in sediment build-up at Town Point, an idea which is yet to be supported by any conclusive evidence. It may be that the Waihi estuary enters the littoral zone in the shelter of Town Point, where the wave energy is lowest and thus the spit orientation of Pukehina Beach is due more to the estuary than the littoral drift regime. Therefore three options are proposed (Figure 3.8):

(i) South-easterly conveyor belt drift (SED). The entire Bay of Plenty coast is thought of as a single littoral drift system by many authors, with evidence pointing to littoral drift in a south-easterly direction along the entire coast.

(ii) Predominantly south-easterly drift (PSED). Although regional littoral drift is to the south-east, a counter-drift system or cell may operate in the vicinity of Pukehina, which would account for the paradoxical orientation of the Pukehina Spit to the north-west.

(iii) Town Point convergence drift (TPCD). A view supported by some (Gibb, 1983; Smith, 1986; Smith *et al.* , 1992) is that littoral drift is in two opposing directions along the coast, and that the nodal point is situated at Town Point. Several problems with this idea exist. Firstly, if sediment is being transported to Town Point then there should be a definite sediment build-up in the area, presently although this occurs on the Maketu side of Town Point the nearshore and offshore zones at Pukehina do not show significant sediment accumulation and have relatively steep profiles. Secondly evidence from previous studies shows that littoral drift at least in the Rangitaiki Plains is definitely moving to the south-east (Healy *et al.*, 1977; Healy, 1978).
Smith (1989; pers. comm., 1992) does however site evidence from local fishermen in the area, and from beach profile monitoring at Newdicks beach, southern Town Point, that sediment infilling in the nearshore and offshore zones is occurring.

Murray (1978) suggests that both the Maketu and Little Waihi Spit (Pukehina Spit) reflect the northwest to southeast littoral drift of the Bay of Plenty as assessed by Healy *et al.* (1977). Pukehina Spit is however suggested as somewhat protected from the northerly or north-easterly swells thus permitting the southeast flow of sediments. Since here the easterly swell component is more important, counteracting the destructive northerly and northeast swells.

Murray (1978) also suggests that the Pukehina and Maketu spits are supplied with sediment from different sources. The Maketu spit receiving sediment from the adjacent littoral system and the Kaituna River, while the Pukehina Spit receives most of its sediments directly from the Pongakawa and Kaikokopu rivers which flow into the Waihi Estuary. His reason for suggesting two different systems is that Town Point acts as a partial barrier to the littoral drift and severely restricts sand movement to the southeast in the littoral system. The evidence given to support this is that, firstly, if large volumes of sand were bypassing Town Point a dominantly sandy bottom off Town Point would be expected. Instead a rocky bottom often covered in mussels is found, and secondly, where rocks are sparse, e.g. about 0.8 km off Town Point, a mud bottom is present.

While Pukehina Spit morphologically reflects a north-east directed littoral drift system, it is known that spit orientation is determined by a combination of factors, including inlet channel

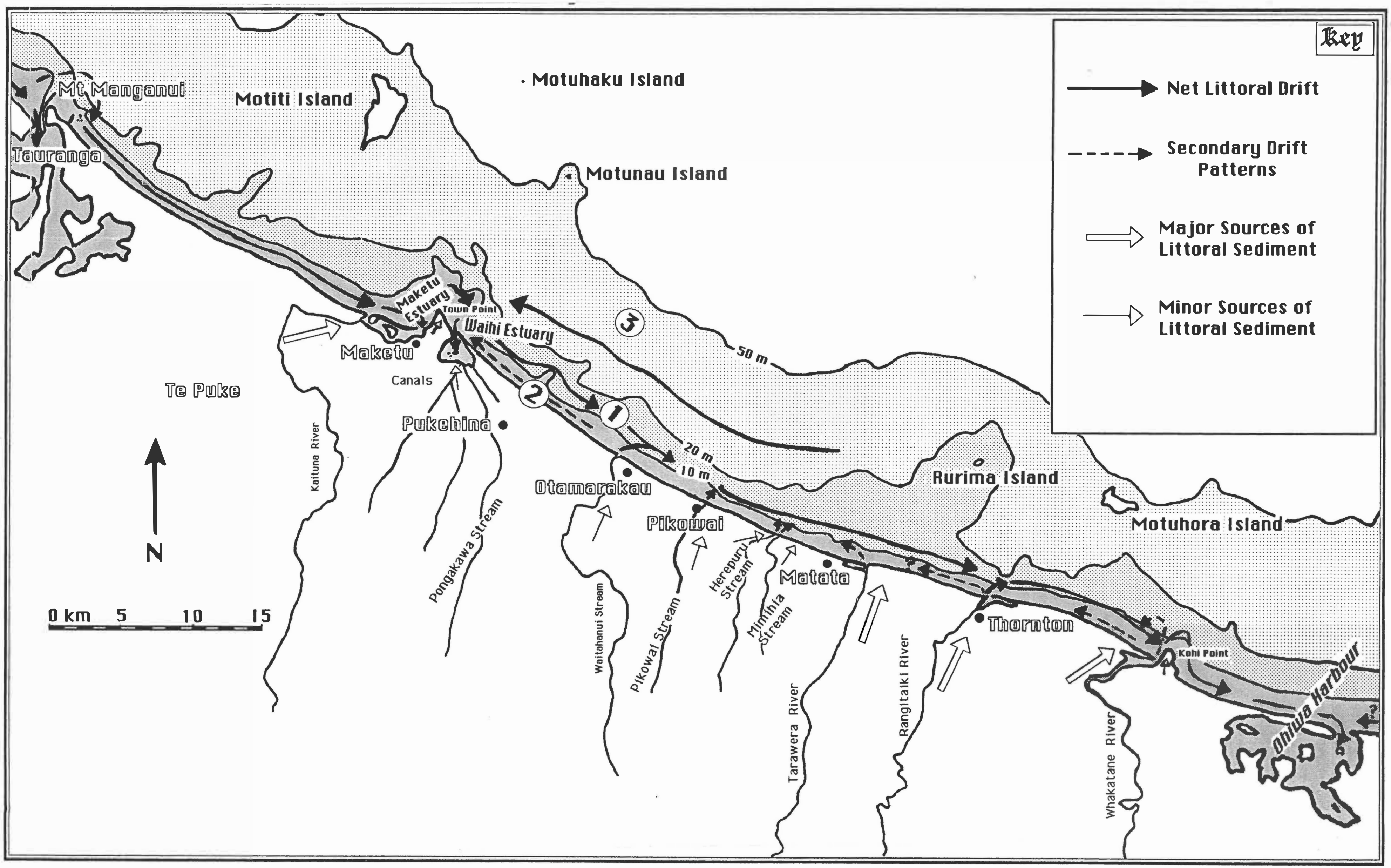


Figure 3.8 Options for inferred net littoral drift direction within the Bay of Plenty, highlighting the Pukehina-Matata coastal sector. Circled numbers correspond to the three possible options: **1** south-easterly conveyor belt drift (SED), **2** predominantly south-easterly drift (PSED), and **3** Town Point convergence drift.

geometry, wave energy, wave refraction, and tidal flow. Consequently spit orientation may sometimes be contrary to dominant littoral drift (Hayes *et al.*, 1970; Hubbard, 1976; Lynch-Blosse and Kumor, 1976). A further example, is the Mangatawhiri Spit, which lies 60 km north of Auckland. Bridgwater (1986), found that although the spit was orientated in a north-south direction with the estuary located at its northern end, littoral drift was actually bi-directional with movement of sediment along the spit from near the centre to both the north and south.

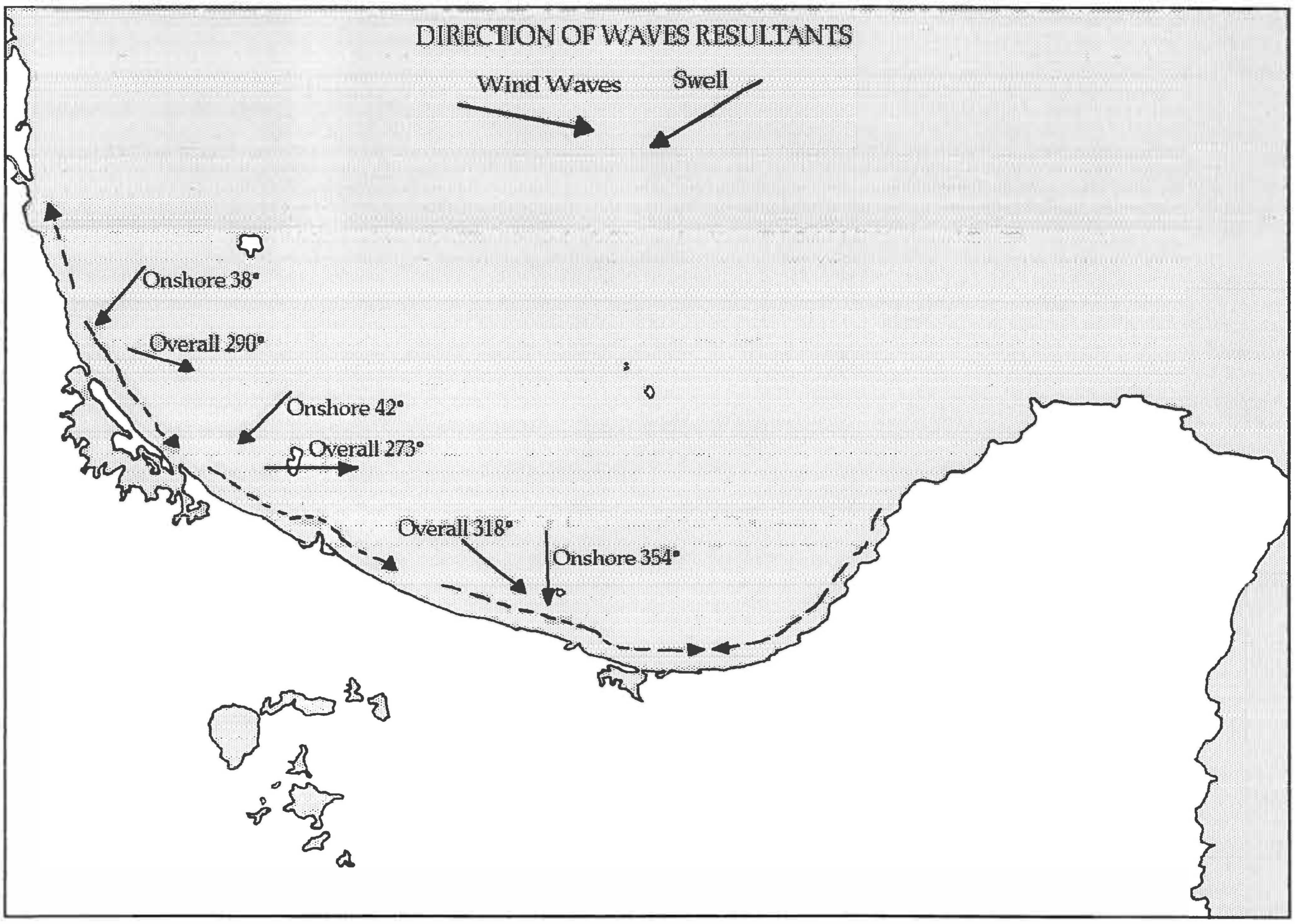


Figure 3.9 Direction of littoral drift of sediments along the Bay of Plenty coastline as proposed by Healy *et al.* (1977), coupled with wind (Harray, 1977; Healy, 1976) and wave (Quayle,1984) resultants. *(source: modified after BOPRC Overview Report, 1991)*

The lack of present understanding of littoral drift in the Pukehina-Matata study area is summarised in Healy *et al.* (1977), who concluded that:

> *"From Pukehina to Matata there is little evidence for determining the direction of net littoral drift and the coast appears to be in close equilibrium with the present wave conditions."*

3.5 Sediment Tracers

Evidence on the direction of sediment movement and the origins of sediment deposits can be found using tracers. Tracers when used in sedimentological studies can be defined as "*any property or characteristic that makes it possible to follow the dynamic behaviour of a sediment*" (Sauzay, 1973), and are of two broad types: *artificial*; and *natural*, if they are already part of the coastal system and have not been intentionally added.

Natural tracers are used primarily for background information about sediment origin and transport, in which an understanding of littoral drift is required over a long period of time, they also have the advantage of averaging out short term trends in sediment transport. In contrast artificial tracers, are commonly used to determine littoral drift over a very short period, as well as variations in sediment supply both cross-shore and longshore.

A variety of natural tracers have been used to study sediment transport. The use of natural tracers may be based on the presence or absence of a unique mineral or sediment compositional species, the relative abundance of a particular group of minerals within a series of samples, or the relative abundance and ratios of many mineral types in a series of samples (CERC, 1984). Examples of the use of natural tracers, such as heavy minerals are moderate (Cherry, 1965; Judge, 1970; Christopherson, 1977; Healy, 1978; Miller, 1981; Healy, 1982), since most studies concentrate on short-term changes in sediment transport and supply in which artificial tracers are more useful, rather than changes over hundreds or thousands of years. Other examples of natural tracers other than mineral suites do exist in the literature. Coulbourn and Resig (1975) used foraminifera as natural tracers in an Hawaiian bay. Of the 53 species of forams found in sediment samples from the bay, 16 species had distribution patterns that provided evidence on sediment transport directions. Similarly, shell species have been used to indicate sediment transport directions from source by progressive breakdown (e.g. Lingwood, 1976). Matthews (1980a, 1980b, 1982) used limestone chips as tracers in a study on the sediment transport and cliff erosion near Wellington. By using a foreign rock type, such as limestone, in a gravel beach consisting nearly entirely of greywacke, it was possible to monitor sediment movements, and calculate rates of abrasion, in the littoral zone.

Another interesting method is measuring the rollability of sediments, based on grain shape. Winkelmolen (1969, 1971) measured the rollability of sand grains to provide a measure of sand grain shape. By computing the relative rollability values of a number of samples, sources and sinks of sediment could be identified. Kirk, 1977, used this technique at Timaru to show that very fine sand moves in an offshore direction, while medium sand moves in a longshore direction associated with a northerly directed littoral drift. Similar work by Hastie (1983), found that the predominant transport directions are onshore-offshore for most sediment types in the region rather than alongshore as noted by other authors.

3.5.1 Heavy Minerals as Tracers of Sediment Source and Transport

The presence of naturally occurring heavy minerals in beach sediments can be used both qualitatively and quantitatively as indicators of the source and transport of sands to the beach system.

Heavy minerals such as hypersthene, augite, hornblende, and cummingtonite, are common in the sediments of the Bay of Plenty (Healy *et al.*, 1977), and occur in differing abundances along the coast as a result of differences in source locations of the parent material from which the minerals are derived and from littoral drift transport. Hence the presence in a beach sand deposit of a particular heavy mineral or suite of heavy minerals can indicate the erosion of a certain rock type as the partial sediment source. By analysing the distribution of heavy minerals along a beach system and from cliffs, streams & rivers, it is possible to pinpoint sediment sources as well as the relative contributions of material to the beach sediment budget. Further to this the direction of littoral drift may then be determined, due to a fining from source of a particular suite of heavy minerals or specific tracer minerals such as cummingtonite.

Healy (1978), undertook mineralogical analysis of sands from the Rangitaiki Plains foreshore adjacent to the study area, and pertaining to this noted that:

- There is a large input of both volcanic glass and alkaline feldspar from the Tarawera River.
- The mineral ratios, especially feldspar:glass and quartz:glass, provide an excellent reflection of sediment transport patterns because the glass is soft and weathers very rapidly in the dynamic breaking wave environment.
- The distribution pattern of the blade-like amphibole crystals makes them very good natural tracers, especially cummingtonite, and gives a clear portrayal of the sediment movement patterns.
- Concentrations of magnetite are associated with eroding, or at best, unstable sectors of the shoreline.

3.5.2 Previous Work on the use of Mineral Tracers

Overseas examples of the use of heavy minerals for predicting sediment transport, were relatively commonplace in the 1950's and 60's (Cherry, 1965; Cherry, 1966; Handin, 1951; Inman, 1953; Judge, 1970; Sayles, 1966; Trask, 1952; Yancey 1968). But with the increased use of artificial tracers, and more modern methods of quantitatively measuring littoral drift, the technique is less widely mentioned in the literature.

One of the best known examples is that of Judge (1970) from a study along the California coast, on the use of heavy minerals in beach and stream sediments as indicators of shore processes. He found however that for this area heavy mineral suites were unsatisfactory as indicators of the direction of longshore transport, due to the lack of unique mineral species and any distinctive alongshore trends. In contrast, nearly all other workers have found heavy minerals important indicators of the direction of coastal sand movement (e.g. Cherry, 1965; Wilde and Case, 1977)

Previous work on the use of heavy minerals as indicators of sediment transport has been undertaken on a fairly limited scale throughout New Zealand. Two major reports inferring littoral drift directions based in part on mineralogical analyses are the Bay of Plenty Coastal Erosion Survey

(Healy *et al.*, 1977) and the Coromandel Erosion Survey (Healy and Dell, 1982). Other relevant examples are:

- Healy (1978) on the basis of heavy mineral analysis showed that the sands of Mataora Beach, on the eastern Coromandel, originated from erosion of the surrounding Beesons Island Volcanics rather than the Minden Rhyolites outcropping further north. Thus Mataora Beach was effectively an isolated pocket beach system, in which there was no sediment exchange with the beaches on either side.

- Similarly, Christopherson (1977) for nearby Whiritoa Beach showed that the beach sediments originated from erosion of catchment rocks, and that no sediment exchange via littoral drift existed.

- Bardsley (1977), analysed two heavy mineral suites as sediment tracers, one of volcanic and the other of plutonic origin, correlating heavy mineral dispersion with sediment transport in a predominantly northerly direction on the Otago-Southland coast.

- Miller (1981) used heavy minerals as a means for divulging sediment sources and the direction of longshore sediment transport for Poverty Bay in the vicinity of the Port of Gisborne.

- Hamill and Ballance (1985), showed that the net littoral drift on the Waitakere coast, near Auckland, is to the north. Longshore trends in the beach sands included: a slight fining to the north, a reduction in rock fragments, an increase in heavy mineral content, and a decline in the feldspar to quartz ratio.

- Bradshaw (1991), in a study of the Eastern Coromandel, found that in comparison to dune mineralogy, beach sands show more noticeable trends in their composition, indicating a stronger influence on beach mineralogy from local catchments.

3.6 Examples of the Application of the Sediment Budget Concept

3.6.1 Overseas

Overseas examples are numerous in the literature, although sediment budgets are undertaken more widely in the United States, Japan, and the Netherlands, mainly for coastal engineering purposes which require knowledge of the sediment budget components before implementing coastal structures and beach nourishment programmes (Bowman and Inman, 1966; Pierce, 1969; Stapor, 1971, 1973; Seelig and Sorensen, 1974; Saville, 1975; Sunamura and Horikawa, 1977; Dewall and Richter, 1977; Armon and McCann, 1977; Jarrett, 1978; Chapman, 1981; Harvey and Bowman, 1987; Zenkovich and Schwartz, 1987; Oertel *et al.*, 1989; Ananth and Sundar, 1990; Vessem and Stolk, 1990; de Ruig and Louisse, 1991).

3.6.2 New Zealand

In New Zealand the concept of the sediment budget for the beach-dune-nearshore system has been applied on a fairly limited scale, although the east coast of the South Island with its sandy and mixed sand-gravel beaches has received considerable attention on the matter (Kirk *et al.*, 1977; Kirk and Hewson,1978; Tierney and Kirk, 1978; Gibb and Adams, 1982; Carter, 1986). Due primarily to the large body of information which has been gained in studying coastal aspects relating to port developments, such as dredging, at Timaru, Dunedin, and Lyttleton, allowing for a more accurate understanding of the sediment dynamics and overall littoral sediment budget in the Canterbury-Otago region. More limited sediment budgets for north-eastern, North Island beaches have been used fairly frequently. These essentially are less detailed and may consider only part of the dune-beach-nearshore system, commonly the beach from foredune to MLWM (Harray, 1977; Gibb, 1977; Foster, 1991; Beca Carter Hollings & Ferner Ltd. 1992; Tonkin and Taylor, 1992; John O'Brien and Associates, 1992; Smith et al., 1992; BOPRC, 1993) .

The first published example in New Zealand which presents a coastal sediment budget, is that of Kirk and Hewson (1978) for 85km of South Canterbury-North Otago coastline from Cape Wanbrow at Oamaru to the Timaru Harbour. Their work is based on methods described by the U.S. Coastal Engineering Research Centre (CERC,1984), and consists of five cells based on wave refraction analysis which showed stretches of coastline as having differing longshore transport regimes. One of the major reasons a sediment budget was initiated was to estimate the possible effects that the Waitaki dam would have on reducing sediment input into the coastal system. They found that catchment control works and commercial gravel extraction coupled with natural erosion causes have accentuated coastal retreat of the Canterbury coast as the beach system attempts to compensate for changes in its morphology and texture. Their calculated total annual sediment budget is 3,560,180 $m^3.yr^{-1}$, which represents all transfers within the 85km of beach. This gross budget affects 17% of the beach volume in a given year, with the total net budget of 922,353 $m^3.yr^{-1}$, representing 26% of the gross exchanges. While it is hard to question the results of the budget it should be noted that the budget given by the authors extends seaward only to the surf zone. This allows for nearly all of the longshore drift to be calculated, but neglects to consider any onshore-offshore transport affects, however small these may be in a mixed sand-gravel system such as occurs on the Canterbury coast. Also the effects of suspended sediments are not discussed and their production via abrasion, which are important if only in mentioning their contribution via river inputs, and offshore losses. This appears common since most budgets deal only with the bedload sediments, assuming suspended load is transported out of the budget boundaries fairly rapidly.

Tierney and Kirk (1978) used known data to produce a generalised schematic sediment budget for the Timaru Port region, shown in Figure 3.10a. The given results though are only broad-scale and relate predominantly with longshore sediment transfers.

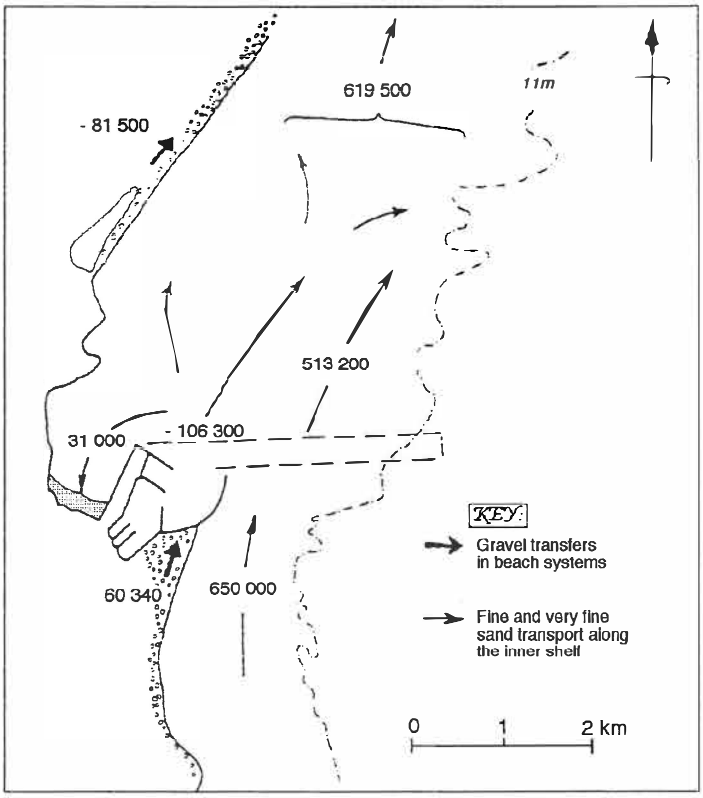


Figure 3.10a Schematic average annual sediment budget around the Port of Timaru. *(source: Tierney and Kirk, 1978)*

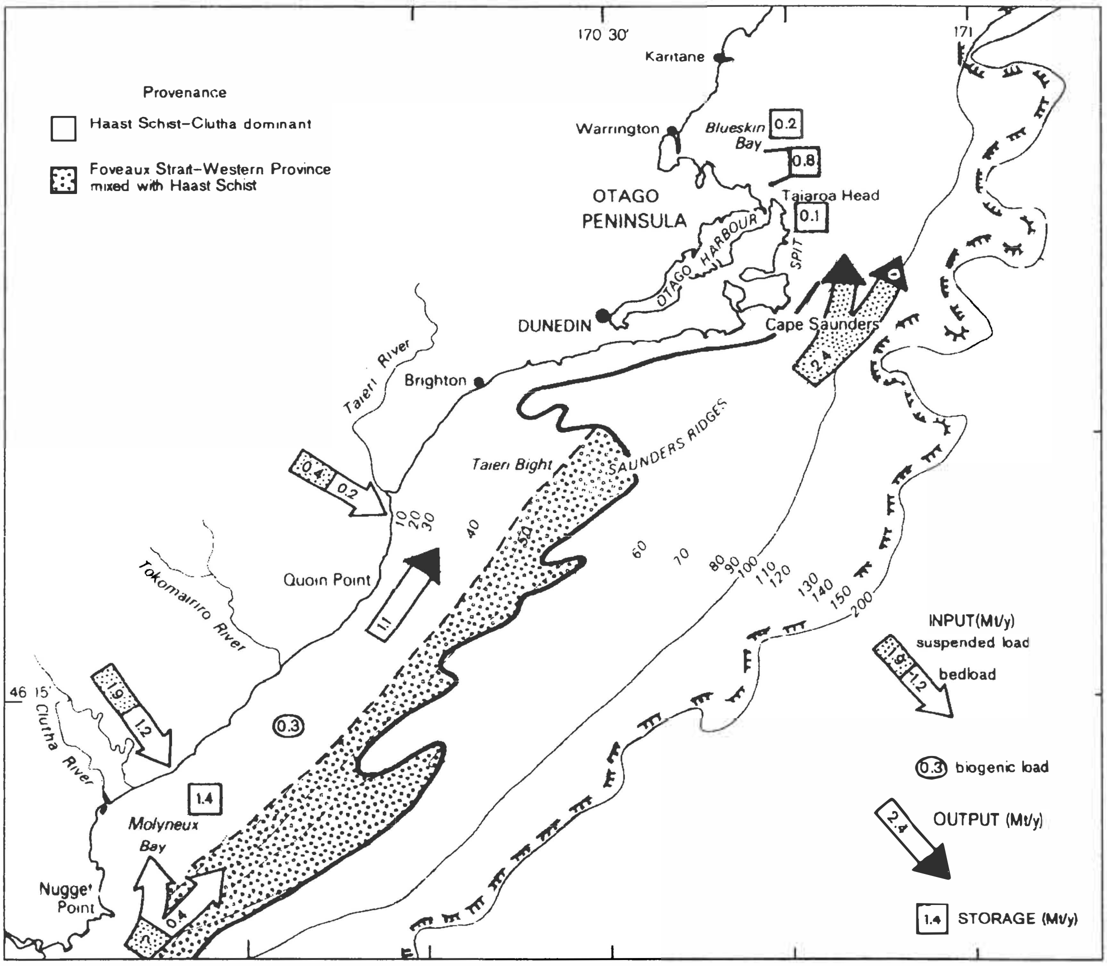


Figure 3.10b Major elements of the South Otago sediment budget. *(source: Carter, 1986)*

Gibb and Adams (1982), produced a sediment budget for the South Island east coast between Oamaru and Banks Peninsula. In their budget they considered the inputs from cliffs and rivers, and the losses by abrasion to give estimates of the suspended load (very fine sand and mud) transported both offshore and northward past Timaru. Hastie (1983) however in comparing data by Gibb and Adams with that by Kirk (1978), feels that the suspended load estimates for river inputs are too high, which would account for a high sediment transport rate at Timaru. This difference appears to be the result of the manner in which the suspended load was calculated using different formulae, discharge rating curves, and data sources. The boundaries of their budget are from Cape Wanbrow to Pegasus Bay, and consist of two beach systems, Waitaki (84km) and Canterbury (136km), separated by the Timaru Harbour breakwater. Offshore boundaries are defined by the Nearshore Transport Zone (NTZ), and extend to depths of 30-60m water depth, to include suspended sediments transported by northerly drift currents at these depths. The overall devised sediment budget is approximately balanced in terms of inputs and outputs, however, it is noticeable that the work by Gibb and Adams (1982) and Kirk and Hewson (1978) on exactly the same system (Waitaki) show major differences.

Carter (1986) developed a sediment budget for modern Holocene sediment on the South Otago continental shelf and coast, between Nugget Point and the Otago Peninsula, which considers both bedload and suspended load as well as estimating littoral and shelf storage of Holocene sediments, and determining the biogenic input to the budget. The resultant budget is given in Figure 3.10b. Carter also found in comparing his budget with others further north that the sediment input per unit length of coastline for the Waitaki-Canterbury systems is approximately double that for the Otago system (0.09 $Mt.yr^{-1}.km^{-1}$ cf. 0.04), and is assumed to be the result of increased fluvial input and much greater coastal erosion.

Table 3.2 Beach sediment budget from 1945 to 1970 for consecutive 2 km lengths of coastline along Ohope and Ohiwa Spits. (*source: Gibb, 1977)*

Location	Ohiwa Coast (m^3)	Ohope Coast (m^3)
Harbour bank	+ 105 400	
1st km	- 141 600	+ 226 400
2nd km	- 46 400	+ 168 300
Net	- 82 600	+ 394 700
Net rate ($m^3/m/yr$)	*- 3.8*	*+ 7.9*

A sediment budget for the open coast beaches of Ohope and Ohiwa Spits and harbour bank, at the extreme of the apparent south-easterly directed Bay of Plenty littoral drift system was calculated by Gibb (1977) for the period from 1945 to 1970. The Ohiwa coastline has a general trend of erosion with accretion along the Ohope coastline. Gibb determined volumes for 2 km of coast along each spit, and harbour bank (Ohiwa harbour) (Table 3.2), determining that as the two sectors failed to balance that dune erosion was most likely to be contributing to the Ohope coast sediment budget.

Recently the application of sediment budgets has been used in estimating coastal sand resources and sustainability, particularly concerning sand extraction from the dune-beach-nearshore system. The foremost example of this is at Pakiri-Mangawhai, on the east coast north of Auckland, where sand is extracted from the nearshore zone. O'Brien and Associates (1992) derived a sediment budget for Pakiri given as:

Inputs	*Outputs*
$F + L_{NI} + C + B + O_N$	$= L_{NO} + D + M_p + M_M + S$
$1{,}500 + 3{,}500 + 5{,}700 + 460 + O_N$	$= 5{,}000 + 27{,}000 + 40{,}000 + 22{,}000 + 70{,}000$
therefore: O_N	= 156, 340 m^3 per year

where:

F= fluvial inputs
L_{NI}= net littoral drift into the area
L_{NO}= net littoral drift out of the area
C= cliff erosion
B= biogenic inputs
O_N= onshore transported sediment
D = dune deflation
M_p= mining at Pakiri
M_M= mining at Mangawhai
S= sand storage at Mangawhai harbour

From the above sediment budget and other information, it has been concluded by O'Brien and Associates (1992, pp. 29-30) and Tonkin and Taylor (1992, pp. 15-18) that current sand extraction has little effect on the dune-beach-nearshore system in the Pakiri-Mangawhai area, and is a sustainable resource.

3.7 Application of the Littoral Sediment Budget

For the Pukehina-Matata study area the sediment budget differs in many ways with the proposed sediment budgets for the Otago-Canterbury regions. The volumes of littoral drift are somewhat smaller in the sandy Bay of Plenty beaches, with longshore sediment transport occurring in a larger zone than for the mixed sand-gravel beaches of the eastern South Island, which differ in both morphology and their zones of sediment transport (Neale, 1987). A generalised schematic diagram of the proposed littoral sediment budget for the Pukehina-Matata region is given below in Figure 3.11.

Determination of the sediment budget thus involves an attempt to identify and quantify all of the major sources, sinks, and transfers of sediment within the study area, and calculation of the state of balance between them. Such calculations require decisions as to the system boundaries across which transfers occur (Kirk and Hewson, 1978). The landward boundary of the littoral sediment budget for this study, is taken as the top of the eroding cliffs at Town Point and Pukehina Redoubt to Otamarakau, and the limit of foreseeable dune erosion in all other areas. The seaward boundary, as given in Figure 3.10, is the depth limit of sediment transport (Dd) similar to Hallermeier's limits (Hallermeier, 1981). This boundary is taken based on evidence of previous budget studies, and is necessary when considering the budget of the entire beach-dune-nearshore system. According to Hay (1991) the closure depth of no significant onshore-offshore sediment movement under average wave conditions for Mt. Maunganui to Papamoa in the Bay of Plenty is 13.5 m based on Hallermeier's formula, with sounding profiles exhibiting a good correlation with this result.

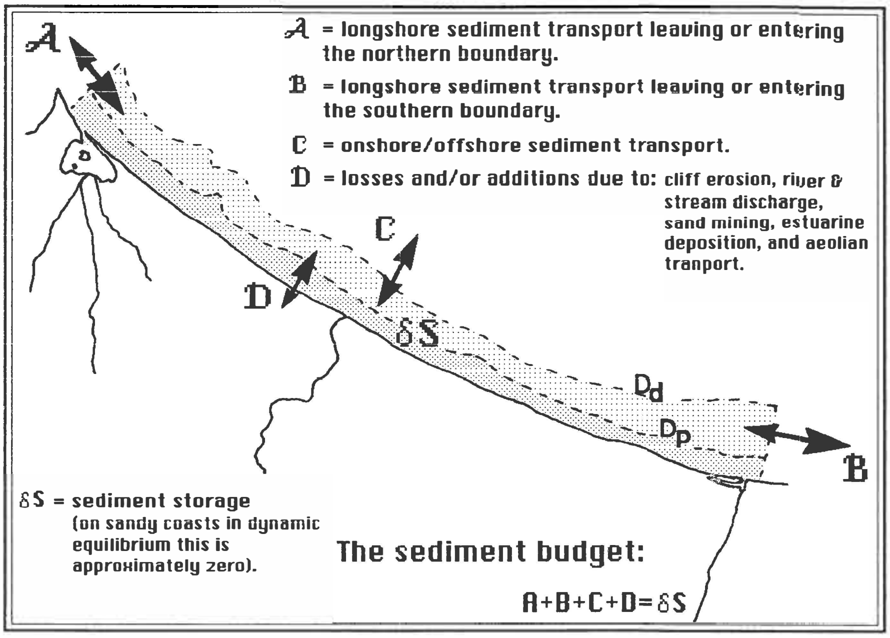


Figure 3.11 Concept of the beach sediment budget for the Pukehina to Matata compartment of Bay of Plenty coast. Where Dd is the diabathic closure depth, and Dp the parabathic limit of sediment exchange.

The boundaries to the north (Town Point) and south (Tarawera River) are constrained by a number of factors. Firstly, it is perhaps the most poorly understood region of the Bay of Plenty coast and as such is an area in which a greater understanding of the coastal environment is needed. Secondly, the boundary to the north, is a natural rocky headland, which has been used in other sediment budget studies, as this is often an area of reduced net littoral drift, or where the littoral drift pattern is interrupted (Kirk and Hewson, 1978; de Ruig and Louisse, 1991). The southern boundary is defined by the Tarawera River, which has a large input into the beach-dune-nearshore system. To the east of this river on the Rangitaiki Plains the coast is undergoing progradation, and so may be thought of as a separate distinct system, linked by longshore sediment transfers from the north.

CHAPTER FOUR:

Beach Morphology

CHAPTER FOUR
BEACH MORPHOLOGY

4.0 Introduction

Over a year, seasonal fluctuations of the sand level occur in the backshore, foreshore, and nearshore zones of the beach system, known typically as 'cut and fill' cycles. This sediment movement is dependant on wave and wind action as well as sediment properties, although Hay (1991) found that it is predominantly wave action that induces beach profile changes. Superimposed on these seasonal fluctuations are short-term (years) and long-term (tens of years) changes in beach planiform, resulting in sectors of the beach eroding, accreting, or remaining in a state of dynamic equilibrium, depending on the time period over which such changes are viewed.

The overall beach configuration tends towards an equilibrium with the wave conditions so there is a balance in the amount of energy available to redistribute beach sediments supplied to the beach. However this also depends on the amount of sediment available for distribution within the beach-dune-nearshore system. The beach configuration is controlled therefore by the wave climate characteristics and the size, location and relative importance of sediment sources and sinks (Smith, 1986).

This chapter investigates the changes that have occurred in historic time to the beach system along the Pukehina-Matata coastal sector, from aerial photographs, maps, and historical accounts. It also uses beach profiles taken at Bay of Plenty Coastal Erosion Survey (BOPCES) sites, from 1977 to 1993, to determine the extent of recent erosion and accretion trends along the shoreline, and the volumes of sediment involved in storm 'cut and fill', necessary in the determination of the littoral sediment budget.

4.1 The Historical Development of the Pukehina-Matata Coast

Much of the Pukehina-Matata inland area was unpassable in the 1800's, and like most of early colonial New Zealand relied on sea and river transport. Travel along the area by the Maori and early settlers was either by canoe or by foot along the beach, which between the Waitahanui stream (Otamarakau) and the Awa-o-te-Atua river (Matata) was described in the 1860's as "a *wide sandy beach between the cliffs and sea"* known as Kaokaoroa (long rib) (Boyack, 1987).

An early newspaper correspondent in 1866 on a cruise of the Bay of Plenty (Anon, 1993) notes that *" After passing Maketu Point, an opening to the Waihi River* (Waihi estuary) *becomes visible, and an open and flat appearance to the south of the river indicate for miles back one dense and immense swamp.... The coast, for about eight miles south of Waihi is one continuous swamp and sand hill, until we reach Otamarakau".* The nature of much of the Pukehina-Matata coast changed in the

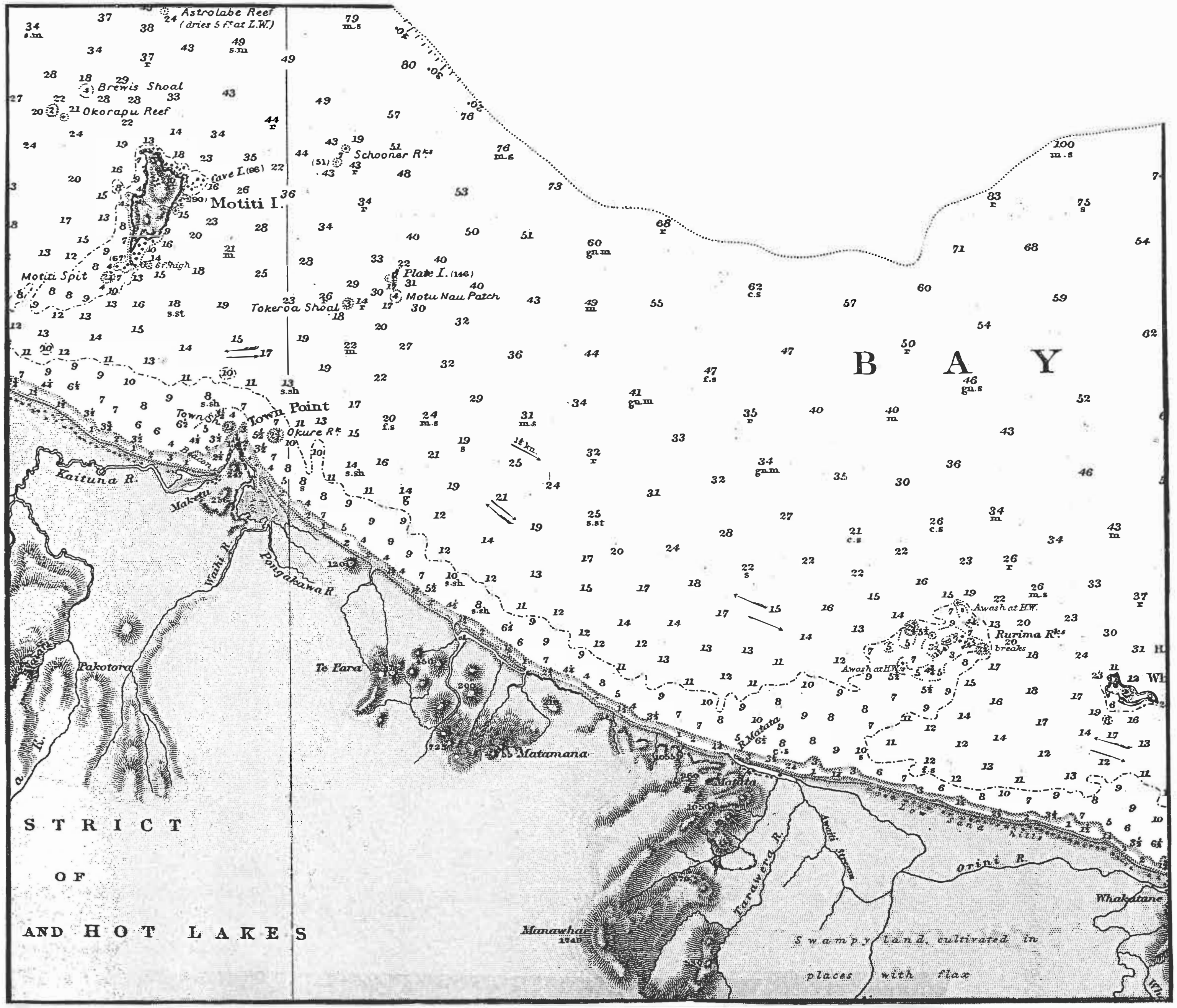


Figure 4.1 Nearshore bathymetry and coastal morphology of the Pukehina-Matata coastal sector in 1901-1902. The Waihi River is now known as the Kaikokopu stream, which along with the other streams draining into the Waihi estuary have been channelised along their lower reaches. The Tarawera River and part of the Rangitaiki prior to 1917 flowed out at Matata some 5 km from the present location of the Tarawera River mouth. *(source: NZ Hydrographic Chart Mayor Island to Poverty Bay, 1906)*

early 1900's with the advent of drainage schemes initiated by the New Zealand Government, such as those for the Rangitaiki Plains and Pukehina area, reducing vast areas of swamp to pasture through river channelisation, canals, and altering coastal outlets of the Tarawera and Rangitaiki rivers. However much of the coast between the foredunes and Pleistocene cliffs from Otamarakau to Matata remains swampy. The coastline morphology and bathymetry prior to river channelisation (e.g. Kaikokopu stream) and drainage, and before the diversion of the Tarawera and Rangitaiki rivers, is shown in Figure 4.1.

Prior to river diversion in 1917 the waters of the Tarawera River and most of the Rangitaiki River flowed out at Matata as a large navigable waterway known as Awa-o-te-Atua ('river of god'), which in the late 1800's and early 1900's was an important shipping port for central North Island trade, with two wharves located on its southern banks close to the entrance bar. Within the Pukehina-Matata area the Waihi estuary also acted as a coastal trade area, particularly for drainage schemes in the early 1920's. The Awa-o-te-Atua river from photographs and accounts of trade in the area (Matheson, 1991) appears to have been rather substantial in appearance with an estimated width at Matata of approximately 140 m and an entrance width of 75 m (Figure 4.2). Prior to river diversion the Matata bar at the mouth of the Awa-o-te-Atua River varied in depth from 9 ft down to 5 ft during dry weather (1.7 to 3 m), making it reasonably navigable, but the entrance bar and channels appeared from all accounts to often be unstable (in comparison with the nearby Kaituna River), and although buoys and beacon lights were present to guide shipping the channels were so changeable that they often had to be reset (Matheson, 1991). Anon (1993) writes that *"a small steamer...could proceed without difficulty as high up as the Rangitaiki...by way of Te Matata"*. The present day Tarawera River was cut through on 23 April, 1917, causing the Matata entrance to soon silt up and cease to be a port of call, with the separation of the two rivers producing two poor ports at the Tarawera and Rangitaiki cuts (Matheson, 1991).

The Waihi estuary in the early 1900's (~ 1911-1924) may have been less accreted than present, since the coastal shipping vessel *Torea* (Figure 4.3) used to occasionally venture into the Waihi estuary. Matheson (1991) found that at this time *"The Waihi had a rocky entrance and could be worked only on spring tides and in very calm weather...There were many rocks both inside and outside the bar standing a couple of feet above the sand"*. Such rocks are not a present day navigational problem, and do not appear to be at the present entrance. This suggests that either the entrance has accreted burying the rocks (and possibly the flood and ebb-tidal deltas have increased in size), and/or that the entrance has moved some metres or tens of metres to the south-east from rocks which are located to the north.

4.2 Analysis of Historical Changes

Aerial photographs from 1943, 1963, 1974, 1977, 1982, and 1991 and early maps and surveys (1918) were used to determine sectors of long-term erosion and accretion along the shoreline, from work

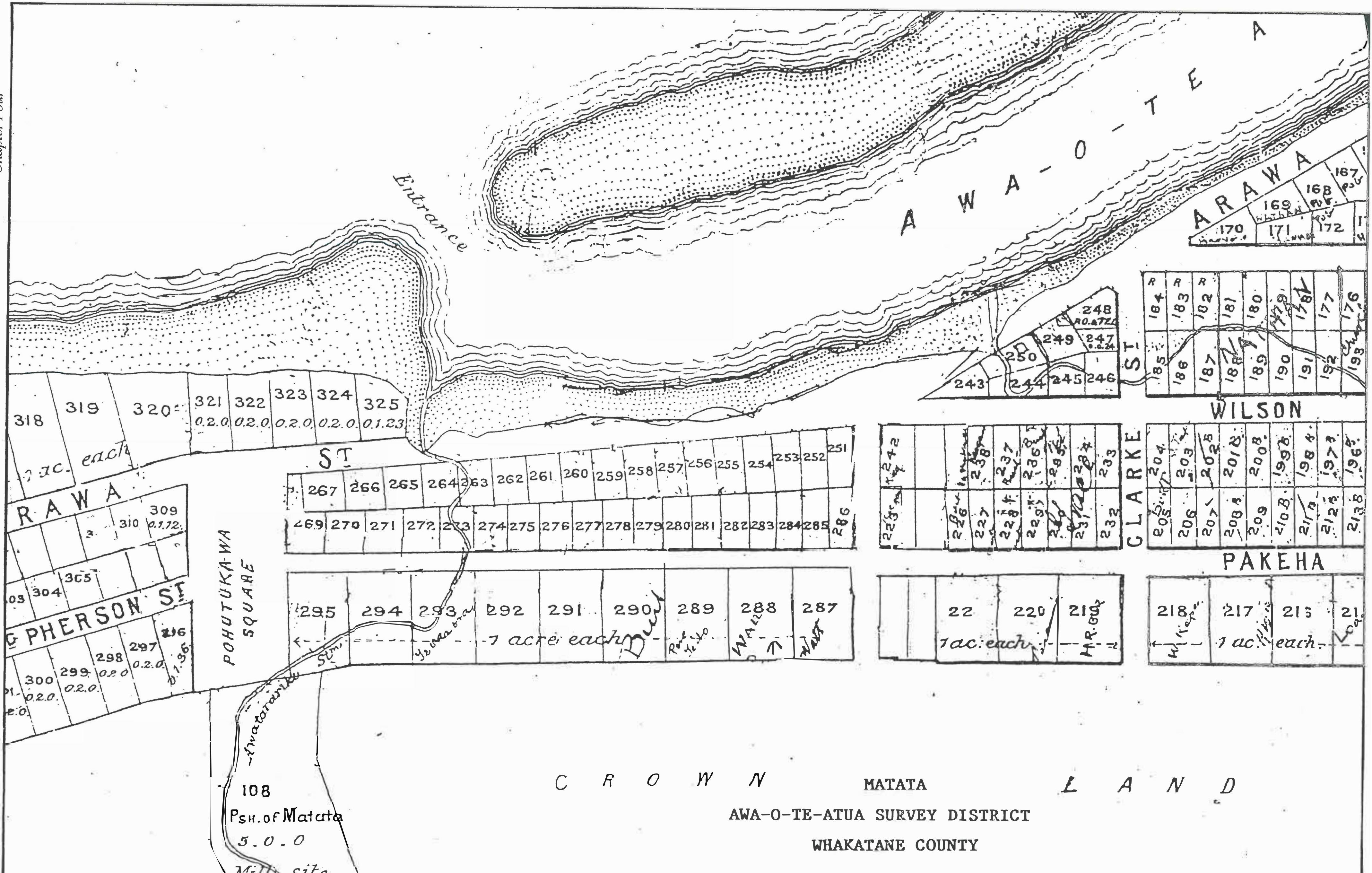


Figure 4.2 Tarawera river entrance at Matata as surveyed in 1868, prior to diversion in 1917. In the latter part of the 19th century and early 1900's this was a major coastal shipping port for the Bay of Plenty.

previously achieved by Healy *et al.* (1977), Smith (1986), and Smith (1989), complemented here with additional information.

Figure 4.3 The coastal shipping vessel Torea at the Tarawera River about 1920. ***(photo: Whakatane Museum)***

4.2.1 Beach and Dune Changes

The dune changes were mapped relative to the position of the toe of the frontal dune delineated by the vegetation line. Frontal dunes are generally considered to act as reservoirs of sand which are used infrequently to nourish the beach system during periods of extreme erosion (King, 1972). The time period between severe erosion events may be several years, during which time lesser storm events may provide the wind to transport sand by saltation processes off the beach. The sand is trapped by dune vegetation thereby causing dune accretion (King, 1972). The importance of dune vegetation is apparent along Pukehina Spit, which in 1943 was a mass of dune blowouts. These blowouts are orientated in a E.N.E. direction, implying a possible littoral drift regime along Pukehina Spit in a N.E. direction if it is inferred that wind direction controls local wave and current motions.

Beach changes, which are more sensitive to short-term morphological trends, are determined from the position of the last high tide (assumed as MHWM). This allows the early coastal surveys of the Lands and Survey Dept., in 1912 and 1918, to be related to later aerial photographs (Smith, 1989).

Figure 4.4 a-d represent the longest historical changes analysed by:
(i) Healy *et al.* (1977) from 1943 to 1974/77 and relate to the extent of dune erosion or accretion, and
(ii) Smith (1989) from 1912/1918 to 1981 determining the beach erosion/accretion trends based on the deviation of MHWM.

These two studies give an indication of the long-term erosion/accretion trends for Pukehina to Otamarakau, Otamarakau to Matata, and Matata to the Tarawera River. In addition Town Point dune changes, including Newdicks Beach, were determined from 1943 to 1981.

For the region from Pukehina to Otamarakau (Figure 4.4a), between 1912 and 1949 there has been both erosion and accretion, with predominantly erosion from 1949 to 1981 (Smith, 1989). The overall net change shows erosion at Pukehina and accretion near Rodgers Road. However as noted by Smith (1989) the amounts of horizontal movement are small, with an averaged overall beach retreat rate annually of 0.1 m/year.

Dune and beach erosion of the distal end of Pukehina Spit appears a common cyclic occurrence, as between 1978 and 1993 the tip of the spit has accreted markedly while historically erosion has dominated. For Pukehina Beach Healy *et al.* (1977) concluded that erosion-accretion cycles occurred along an embayed coastline.

On the eastern side of Town Point, the coastline is apparently stable for northern Newdicks Beach, with some accretion nearer the Waihi estuary, and erosion immediately adjacent to the inlet (Figure 4.4b), associated with oscillation of the estuary mouth.

The Otamarakau-Matata region (Figure 4.4c) shows significant beach erosion of up to 30 m over a 63 year period (1918-1981) for much of this section of coast. This equates to upwards of 0.5 m per year, which, considering the neighbouring Rangitaiki Plains are estimated to have prograded during the Holocene at a rate of 0.5-1.5 m per year (Pullar and Selby, 1971), would indicate a deficit of sediment within the Otamarakau-Matata beach-nearshore system. This may however be due to differences in the interpretation of the MHWM discussed in Smith (1989). *"If the discrepancy in the interpretation of the high water mark is accounted for the beach may be regarded as stable or slightly accreting since the average width of the backshore is 10-20 m along much of this length of beach"* (Smith, 1989, p. 7). Both Healy *et al.* (1977) and Smith (1989) for the Otamarakau-Matata section infer dune and beach erosion around the stream mouths as a result of stream migration along the beach.

Based on dune changes accretion appears prominent between Matata and the Tarawera river mouth from 1943 to 1974 (Figure 4.4d), but the beach changes however show far less accretion with some

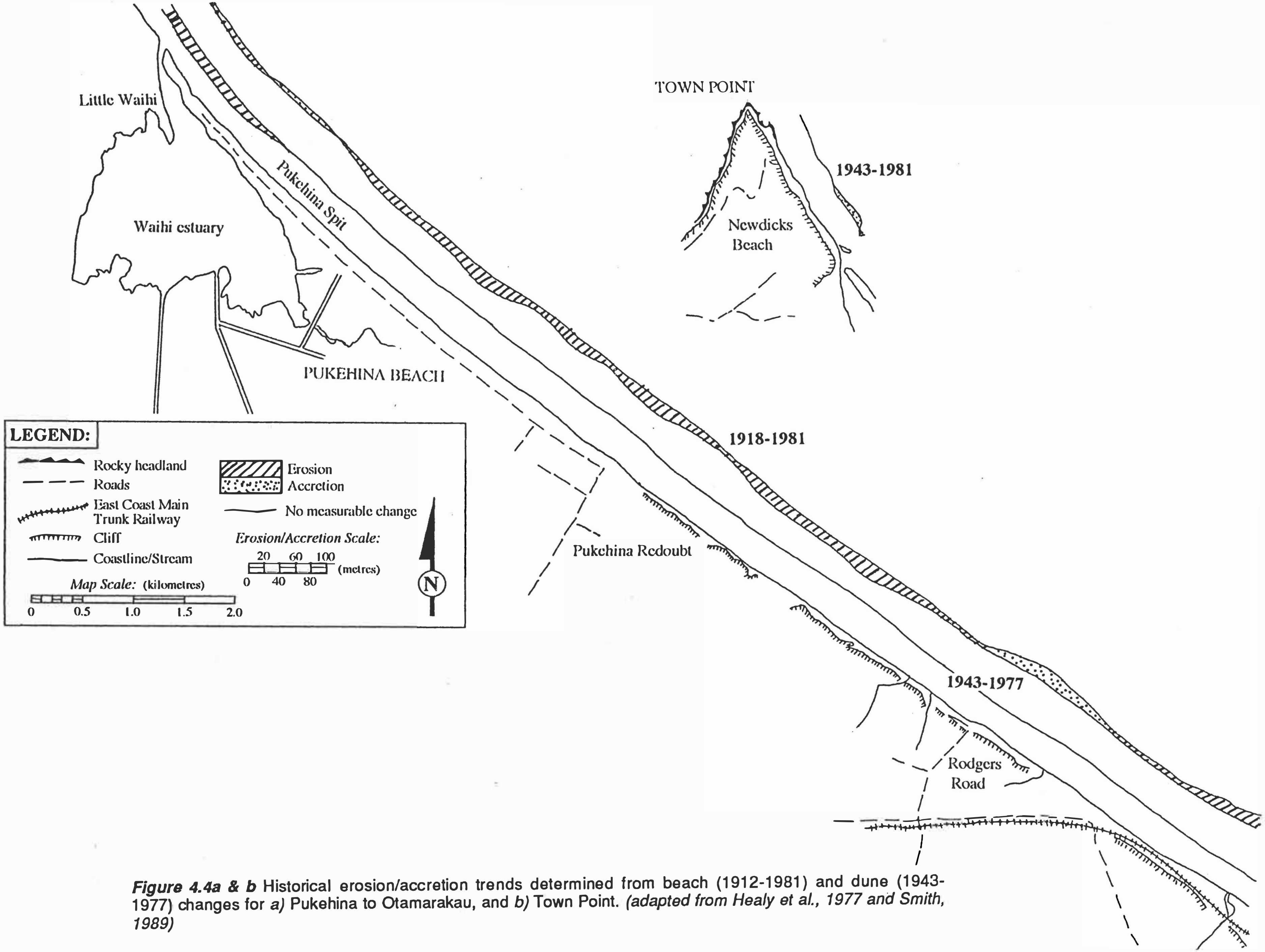


Figure 4.4a & b Historical erosion/accretion trends determined from beach (1912-1981) and dune (1943-1977) changes for *a)* Pukehina to Otamarakau, and *b)* Town Point. *(adapted from Healy et al., 1977 and Smith, 1989)*

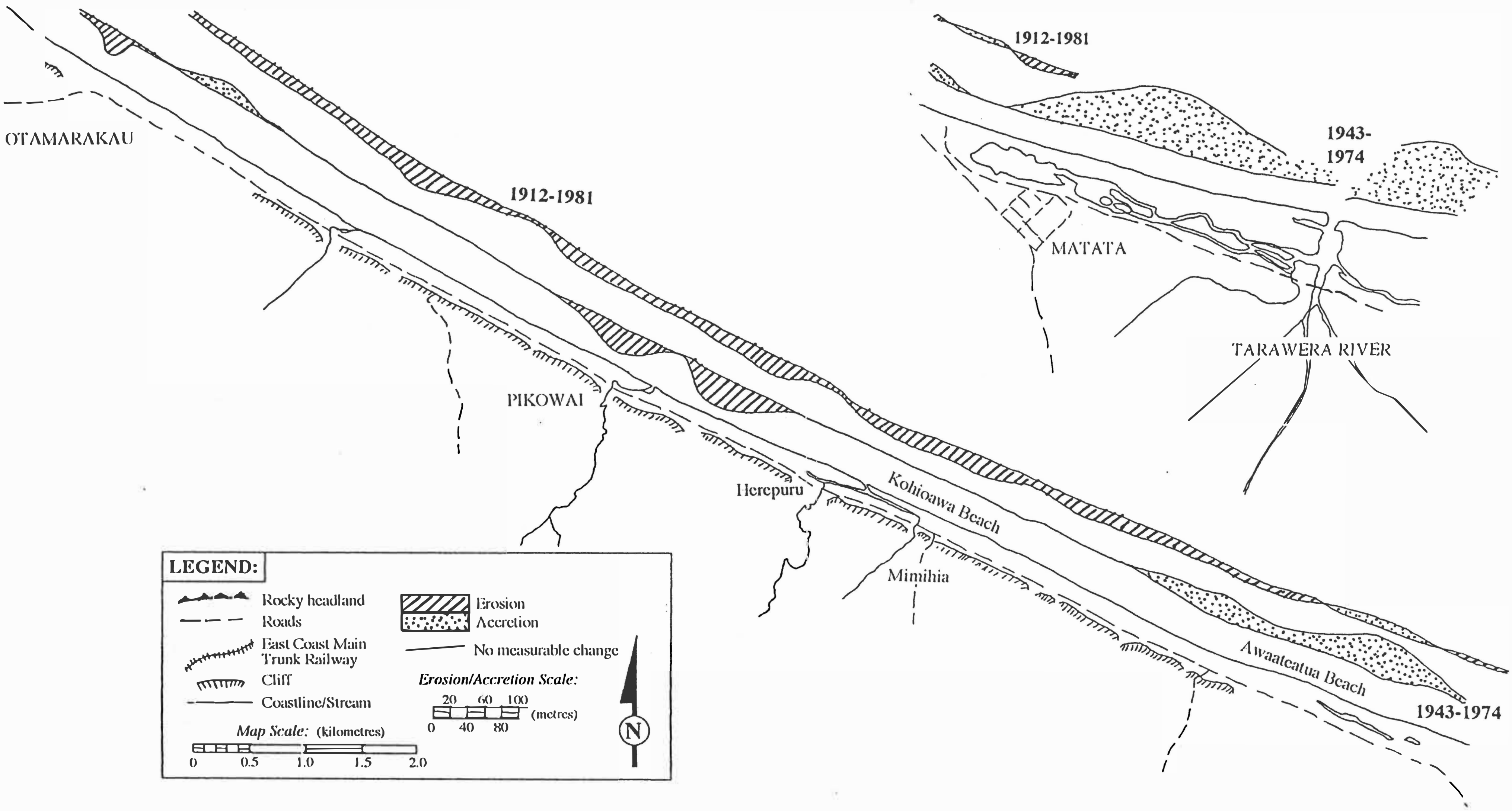


Figure 4.4c & d Historical erosion/accretion trends determined from beach (1918-1981) and dune (1943-1974) changes for *a)* Otamarakau to Matata, and *b)* Matata to Tarawera river. *(adapted from Healy et al., 1977 and Smith, 1989)*

erosion apparent. Again this is thought to be due to the differences in the MHWM used (Smith, 1989).

From analysis of the coastal geomorphology the Pukehina-Matata shoreline appears to have been undergoing gradual erosion since the late Holocene, after an initial accretionary formation phase associated with large sedimentation loads entering the coastal zone during the late Pleistocene developing much of the sandy beaches and dune systems within the study area. However, although sectors of the study area show a potentially disastrous state, long-term erosion on a large-scale has not yet occurred. This is particularly noticeable along Pukehina Beach, a substantial housing area and summer holiday resort, of which more than 60 % lies within the delineated coastal hazard zone of Healy (1993). The extremely steep nature of the faceted dunes along Pukehina Spit, which consist of a single dune ridge, appears to indicate that the dunes extended further seaward when formed in the early Holocene, and that they have since been eroded back to their present position, with dune blowouts creating an irregular dune line which varies in height from approximately 12 to 4 m or less above mean sea level.

4.2.2 Waihi Estuary

The Waihi estuary enclosed by Pukehina Spit has accreted along its southern margins where sediment discharges occur from the streams feeding the estuary, particularly in the vicinity of the Kaikokopu and Pongakawa stream mouths. The changes over a 38 year period between 1943 and 1981 are illustrated in Figure 4.5. The main channels within the estuary have changed little between 1943 and 1981, except near the entrance, presumably in relation to the flood tidal delta and wave effects. Erosion of the distal tip of Pukehina Spit noted in 1981 appears an infrequent event in early aerial photographs, with the entrance being predominantly located against the Town Point cliffs at Little Waihi. However, more recent aerial photographs from February and April 1993 show a similar spit and inlet morphology as December 1981. The main harbour spit at Little Waihi where the motor camp is presently located has accreted approximately 80 metres to the south-east. The small sandy cay islands contained within the centre of the estuary have accreted little between 1943 and 1981, although intertidal vegetation has increased in the south-western and eastern fringes of the estuary, indicating that tidal flushing in the upper parts of the estuary may have decreased. The south-eastern corner of the estuary appears to have a much smaller freshwater input from the Pukehina canal than for 1943, resulting in rapid sedimentation in this part of the estuary. Although sedimentation of the estuary may be occurring this is not significant within much of the estuary and is possibly due to downfaulting of the estuary along an inferred fault which runs through the boundary between the estuary and the Town Point promontory. This is in common with Ohiwa Harbour which has recently been found to be downwarping, evidenced by peat deposits within the present day estuary (Healy pers. comm., 1993). Downwarping of the estuary may also explain the lack of submarine rock outcrops in the adjacent Pukehina Spit nearshore zone (Chapter 7), since this offshore area may also be subsiding. Further evidence of a fault between the estuary and Town Point is provided by the recorded foreshock epicentres of the

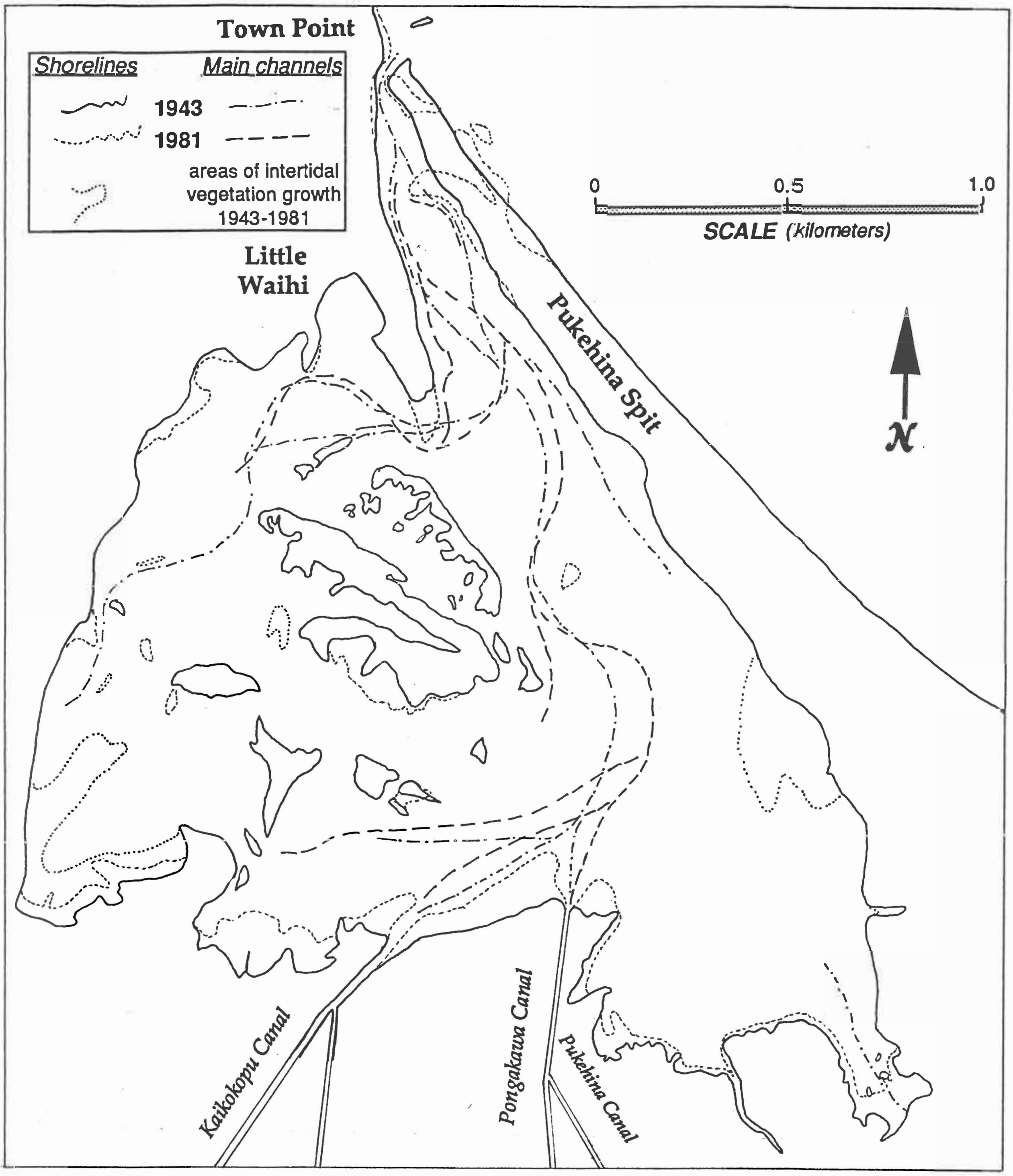


Figure 4.5 Changes to the shoreline morphology and main channels in the Waihi estuary between 1943 and 1981 from aerial photographic analysis, showing accretion along the southern margins of the estuary associated with sediment input from the Kaikokopu and Pongakawa streams.

Edgecumbe earthquake in March 1987 (Smith and Oppenheimer, 1989), showing a lineation of epicentres which pass between the Town Point-Waihi estuary boundary (Figure 4.6).

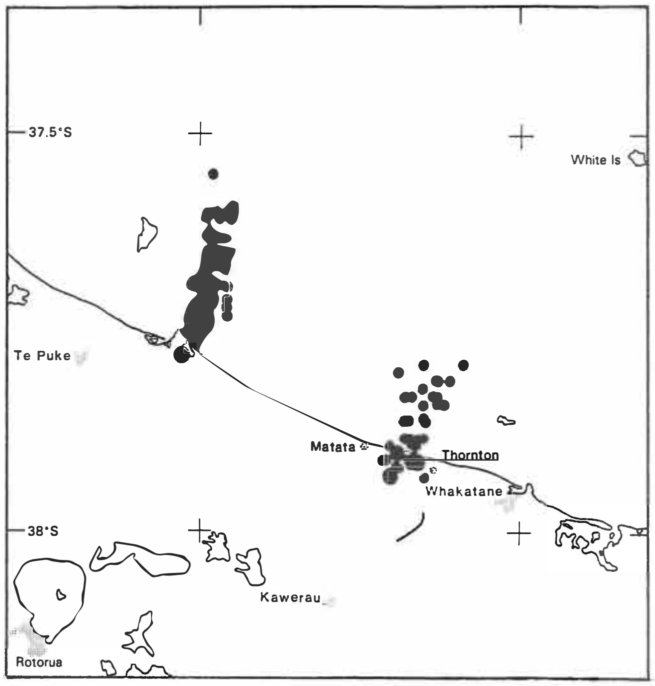


Figure 4.6 Foreshock epicentres of the March 1987 Edgecumbe earthquake, in the Bay of Plenty. The linear clustering of the earthquake group near Town Point indicates a fault line which dissects this promontory and the Waihi estuary. *(source: Smith and Openheimer, 1989)*

4.2.3 Stream and Beach Interaction

The Waitahanui, Pikowai, Herepuru, and Hauone streams are all classified as "beach impounded" systems (BOPRC, 1991), i.e. subject to blocking by beach berms, allowing the streams to migrate up or down the beach, possibly indicating the predominant littoral drift direction at each location. The migration, or offsetting, of these four streams is depicted in Figure 4.7. The offsetting of each stream (distance from dune/beach entrance to stream mouth) along the beach is considered the result of stream and beach interaction, which in turn is a combination of:

- *stream size, in terms of discharge.* The greater the stream size the less migration is expected with decreased impoundment by the beach system.

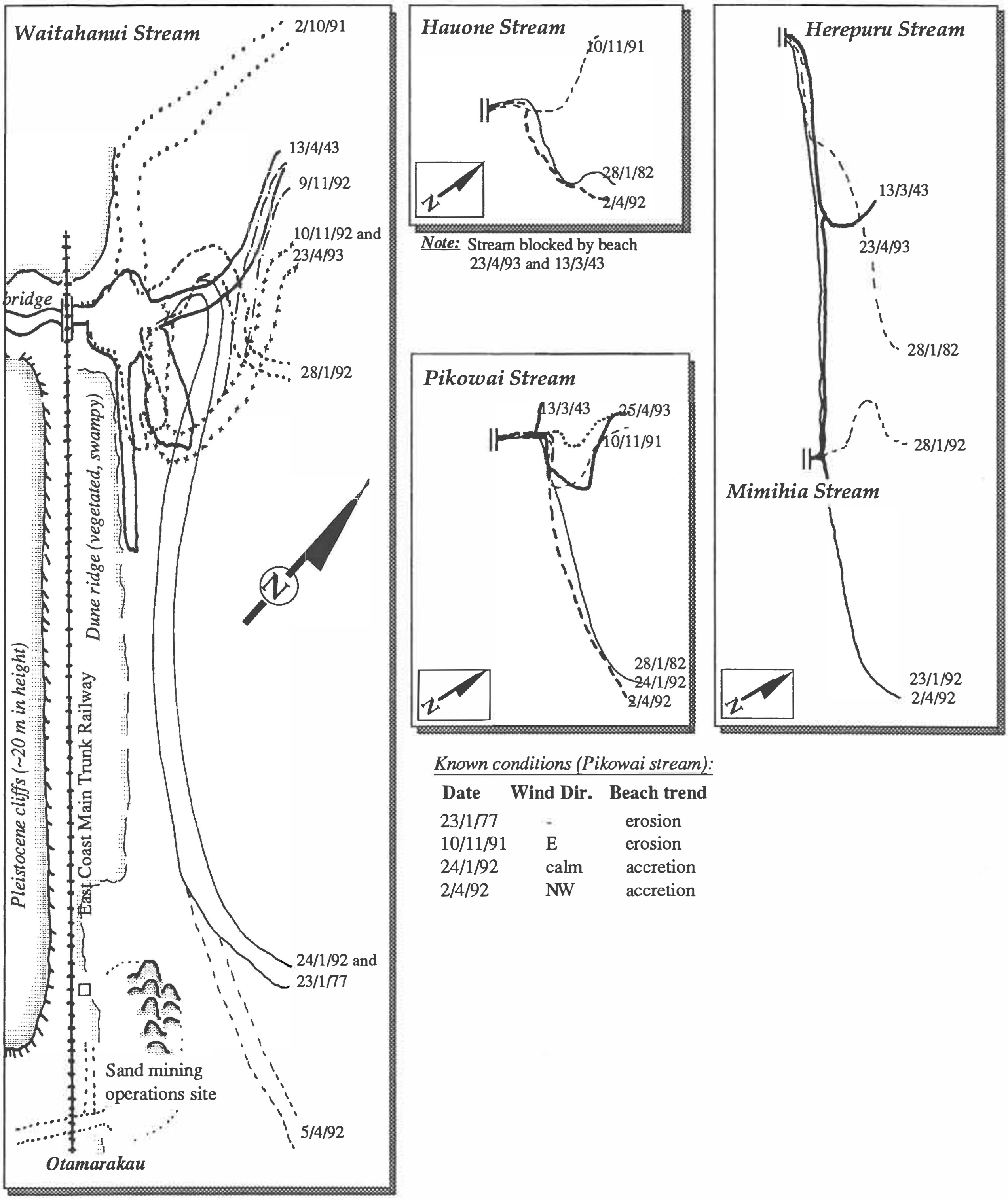
- *seasonality of flow.*

- *antecedent wave and wind conditions.* Strong onshore winds with large storm waves breaking at a high angle to the beach will cause substantial alongshore drift and hence the greatest expected stream migration.

- *beach state.* A well developed berm and accreted beach system will increase offsetting, compared with a lower angled eroded beach.

- *littoral drift volumes.* High littoral drift causes greater stream impoundment.

- *anthropogenic effects, e.g. sand mining.* Sand extraction operators at Otamarakau on occasion pile sand along the south-eastern side of the stream to prevent stream migration into the Otamarakau mining strip and operations plant areas.



Note: Stream blocked by beach 23/4/93 and 13/3/43

Known conditions (Pikowai stream):

Date	Wind Dir.	Beach trend
23/1/77	-	erosion
10/11/91	E	erosion
24/1/92	calm	accretion
2/4/92	NW	accretion

Figure 4.7 Schematic stream off-setting, caused by beach-stream interaction, and indicative of local littoral drift, at various dates for the Waitahanui, Hauone, Pikowai, and Herepuru/Mimihia streams. Stream positions are based on aerial and ground photographs of the dates shown.

Due to these factors not all streams have the same orientation or are offset at their mouths by the same amount at each date. The Waitahanui Stream has the largest discharge and should therefore migrate to a lesser extent than the Hauone Stream which is the smallest of the four streams analysed, and has been known on occasion to become cut-off from the coast and completely beach impounded (e.g. Sept-1943, April-1993). The Pikowai, Hauone, and Herepuru streams show an

Figure 4.8 Example of stream migration associated with the Pikowai stream, with the stream mouth in the top photograph sited opposite the Pikowai bridge to the north-west (25-April, 1993), and in the lower photograph discharging approximately 800 m to the south-east (24-January, 1992).

Figure 4.9 *a)* Effects of stream migration on the dune system with substantial natural erosion caused by a south-easterly migration of the Herepuru stream. The scale shown in the photograph is approximately 0.4 m high.

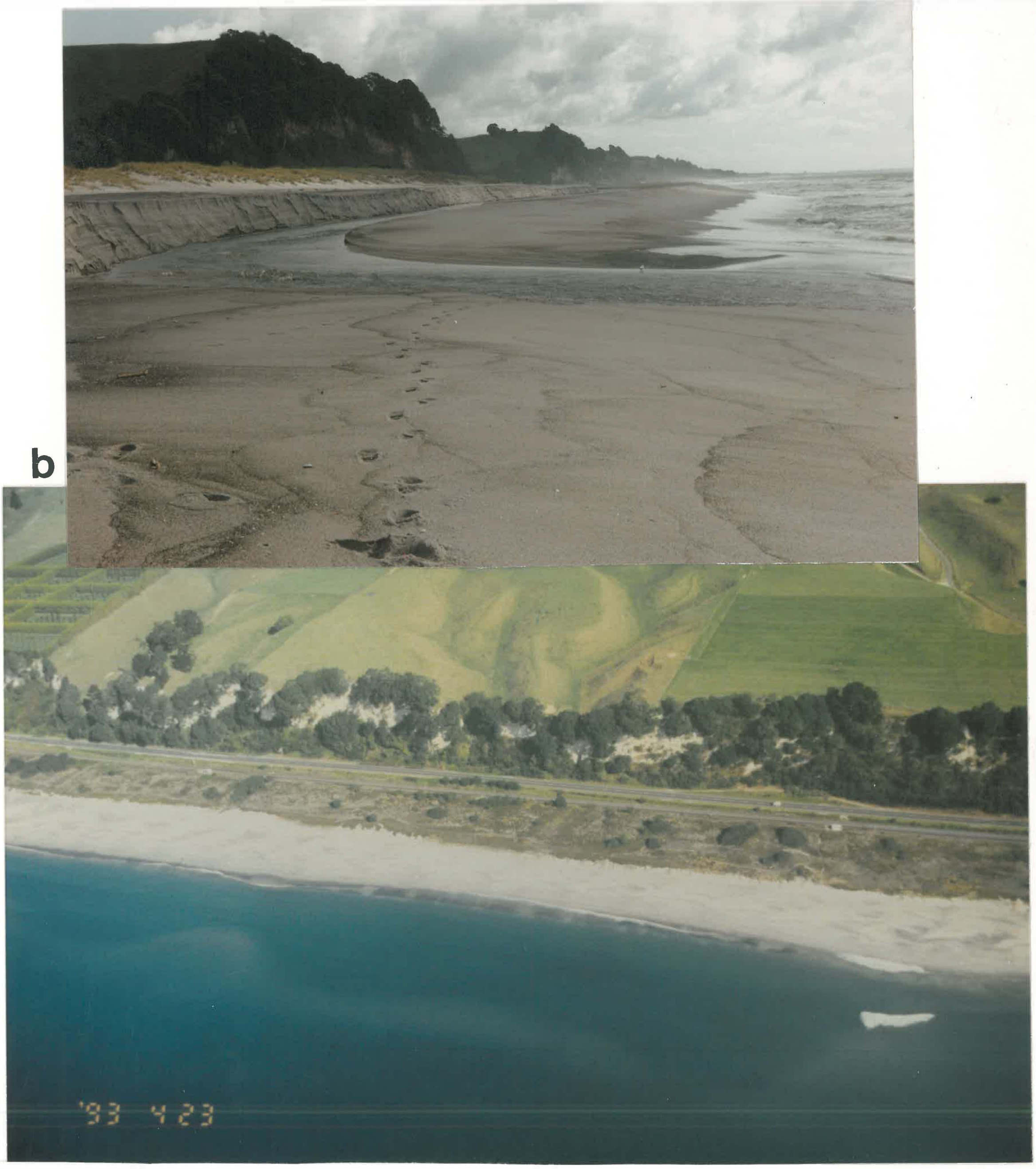


Figure 4.9 *b)* Aerial photograph demonstrating the beach impounded nature of the Pikowai stream (23-April, 1993). Also shown are cresentic bars in the surf zone.

overall tendency to migrate in a south-easterly direction along the beach, with the greatest stream offsetting occurring to the south-east for all four streams. This is substantiated by greater dune erosion caused by stream migration in this direction, shown in aerial photographs and from field evidence of dune cutback either side of the streams (Figures 4.8 and 4.9a). The situations in which the streams orientate towards the north-west are less frequent, and the stream offset is less pronounced. This suggests that within the Otamarakau-Matata area where these streams are located there is an overall trend of predominant south-easterly sediment transport. The Waitahanui Stream does however appear to show a greater tendency for NW migration in comparison with the other streams, and may indicate an oscillatory longshore drift, rather than unidirectional drift, in this area.

The Herepuru/Mimihia stream complex shows definite inferred net south-easterly littoral drift as migration of the Herepuru Stream was observed on all occasions to the south-east. Commonly the two streams join at some point before entering the littoral zone.

4.3 Beach Profiles

Beach profile data was obtained from the Bay of Plenty Regional Council who undertake quarterly monitoring of Bay of Plenty Coastal Erosion Survey (BOPCES) sites, first profiled and described by Healy *et al.* (1977). A large profile data set collected by the Water Quality Centre (DSIR) and NIWA-Ecosystems exists for the Otamarakau to Hauone mining strip, Matata, and Pikowai, as these sites have either presently or in the recent past been the subject of sand extraction activities. Smith (1990a; 1990b) and Smith *et al.* (1992) have used this data set previously and so little mention of it will be made here other than for comparative purposes.

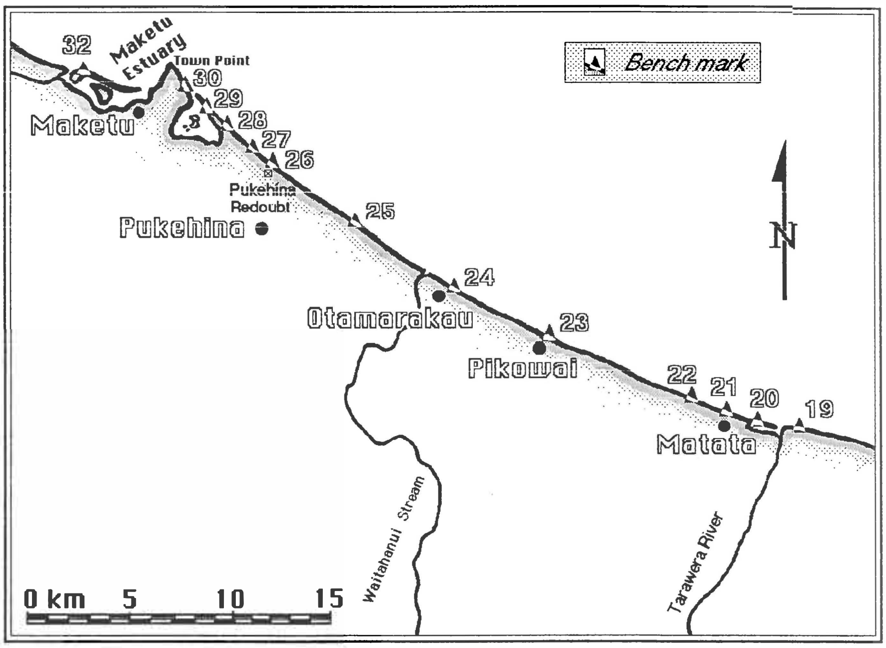


Figure 4.10 Locations of the beach profile survey sites within the Pukehina-Matata coastal sector used in this study. All benchmarks have been established from the original BOPCES survey sections, whose exact locations are given in Healy (1978d).

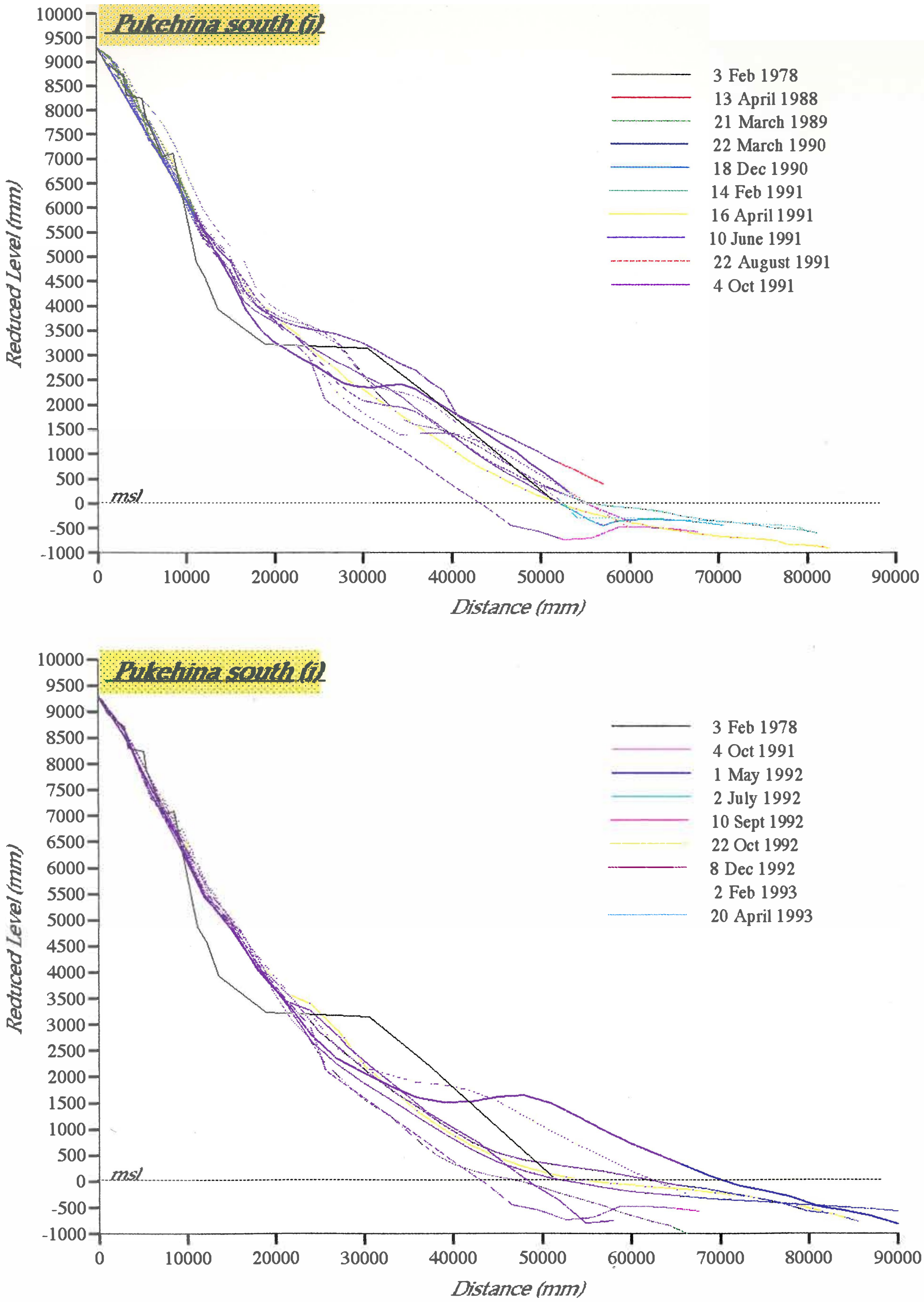


Figure 4.11 Example beach profiles for BOPCES site 27, southern Pukehina Beach, of surveyed profiles from 1978 to 1993. Accretion is evident at the base of the duneface since 1978, while the beach shows erosion and accretion cycles. *(profile data from BOPRC)*

In addition to the original 1977/78 surveyed profiles (Healy *et al.*, 1977; Healy, 1978d) the profile data used in this study covers those sites within the Pukehina-Matata coastal sector from BOPCES sites 19 to 30 (east of the Tarawera River mouth to Newdicks Beach) (Figure 4.10) from approximately 1987/88 onwards. However there is some variability in survey dates between sites. Further information and surveyed beach profiles for each site are included in Appendix I, with an example of the beach profile variability given in Figure 4.11, for BOPCES site 27 (Pukehina south).

4.3.1 Survey Site Profile Descriptions

All survey sites were established by the BOPCES (Healy *et al.*, 1977) and have had their benchmarks levelled to Moturiki datum (0.0 RL). However the benchmarks at several sites have disappeared over the years and have been subsequently replaced. In some cases it is possible that the new benchmark may differ in position from the original, for example the Pukehina Redoubt profile (site 26) from site photographs in 1977 and 1992 appears to have moved about 50 m to the north-west of its original position. Smith (1989) suggests that this may also have occurred at site 29 (Pukehina north) where the profiles surveyed after 1978 display an apparent seaward horizontal displacement of perhaps 5 m.

From observations by the author and the beach profiles from 1978 to 1993, the following site characteristics and associated changes during this 15 year period are described. Discussion of excursion distances is based on a definition given in Smith and Ovenden (1992), where "*An excursion distance is the distance a specified elevation on the beachface is from the bench mark*". In the profile site descriptions below this elevation is taken as mean sea level (Moturiki datum), and is equivalent to the zero metre elevation level. Hence in addition to changes in the beach profile volume, the variation in excursion distance is a very good way of determining what is happening to the beach profile over a given time interval. The excursion distance, and other relevant definitions of terms used, are displayed in Figure 4.12.

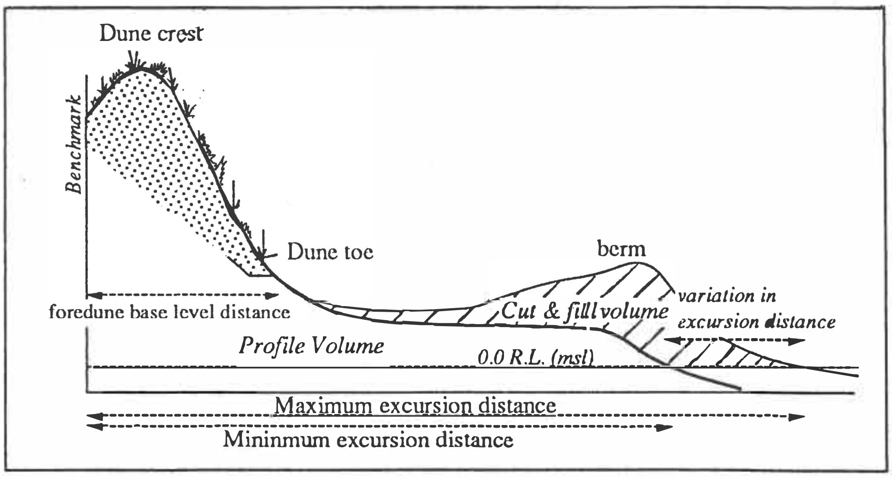


Figure 4.12 Illustration of the excursion distance and some of the terms used in describing the profile sites.

4.3.1.1 *Tarawera River East (Site 19)*

This site to the east of the Tarawera River mouth is part of the prograding Rangitaiki Plains foreshore. In 1978 the beach had a low frontal dune, with slow accretion noted (Healy, 1978a). The beach possessed moderate berm development, with a narrow backbeach area consisting mainly of berm washover deposits. As a result of the July, 1978 storm and associated wave washover effects, the low frontal dune was scarped. Since then however, the dune has neither eroded or accreted, with a consistent well-developed berm. Between 1978 and 1988 the beach gradually accreted, followed by a brief period of some erosion to 1990. Currently this site indicates some slight accretion but no significant changes have occurred in the past three years (1991-1993).

The excursion distance from bench mark to mean sea level varies by 32 m, with a partial decline evident since 1988. The smallest excursion distance recorded was 74 m in comparison to a horizontal distance from benchmark to the toe of the foredune (foredune base level distance) of 14 m.

4.3.1.2 *Tarawera River West (site 20)*

Currently this site is in an accretionary phase. The excursion distance to mean sea level varies by 20 m between the maximum and minimum values, with definite accretion since 1991 in contrast to the Tarawera east site. The smallest excursion distance value recorded was 47 m in relation to the foredune base level distance of about 15 m.

The low foredune shows signs of accretion associated with *Spinifex* colonisation, and has accreted at its base since October 1991. Beach accretion has occurred since April 1991. The beach system is commonly associated with some form of bar system, with a steep beach face of up to 12° (average of 7-9°), and commonly well-developed berms which become scarped during periods of erosion.

4.3.1.3 *Matata (site 21)*

The Matata profile is located at the old Matata sand mining site (Patterson's) with the profiles showing a large increase in the sand stored in the foredune from 1978 (Figure 4.13). As sand extraction ceased in 1985 this appears to be the effect of dune recovery. Smith (1989) monitored this site following the cessation of sand extraction and found the beach had accreted substantially between 1985 and 1987, after which the beach had recovered to a stable form. From the beach profile data continued beach recovery is not evident. The beach here has accreted since 1988 but from December 1991 onwards shows a slight decline in beach volume, although as for site 20 the surveyed profiles often have a well-accreted berm. When cuspated this sites contains some of the largest beach cusps of any of the Pukehina-Matata coastal sector with a cusp spacing of up to 40 m. The beach in this sector to Kohioawa Beach does show duneline arcuate erosion embayments, related to either wave focussing and/or rip currents (Figure 4.14). The beach face angle may be up to 9.5°, with variation in the beach volume, possibly due to the beach cusps, or erosion-accretion

Figure 4.13 Photographs of BOPCES site 21 (Matata) in *a)* 1977, and *b)* December 1991, viewed to the north-west.

cycles of the berm.

The excursion distance has varied by 22 metres, with no apparent long-term trend, indicating a reasonably stable beach system. The minimum value was 64 m in comparison with the foredune base level distance of 35 to 40 m.

4.3.1.4 Kohioawa Beach (site 22)

The original survey peg was replaced at this site in April 1988, with the beach profiles surveyed from this date onwards. The amount of beach variability at this site is comparatively high, with cut & fill volumes of up to 25 % of the total volume of sediment available within the beach. The variation in excursion distance is 23 m, with a minimum of 46 m, and a foredune base level distance of 10 m.

This site exhibits a similar steep beach profile to Matata, with a beachface angle of up to 9.5°. Beach change at this site occurs over the entire beach from the base of the duneface to the swash zone, with some indication of an overall accretionary trend in the sediment volume.

4.3.1.5 Pikowai (site 23)

The Pikowai profile is located 500 m to the south-east of the Pikowai motorcamp. The variation in excursion distance is 26 m, with a minimum of 97 m, and a foredune base level distance of 54 m. The foredune system here consists of low, moderately developed isolated dunes (1.5 m high). Currently they appear to be recovering where *Spinifex* vegetation is present amongst small irregular blowouts. The beachface angle is between 5° to 9°, with large cusp formation also common. The beach system has shown signs of periodic erosion and accretion, with some slight accretion since December 1991. This site is also occasionally affected by the migration of the Pikowai stream along the beach, as recorded by the April 1992 profile and in Figure 4.8.

4.3.1.6 Otamarakau (site 24)

This is the most monitored location within the Pukehina-Matata coastal sector due to the sand extraction operation between Otamarakau and Hauone. Smith *et al.* (1992) indicate that the mean beach volume for the active beach (toe of the foredune to mean sea level) is 170 m^3/m, with a standard deviation of 22.5 m^3/m, agreeing closely with the beach volume and cut & fill changes presented and discussed later from the BOPRC data. They consider that the beach consists of a core of pea-gravel (pebble to granule sized rounded greywacke and sub-rounded volcanic gravels) with the sand deposit lying on top during periods of fairweather accretionary conditions. Given a gravel base layer which may act to stabilise the beach system and maintain a threshold profile shape, an estimate of the minimum beach sand volume from foredune to mean sea level has been made of 79 m^3/m of beach (Smith *et al.*, 1992). Hence, under storm cut periods much of the sand stored in the

Figure 4.14 Dune erosion in an embayed arcuate duneline at Awaateatua Beach between BOPCES sites 21 and 22. The erosion is due to wave encroachment and washover, indicated from the drift wood deposited both on the low foredune and in the swale behind, associated with storm waves and probable wave focussing.

Figure 4.15 Dune erosion within the Otamarakau-Hauone mining strip, with the pole marker for BM1200 (Smith, 1990a) in the centre of the photograph. The dune and beach here are in an unhealthy state with a decreased sediment budget consistent with a decline in the beach volume at nearby BOPCES site 24 (June, 1993).

sub-aerial beach may be removed.

O'Shaunessy (1993) constructed a frequency distribution for the return periods of erosion induced beach cut volume at Otamarakau (Table 4.6), using an extremal type I probability function to analyse the annual beach cut data series. This produced a 100 year return period erosion value of 62 m^3/m. In comparison Smith (1989) and Smith (cited in BOPRC, 1993) estimated this 100 year buffer volume as 50 m^3/m and 43 m^3/m respectively.

Table 4.1 Beach cut volume removed due to erosion events of varying magnitude. *(source: O'Shaunessy, 1993)*

Return Period	*Beach Volume Eroded* (m^3/m)
10 year	44
20 year	49
50 year	56
100 year	62

The variation in excursion distance at Otamarakau is 30 m, with a minimum of 43 m, and a foredune base level distance of 17 m. The beach volume shows a declining trend since 1989, with small-scale scarping at the base of the duneface and an eroded beach state, contrasted with moderate berm development, and poor backbeach development. Commonly it was observed that an incipient false berm is created by the beachface joining the backbeach slope at this site, as was also found by Healy (1978a) in 1977/78. The foredune is still largely scarped in comparison with 1977/78 and may be in a worse condition than that noted by Healy (1978a), following the erosive events of June 1993 (Figure 4.15).

4.3.1.7 Rodgers Road (site 25)

The Rodgers Road site consists of a single steep foredune (8.5 m high) developed in front of Pleistocene cliffs some 20 m in height (Figure 4.16a). The beach has changed little in terms of beach volume since 1977 at this site although further to the east and west recent erosion is apparent with wave run-up often encroaching into the base of the foredune (Figure 4.16b). The variation in excursion distance is 50 m, with a minimum of 43 m, and a foredune base level distance of 11 to 16 m.

4.3.1.8 Pukehina Redoubt (site 26)

The frontal dune consists of slumping sand pushed against 40 m high vegetated Pleistocene cliffs; however, erosion of much of this sand reservoir occurred between May 1992 and July 1993 (Figure 4.17). As stated earlier this site location differs from the original 1977 location shown in Figure 4.17a. The re-established site shows some slight longer-term erosion, with occasional scarping along the base of the frontal dune caused by berm washover and removal of the sub-aerial sand reservoir. The variation in excursion distance is 36 m, with a minimum horizontal distance to mean sea level of 54 m, and a foredune base level distance of 25 m.

Figure 4.16 *a)* Holocene foredunes at Rodgers Road, showing no current dune development, as with Pukehina Beach these dunes may once have been more extensive than present. *b)* Long-term dune erosion between Otamarakau and Rodgers Road, where these steeply faceted dunes expose sands deposited tens to hundreds of years ago, indicated by the yellow humic stained nature of the sand grains and the well colonised *Muehlenbeckia* vegetation (June, 1993).

Figure 4.17 Photographs of BOPCES site 26 (Pukehina Redoubt) in *a)* 1977, and *b)* June 1992, viewed to the north-west, showing erosion of the poorly developed accumulation of sand in front of the vegetated and eroding Pleistocene cliffs.

The texture varies markedly at this site from extensive gravel patches on the beachface between sites 26 and 27, to contrasting fine sand over the entire beach (Figure 4.18).

4.3.1.9 Pukehina south (site 27)

This site was described in Healy *et al.* (1977) and Healy (1978a) as having a regenerating steeply faceted frontal dune 5.0 m high with a poorly developed backbeach, and profile width of 50 m. The beach possesses a well-developed berm approximately 8 m in front of the frontal dune, with large cusp development associated with a reflective beach state and/or post-storm conditions. The berm consists primarily of sand and gravelly sand, although occasionally this may be removed with rocks and gravels present.

Since 1978 the surveyed profiles show an overall seaward displacement of the beach profile, with accretion at the base of the foredune developing an attached low frontal dune. Although wind blown sand affects the foredune to some degree as evidenced by the surveyed profiles, no significant further changes have occurred to the frontal dune since 1988. From 1988 to 1993 the landward limit of profile change has been the toe of the frontal dune in which scarps of < 1m are sometimes present (e.g. 4 Oct 1991). The seaward limit is variable with a maximum recorded beach elevation at the berm of 2.1 m. The variation in excursion distance at southern Pukehina Beach is 24 m, with a minimum of 47 m, and a foredune base level distance of 17 m. The beach volume indicates some longer-term erosion at this site since 1988.

At the time of the 1 May 1992 profile the beach had experienced a long period of accretionary wave conditions which account for the well-developed berm, which at all other survey dates, when present, is at best moderately developed. This site experiences constant changes in beach profile and sediment texture, with gravel sediments often exposed or brought onshore to the beachface and swash zones. This material can literally disappear overnight, as fine sand is deposited on top, or the coarser sediments are removed offshore.

The beach state observed at this site varies from reflective to longshore bar trough tending towards dissipative under storm conditions, however the most common beach state is reflective or transverse bar rip with occasional flatter profiles corresponding with a low-tide terrace beach state (e.g. 4 Oct 1991, 8 Dec 1992). This appears to occur immediately after small storms and before the beach starts accreting from sand stored in the terrace or bar and brought onshore to rebuild the berm.

Pukehina south was one of the sites resurveyed in detail in Healy (1978b), in order to compare net change between the 1976/77 and 1977/78 survey period, examine trends in cut and fill, and determine an order of magnitude of volumetric cut and fill. At site 27 Healy (1978b) found that the volumetric change from July 1977 to Jan 1978 was 70 m^3/m determined from quasi monthly profile changes during this brief period (Figure 4.19).

Figure 4.18 North-east of BOPCES site 26 (~200 m) viewed to the south-east, showing the large textural fluctuations that occur at this site from *a)* extensive patches of greywacke-volcanogenic gravels and rocks (20-April, 1992), to *b)* storm erosion of the berm and scarping of the backbeach regions with only fine-grained sands present (10-November, 1992), and c) gravel cusps which have been partially covered with finer sands (25-April, 1993).

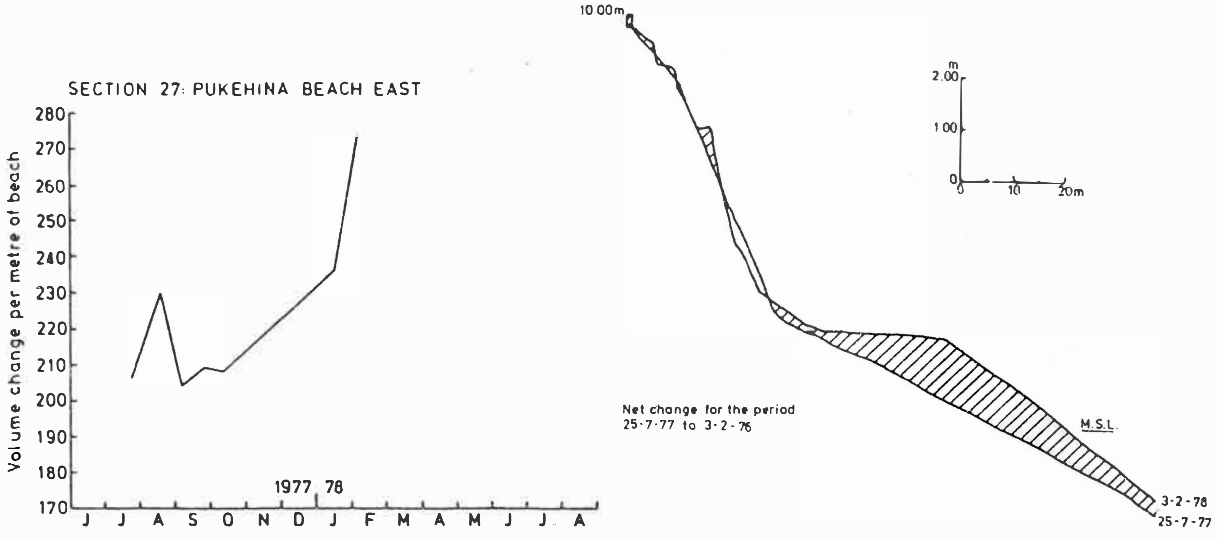


***Figure 4.19** a)* Quasi monthly profile changes in beach volume and *b)* net profile change for the period 25-7-77 to 3-2-78 for BOPCES site 27. Accretion is shown by stripping and erosion by lack of shading. Overall some erosion has occurred at the base of the foredune with accretion of the berm region. *(source: Healy, 1978b)*

4.3.1.10 Pukehina central (site 28)

Pukehina central is described in Healy *et al.* (1977) as having a regenerating frontal dune 8.5 m high with a poorly developed backbeach, and profile width of 60 m. Healy (1978d) notes a similar dune state to 1976-77, consisting of a scarped frontal dune colonised by *Spinifex* vegetation along the slump face. The base of the foredune was noted as susceptible to sapping during "cut" events. The beach had a poorly developed berm, narrow backbeach area (~ 1 m), with wave run-up in calm conditions ceasing at this point.

The excursion distance variation at central Pukehina Beach is 56 m, with a minimum of 58 m, and a foredune base level distance of 36 m. The beach has accreted by about 110 m^3 from 1978 to 1987, which appears to be due to a translocation of the beach profile in a seaward direction giving a false level of beach change, especially since a very steep, 13 m high foredune has supposedly accreted by 5 m. However, some accretion has occurred at the base of the foredune since 1977, with accretionary development of low 1 m high dunes colonised with *Spinifex* (Figure 4.20).

4.3.1.11 Pukehina north (site 29)

This site is described in Healy *et al.* (1977) as having an actively scarped frontal dune 5.0 m high with a non-existent backbeach, and profile width of 90 m. Since 1977 however the largest dune accretion along Pukehina Spit has occurred at this site. At this distal end of the spit the beach becomes flatter, with low-tide terrace beach states more common. This supports the view of the Waihi-estuary ebb-tidal delta system actively interacting with the beach system along the distal end of the spit.

Figure 4.20 *a)* Dune development along central Pukehina Beach (site 28) viewed to the south-east (23-June, 1993) showing low frontal dunes colonised by *Spinifex*. In 1977/78 the toe of the foredune was located less than a metre from the base of the older steeply faceted foredunes to the right. *b)* Similar, yet more extensive foredune development (dunes are approximately 30-40 m wide here) north-west of site 29 (northern Pukehina Beach, distal end) viewed to the south-east (23-June, 1993).

Figure 4.21 The distal tip of Pukehina Spit north-west of site 29 looking towards Town Point, on three different occasions. *a)* Erosion of the foredune at the distal end of Pukehina Spit (P1-P3), north of BOPCES site 29 (23-June 1993). The scale is approximately 1.75 m, showing vertical erosion of 2-2.5 m at this site, along a 100 m strip associated with complete removal of the sub-aerial beach sand reservoir. *b)* Reasonably healthy beach, with dissipative beach state (4-April 1992). *c)* Scarping of the beach berm and inter-tidal areas, with large quantities of exposed heavy mineral indicating erosion and an unhealthy beach state (24-January, 1992).

During a three week period from 7 June to 23 June 1993, the tip of the spit experienced significant dune erosion as the result of the combined effect of two small and one moderate sized storm events from the NW, NE and N respectively, resulting in vertical erosion of up to 2.5 m over a 500m length of beach (Figure 4.21).

The variation in excursion distance is 76 m, with a minimum of 47 m, and a foredune base level distance of 29 m. However the large variation in excursion distance may be due to the inclusion of a non-reduced profile, even allowing for the low-tide terrace beach state at the time. Discounting this profile the excursion distance variation is only 36 m.

4.3.1.12 Newdicks Beach (site 30)

In morphological contrast to the Maketu side of Town Point where no significant beach exists, the eastern side of this promontory (Newdicks Beach), is a kilometre section of beach similar in sediment texture to Pukehina Spit (Chapter 5). Newdicks Beach from aerial photographic changes has shown some accretion during historic times, consistent with the findings of Smith (1989). In comparing the 1978 and 1988 beach profiles for sites 30 and 32 (either side of Town Point) Smith indicates long-term erosion on Maketu Spit (BOPCES site 32) of -33 m^3/m that is *"still within the natural volume changes likely along Bay of Plenty coast"*. In contrast a large growth of 52 m^3/m at Newdicks Beach (BOPCES site 30) was found (Smith, 1989). Although this may be the result of local effects, it implies that sediment is being removed from the western side of Town Point and conversely accretion is occurring on the eastern side, suggesting that littoral drift may be to the north-west, with Town Point acting as a natural groin structure causing accretion on the updrift side and erosion on the downdrift side. Beach profile changes for Newdicks Beach in this study again show evidence of long-term accretion which may be connected with sediment addition from the Waihi estuary and ebb-tidal delta system, due to its close proximity.

The variation in excursion distance is 53 m, with a minimum of 60 m, and a foredune base level distance of 35 m. From beach profiles accretion is indicated with the low foredune consisting of a prograding ramp of accumulated sand with *Spinifex* runner colonisation.

4.3.2 Excursion Distances

The excursion distances to mean sea level elevation for each of the BOPCES sites briefly examined in the profile descriptions are given in Figure 4.22, representing changes to beach width with time. Sites which show some accretion are Newdicks Beach (30), Pukehina north (29), Pukehina central (28), Rodgers Road (25), Kohioawa Beach (22), and Tarawera West (20). Sites which show erosion are Otamarakau (24), and Pikowai (23), while Pukehina south (27), Pukehina Redoubt (26), Matata (21), and Tarawera East (19) sites show no long-term trend. Comparison of the Otamarakau site with Figure 5 from Smith *et al.* (1992), shows similarities, although their data indicate this site to be in a more stable condition. Between 1978 and 1993 the beach has retreated about 13.5 m, or

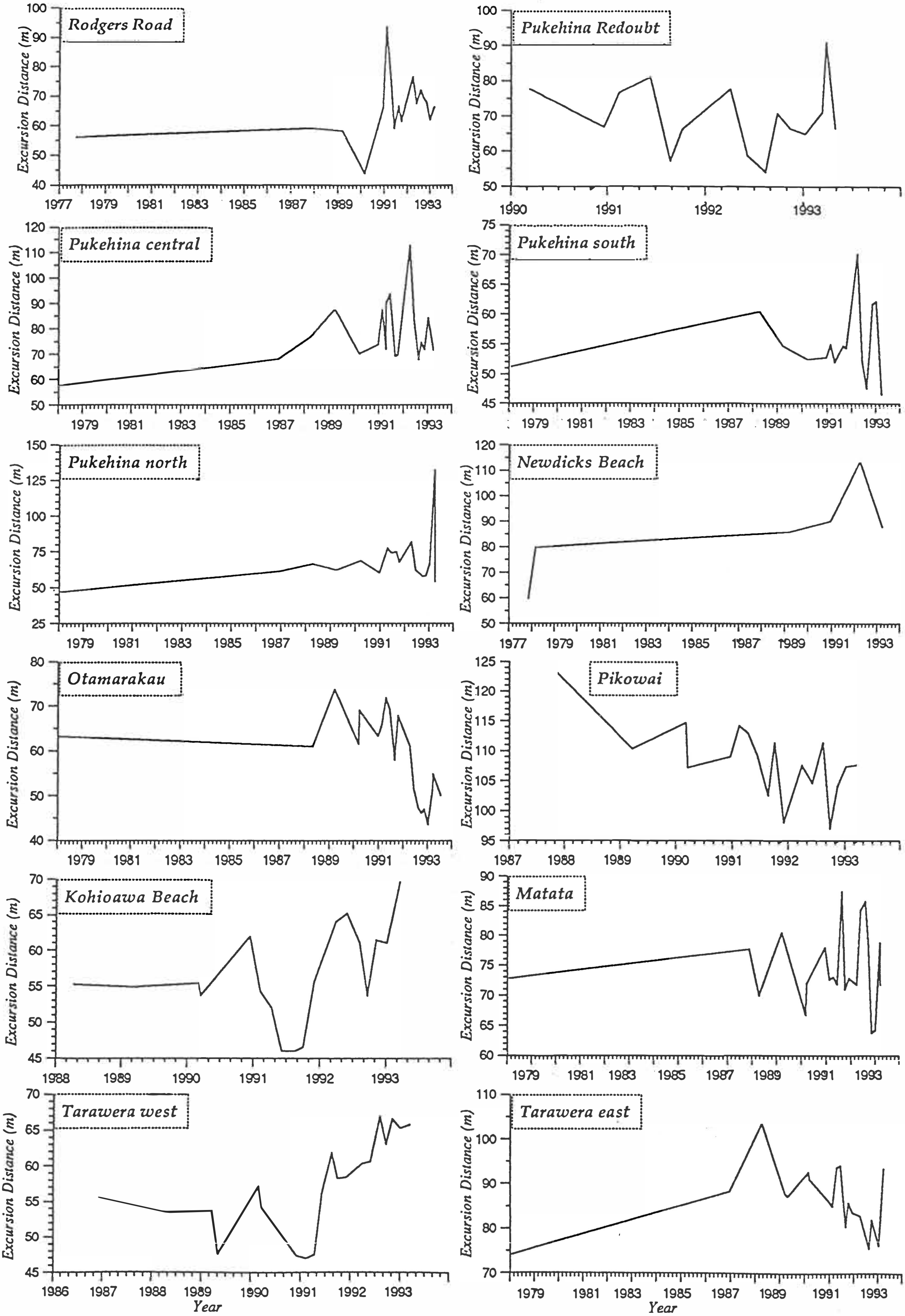


Figure 4.22 Excursion distances to mean sea level for BOPCES sites 19 to 30 inclusive, over the profile period available at each site.

21 % of the 1978 beach width from bench mark to mean sea level. At Pikowai the beach has similarly retreated about 13 m since 1987 (12 %). The retreat of both these sites may be a reflection of the sand extraction at Otamarakau and its downdrift effects on the sediment budget at Pikowai.

4.4 Beach Change Model

Smith (1986) infers that the nearshore zone at Otamarakau is characterised by the presence of crescentic offshore bars, which is indicative of low longshore drift rates. Smith (1986) states from Hom-ma and Sonu (1963) that *"in areas where there is longshore drift crescentic bars are not present and the offshore bar forms a linear feature parallel to the coast"*. Even under these conditions some littoral drift is still expected to occur, and it is likely that under storm conditions drift rates are orders of magnitude higher and the offshore bar becomes significantly altered. The movement of such crescentic bars along the coast under a dominant oblique wave approach is suggested as occurring between Otamarakau and Matata (Smith, 1986; p.25) (Figure 4.9b), and may cause periods of erosion and accretion along the coastline in the vicinity of the sand extraction operation (Otamarakau to Hauone) which is not related to either sand extraction or storms (Smith, 1986). While these features of the nearshore morphology are undoubtedly present, and are often noticeable within the Otamarakau-Matata area, they do not appear to be present all the time. Instead accretionary and erosional extremes exist, in which the offshore bar migrates due to diabathic sediment transport either landward or seaward, and thereby alters shape. Also the embayed arcuate duneline sectors with approximate 200 m spacings observed by Healy *et al.* (1977), may be due in part to known wave focussing along this part of the coast (Chapter 7), and which may then induce development of crescentic bars.

Sunamura (1985) developed a model for short term beach change, relating the movement of offshore bars under accretionary and erosional conditions based on the wave conditions and beachface sediments (Figure 4.24). The model is based on a dimensionless parameter K* which represents the net diabathic sediment transport direction (Eqn. 4.1).

$$K^* = \frac{\overline{H_b}^2}{g} \overline{T}^2 d \qquad \text{...equation 4.1}$$

where: H_b= daily average breaker wave height (m)
T= daily average breaker wave period (m)
g= acceleration due to gravity (m/s^2)
d= grain size of the beach sediment (mm)

The crescentic bars formed at Stage 3a, appear only during accretionary beach processes, when the prevailing sediment migration direction is onshore (Horikawa, 1988). Beach observational data of wave conditions in relation to observed beach changes for southern Pukehina Beach were compared based on this model. The variation in the beach states during the observation period predicted by the model is presented in Table 4.2.

Table 4.2 Values of K* indicating the direction of net diabathic sediment transport, calculated from observational wave measurements for a 108 day period from 20th May to 26th June and 16th July to 26 August, 1993 (Chapter 7). The numbers shown in the last two columns are the predicted beach states from the Sunamura (1985) model for beach change based on the K* value, and the actual beach state observed, based on observations of the beach morphology at the time.

Date	*Wave Height (m)*	*Period (s)*	*K**	*Actual States*	*Predicted States*
20/4/93	0.4	15	1.5	4	4
21/4/93	0.8	12	3.8	4 to 5	5
22/4/93	0.3	12	0.5	5	5
23/4/93	0.25	15	0.6	5	5
24/4/93	0.1	15	0.1	5	5
26/4/93	0.3	15	0.8	5	5
27/4/93	0.1	15	0.1	5	5
28/4/93	0.6	6	0.5	5	5
29/4/93	1.05	6	1.6	5	5
30/4/93	0.5	7.5	0.6	5	5
31/4/93	0.5	5	0.3	5	5
1/5/93	0.5	7.5	0.6	5	5
2/5/93	0.3	9	0.3	5	5
3/5/93	0.3	7.5	0.2	5	5
4/5/93	0.25	10	0.3	5	5
5/5/93	0.25	6	0.1	5	5
6/5/93	0.25	7	0.1	5	5
7/5/93	0.5	6	0.4	5	5
8/5/93	0.65	6	0.6	5	5
9/5/93	1.25	8	4.1	6	5
10/5/93	1	8	2.6	6	5
11/5/93	0.8	10	2.6	6	5
12/5/93	0.75	5	0.6	4	5
13/5/93	1.5	6	3.3	6	5
14/5/93	1	10	4.1	7	5
15/5/93	0.3	8	0.2	3a	5
16/5/93	0.3	8	0.2	3a	5
17/5/93	0.6	9	1.2	3a	5
18/5/93	0.5	10	1.0	3a	5
19/5/93	0.3	8	0.2	4	5
20/5/93	0.2	9	0.1	5	5
21/5/93	0.15	10	0.1	5	5
22/5/93	0.15	10	0.1	5	5
23/5/93	0.2	9	0.1	5	5
24/5/93	0.3	10	0.4	5	5
25/5/93	0.2	10	0.2	5	5
26/5/93	0.3	9	0.3	5	5
27/5/93	0.6	7	0.7	5	5
28/5/93	0.1	10	0.0	5	5
29/5/93	0.1	10	0.0	5	5
30/5/93	0.1	10	0.0	5	5
31/5/93	0.15	9	0.1	5	5
1/6/93	0.2	10	0.2	5	5
2/6/93	0.25	15	0.6	5	5
3/6/93	0.3	6	0.1	5	5
4/6/93	0.6	6	0.5	5	5
5/6/93	0.9	7	1.6	4	5
6/6/93	2.1	7	8.8	6	5
7/6/93	2	10	16.3	1	6
8/6/93	1.1	10	4.9	2a	4
9/6/93	0.8	12	3.8	2a	4
10/6/93	0.5	12	1.5	2a	5
11/6/93	0.3	12	0.5	3a	5
12/6/93	0.3	8	0.2	3a	5
13/6/93	2.5	8	16.3	1	6
14/6/93	1.8	9	10.7	2a	6
15/6/93	0.6	8	0.9	5	4
16/6/93	0.25	8	0.2	5	5
17/6/93	0.2	10	0.2	5	5
18/6/93	0.25	12	0.4	5	5
19/6/93	0.3	10	0.4	5	5
20/6/93	0.6	5	0.4	5	5
21/6/93	0.8	10	2.6	6	5
22/6/93	0.3	9	0.3	5	5
23/6/93	0.4	10	0.7	5	5
16/7/93	0.2	9	0.1	5	5
17/7/93	0.2	12	0.2	5	5
18/7/93	0.15	10	0.1	5	5
19/7/93	0.15	9	0.1	5	5
20/7/93	0.2	10	0.2	5	5
21/7/93	0.5	10	1.0	5	5
22/7/93	0.4	9	0.5	5	5
23/7/93	0.3	8	0.2	5	5
24/7/93	0.25	10	0.3	4	5
25/7/93	0.35	9	0.4	4	5
26/7/93	0.3	10	0.4	4	5
27/7/93	0.2	12	0.2	5	5
28/7/93	0.3	10	0.4	5	5
29/7/93	0.4	9	0.5	5	5
30/7/93	0.4	8	0.4	5	5
1/8/93	0.5	9	0.8	5	5
2/8/93	0.4	7	0.3	5	5
3/8/93	0.8	6	0.9	5	5
4/8/93	0.8	9	2.1	6	5
5/8/93	0.6	8	0.9	6	5
6/8/93	0.3	9	0.3	6	5
7/8/93	0.2	10	0.2	4	5
8/8/93	0.2	8	0.1	4	5
9/8/93	1.5	8	5.9	6	5
10/8/93	2	9	13.2	8	6
11/8/93	1.5	12	13.2	8	6
12/8/93	0.8	10	2.6	2a	4
13/8/93	0.6	10	1.5	3a	5
14/8/93	0.3	9	0.3	5	5
15/8/93	0.2	9	0.1	5	5
16/8/93	0.4	7	0.3	5	5
17/8/93	0.3	10	0.4	5	5
18/8/93	0.3	12	0.5	5	5
19/8/93	0.5	10	1.0	4	5
20/8/93	0.4	10	0.7	5	5
21/8/93	0.3	10	0.4	5	5
22/8/93	0.3	10	0.4	5	5
23/8/93	0.5	6	0.4	5	5
24/8/93	0.5	10	1.0	4	5
25/8/93	0.4	11	0.8	5	5
26/8/93	0.2	9	0.1	3a	5

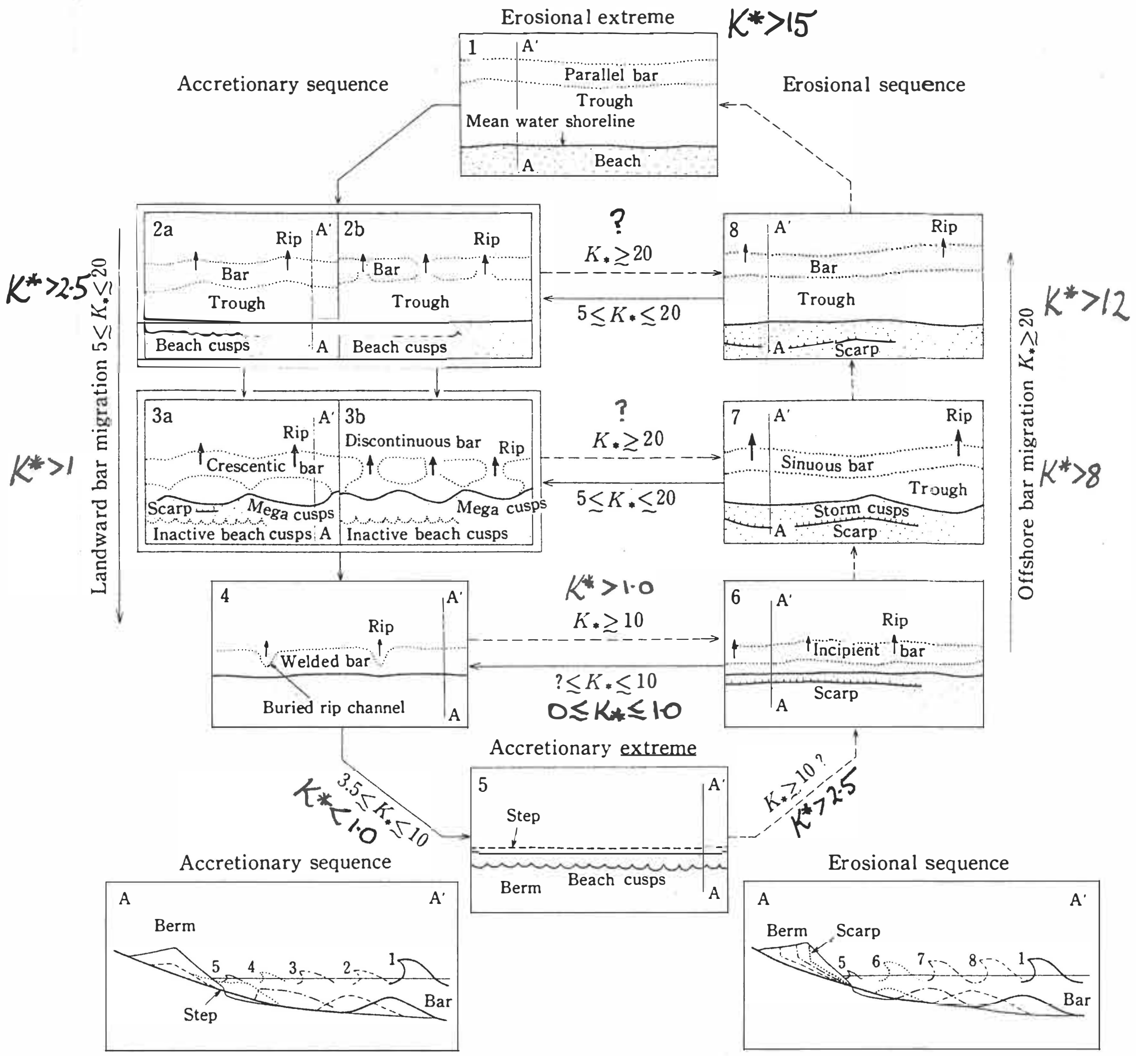


Figure 4.24 Beach change model of bar migration from erosional to accretionary extremes and six intermediate phases, based on the dimensionless parameter K* for predicting the net onshore/offshore movement of sediment. *(source: Horikawa, 1988)*

Based on the Table 4.2 the calculated K* values are rarely sufficient to predict a change in beach morphology, and instead it is suggested that the K* values added to Figure 4.24 would be more appropriate. Given these changes the model in terms of beach states and beach-nearshore interactions during erosional and accretionary extremes is approximated fairly well. The model shows that cyclic storm and accretion periods occur within the beach system at Pukehina Beach, from accretionary reflective beaches (5) to erosional multiple longshore bar trough beaches (1) under periods of prolonged storm conditions, with continual bar migration dependant on the beach conditions. The beach from observational data is commonly stage 5 type, which correlates with the generally reflective rather than dissipative nature of this coastal sector. In addition the beach-dune-nearshore system along Pukehina Spit is observed to show increased periods of low-tide terrace beach state (Wright and Short, 1983) from the basal to the distal end of Pukehina Spit, which is associated with more reflective type conditions.

4.5 Beach Volumetric Analysis

4.5.1 Introduction

The results of Smith (1989) are briefly discussed here as a pre-emptive comparison with later analysis of BOPRC profile data, based on calculated beach site volumes. Analysis of the longer-term changes in total beach volume within the Pukehina-Matata coastal sector over a decade (Table 4.3) are relatively small, especially east of the Pukehina Redoubt, and are probably indicative of a stable coastline which is in dynamic equilibrium with the wave environment (Smith, 1989). Smith (1989) also suggests that these volume changes are within the natural range of beach change. The volume changes over the decade period do mask to some extent the true beach volume changes occurring, since the 1988 volume is particularly larger than normal, representing a possible peak on an accretionary beach volume change cycle.

Table 4.3 Net beach volume change at selected sites between Matata and Maketu 1977-78 to 1988. *(source: Smith, 1989).*

BOPCES Site	Net volume change m^3/m
BM20 (Matata)	14
BM24 (Otamarakau)	18
BM25 (Rodgers Road)	18
BM29 (Pukehina north)	62
BM30 (Newdicks Beach)	52
BM32 (Maketu)	-33

Based on the above changes (assumed to reduce seasonal variability) then between Otamarakau and Matata the total volume change over a 16 km stretch of beach is 25,600 m^3 per year. This contrast with the total change in the volume of sediment between the distal end of Pukehina Spit and Newdicks Beach over nearly four kilometres is approximately 20,000 m^3 per year or nearly three times the sediment volume (m^3/m of beach) as for the beach from Otamarakau to Matata. This suggests that the larger beach volumes on either side of the Waihi estuary are most likely due to sediment additions to the beach system from the Waihi estuary ebb-tidal delta, or a greater inferred sand reservoir within the beach system and possibly the upper nearshore zone at sites 29 and 30 compared with the Otamarakau, Matata, and Rodgers Road sites. Alternatively the larger rates of accretion along Pukehina Beach may be due to increased parabathic and/or diabathic sediment supply in this region. Further investigation is provided by volume calculations of all BOPCES sites profiled by the BOP Regional Council within the Pukehina-Matata coastal sector.

4.5.2 Methodology

Beach volumes in this study are calculated as the amount of sediment contained within a beach profile from a given datum, usually taken as 0.0 reduced level (R.L.) (equivalent to mean sea level, Moturiki datum) to a benchmark located behind the frontal dune. For the coastal sector under consideration the dune crest is approximately equivalent to the site bench mark peg at most sites, with the exception of Newdicks Beach, Pikowai, and Kohioawa Beach. The beach sediment volumes calculated in this study differ from those given by Smith (1989) and Smith *et al.* (1992) whose volumes are calculated for the active beach in relation to sand extraction, measured from mean sea level to the vegetation line at the toe of the foredune (Smith pers. comm., 1993). Beach volumes in this study include the sand stored within the foredune, which under storm conditions has been known to historically erode and/or accrete. The volumes of cut and fill involved at each site should be comparable regardless of the total beach volume used.

Other studies of beach sediment volumes (Christopherson, 1977; Harry, 1977; Healy, 1978) in the Bay of Plenty calculate profile volumes to MLWS; however in general the profiles do not extend far enough seawards to permit measurement to this level without some extrapolation, which would then lead to inaccuracies in the calculated results.

Volumes were calculated for each beach profile using the programme *Profile Volume* written by Mr Albie Dommerholt of the Marine Geosciences Group, University of Waikato (Appendix II), on the University of Waikato's VAX system. The programme integrates volume change at 0.1 m vertical and horizontal intervals over the entire profile by interpolating between linear data points, given a vertical end point at 0.0 R.L.

4.5.3 Results

The net volume change since 1977/78 when surveying first commenced to 1993 is given in Figure 4.25 showing that apparently there has been a greater amount of accretion at the north-western end of the study area at Newdicks Beach and Pukehina north. At Pukehina south, Pukehina Redoubt, and Rodgers Road this is not apparent, suggesting that littoral drift in a north-west direction along Pukehina Spit may be building up the spit at its distal end with possible sediment supply from the updrift sites. This is consistent with field observations, although this may also be attributed to a possible lack of strong northerly and north-westerly winds in the last 5 or so years which have greatest erosional effect along Pukehina Spit, and sediment addition from the Waihi estuary ebb-tidal delta. The erosion in the vicinity of the Pukehina Redoubt also promotes the idea that this is an area of possible sediment supply to the spit. The main sites of erosion are at Otamarakau and Pikowai. Despite the close proximity of the Waitahanui stream as a sediment source this erosional trend amongst a general trend of accretion would suggest that the sand mining has had a definite impact in the amount of sediment available within the beach system, given the lack of historical evidence from aerial photographic analysis of enhanced erosion in this region. The small erosion figure at Pikowai is consistent with some downdrift impacts from sand extraction and sediment removal within the littoral system, assuming that littoral drift is in a south-easterly direction from Otamarakau to Matata as advanced by Healy *et al.* (1977) and supported by evidence in this study.

Volumes of cut and fill involved at each site within the profile period were determined from the beach volumes between survey dates (Figure 4.26). In some cases this may lead to inaccuracies of cut

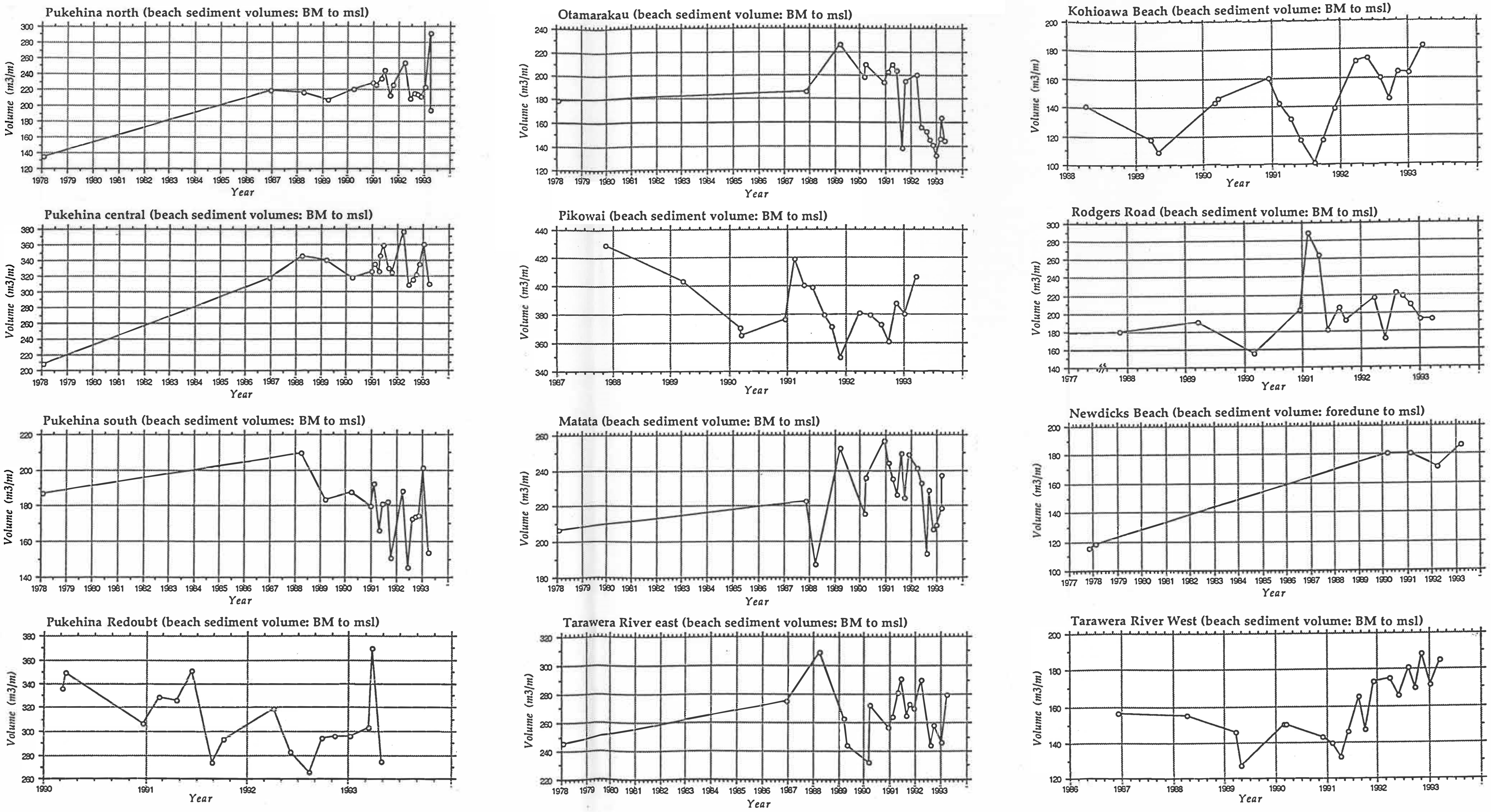


Figure 4.25 Available beach sediment volumes for BOPCES sites 19 to 30 inclusive, for the length of profile record available. Beach volumes are calculated using the computer program *Profile Volume*, from approximately the crest of the foredune to mean sea level. *(original profile data obtained from BOPRC)*

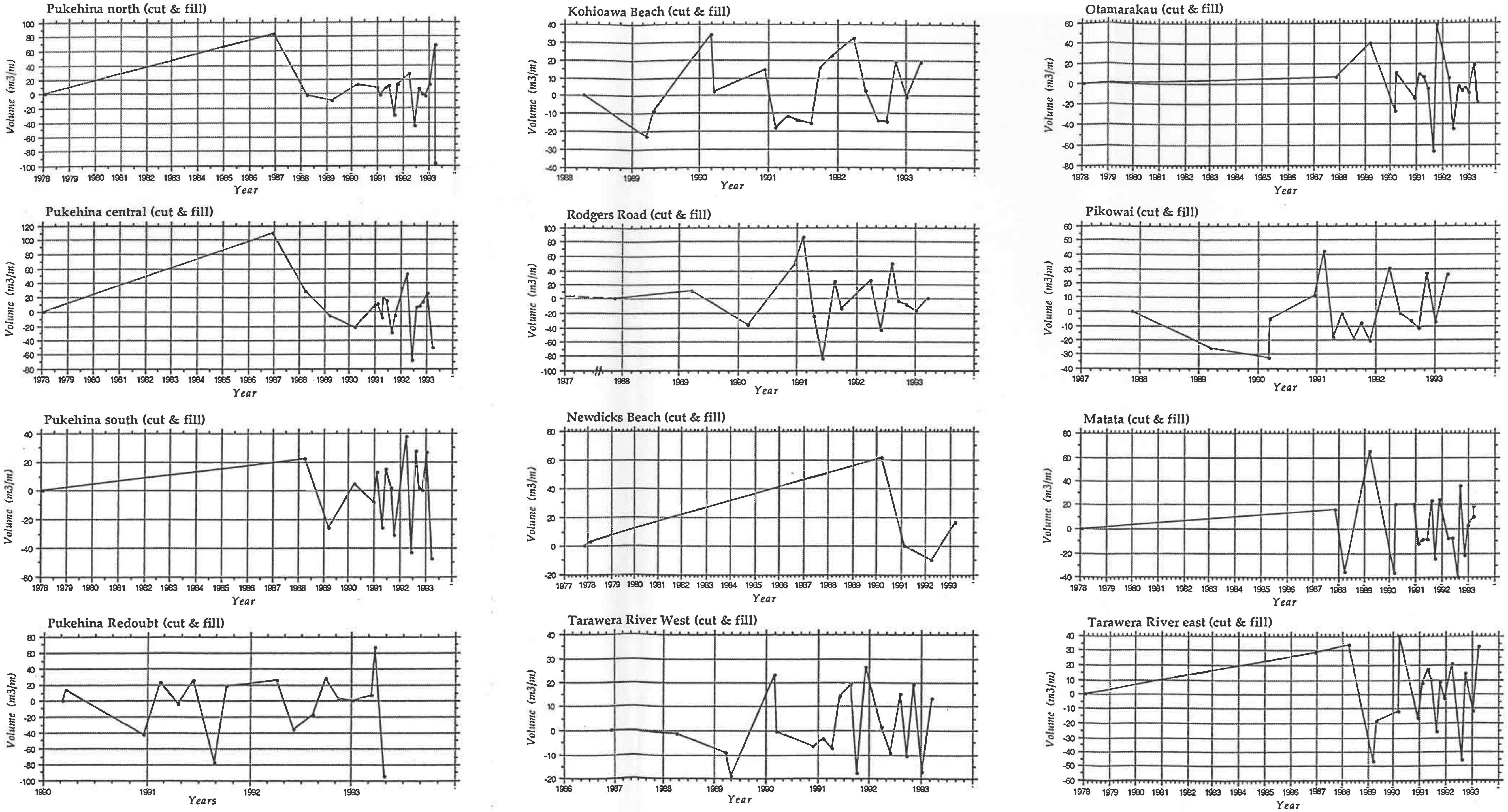


Figure 4.26 Volumes of cut and fill for BOPCES sites 19 to 30 inclusive, for the length of profile record available, determined from the inter-survey beach volume difference of available sediment. *(original profile data obtained from BOPRC)*

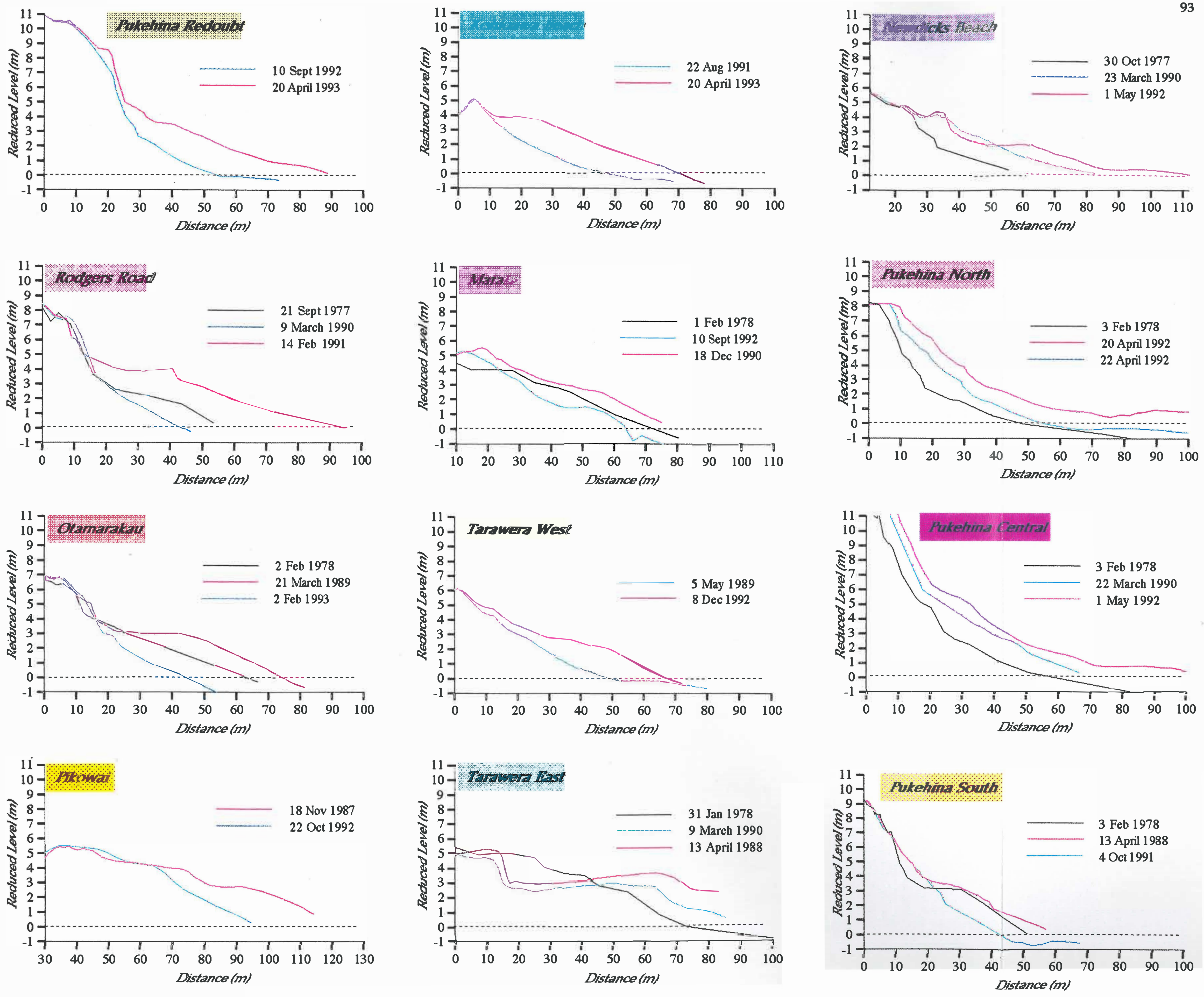


Figure 4.27 The maximum (red) and minimum (blue) beach profiles for BOPCES sites 19 to 30 inclusive, between 1988 and 1993, with their 1977/78 comparisons (black) also given where available.

and fill volumes due to the often large inter-survey period. Multiple erosion events between survey dates may infer a significant volume of beach cut for that period, or commonly impacts such as erosion events may be mitigated due to post-storm accretion of the beach sand reservoir, thereby underestimating the cut volume.

For the Pukehina-Matata coastal sector multiple storm events have the greatest potential for erosion of the beach-dune system. Each successive storm reduces the sand reservoir available to buffer the erosion effects. For example, during autumn 1993 the beach experienced some significant erosion, which in places has eroded the foredune (e.g. Figure 4.21a), with irregular well developed multiple offshore bars. Rather than a single erosion event this appears to have been the result of three storms at approximately weekly intervals in combination with spring tides (beach observational data 20/4/93-23/6/93, Chapter 7). It is therefore apparent that the volume of the buffer zone along the Pukehina-Matata coastal sector can cope with most single storm events, but it is a combination of events in which the beach does not have time to recover and accrete that pose the biggest threat.

The maximum and minimum beach profiles monitored between 1988 and 1993, and their 1977/78 comparisons where available, are depicted in Figure 4.27, with the corresponding calculated maximum beach volume fluctuations during the 1988-1993 period given in Table 4.4. It should be noted that these volumes are affected markedly by the number and frequency of the surveyed profiles. Hence, for example the fluctuation for Newdicks Beach is based only on four survey dates and the actual maximum change is expected to be much higher.

Table 4.4 Maximum, minimum, and maximum volume fluctuation for each BOPCES site in the Pukehina-Matata coastal sector from 1988 to 1993.

Site	Maximum Volume (m^3/m)	Minimum Volume (m^3/m)	Maximum Volume Fluctuation at Site (m^3/m)
Newdicks Beach	186	170	16
Pukehina north	291	193	98
Pukehina central	360	308	52
Pukehina south	209	150	59
Pukehina Redoubt	369	265	104
Rodgers Road	289	155	134
Otamarakau	225	131	94
Pikowai	429	361	68
Kohioawa Beach	182	101	81
Matata	256	187	69
Tarawera River west	189	127	62
Tarawera River east	309	232	77

Comparing these results with other studies (Table 4.5), Healy (1978b) determined that the maximum profile volumetric change for site 27 (Pukehina south) between 1977 and 1978 was 70 m^3/m. The envelope of cut and fill in this study for site 27 was calculated as 59 m^3/m for the period from 1988-1993. The main difference arises from the determination of the beach volumes. In the Healy (1978b) study volumes were calculated from the benchmark peg to MLWS, compared to mean sea level in this study. Also the inter-survey periods are larger than for Healy (1978b), combining to produce a smaller envelope of change.

Table 4.5 Maximum beach changes associated with various Bay of Plenty beaches. #= figures are based on storm erosion from the 18th to 20th July 1978 storm. * estimated maximum storm cut.

Location	*Maximum Change* (m^3/m)	*Source*
Whiritoa Beach	70	*Christopherson (1977)*
Whiritoa Beach*	99	*Christopherson (1977)*
Waihi Beach	98-260	*Harray (1977)*
Ohope #	52	*Healy (1978)*
Ohope	80	*Healy (1978)*
Piripai #	79	*Healy (1978)*
Piripai	204	*Healy (1978)*
Papamoa	64	*Healy (1978)*
Mt. Maunganui Beach	92	*Foster (1991)*

This envelope of change is useful in determining the volumes of sediment moved, however the volumes moved in any one location will depend on the important parameters of beach grain size, wave intensity, sediment budget, and offshore slope (Healy, 1978).

4.5.4 Seasonal Changes

Data from Smith (1990a) for site 1400 in the Otamarakau-Hauone mining strip was used to determine detailed seasonal excursion distance behaviour at various elevation levels above mean sea level. This site was chosen since it was profiled at approximately weekly or fortnightly intervals over a six month period. Excursion distances were plotted at 1 m intervals for the period from June 1989 to January 1990 (Figure 4.28). Overall this site exhibits typical seasonal changes in beach profile, with no apparent longer term trends observed, other than a slight retreat of the foredune and dune face (6 to 4 m elevations) over the profile period. September and October, typically erosive months, are responsible for the decline of the 3, 2, and 1 m elevations, which show corresponding accretion during the summer months of December and January.

Smith (1989) determined the seasonal variation in beach volumes from the annual average volume at Matata, Otamarakau, and Rodgers Road based on a four year profile record (Figure 4.29). From this the beaches tend to be well-nourished during the summer and autumn months (January to April)

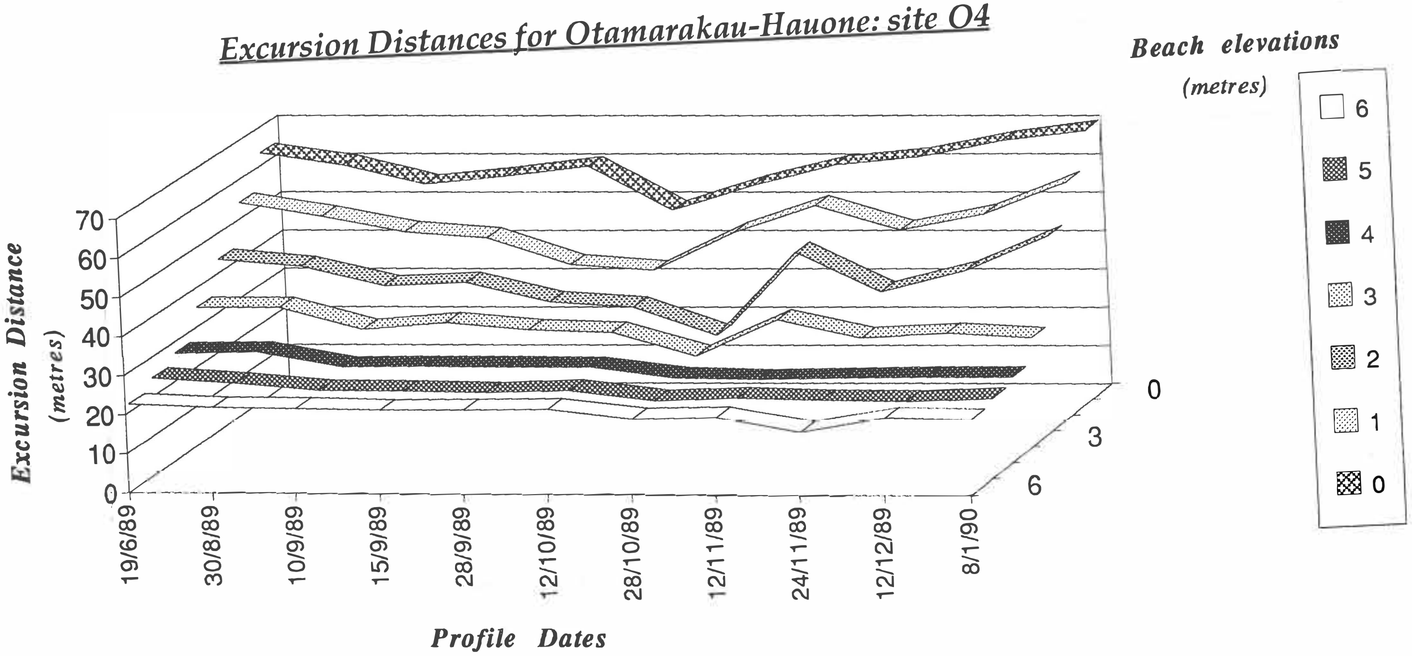


Figure 4.28 Excursion distances at BM400 (Smith, 1990a) equivalent to sediment sampling site O4 in this study (Chapter 5), within the Otamarakau-Hauone mining strip. Dates shown are for the 6-month period from June-1989 to January-1990, with excursion distances taken at 1 m elevations from mean sea level to the approximate crest of the foredune *(data from Smith, 1990a).*

and reach maximum depletion in late winter-early spring (August to October), with October to January the period in which beach deposits are renourished (Smith, 1989).

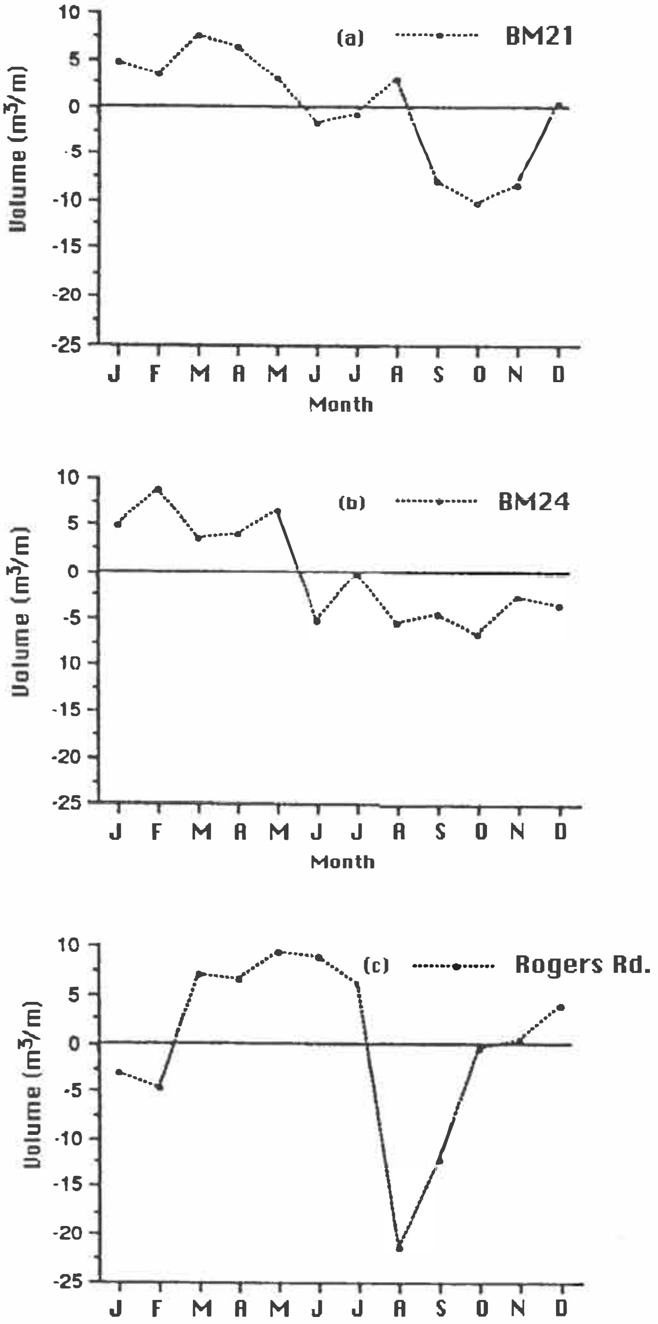


Figure 4.29 Seasonal variation in beach volume at Matata (BM21), Otamarakau (BM24), and Rodgers Road (~BM26). *(source: Smith, 1989)*

Hay (1991) found that storms in the Bay of Plenty, which are responsible for most of the sub-aerial beach erosion, were most frequent during the autumn months, with May having the highest monthly incidence of storms (15 %).

The seasonal variation of cut and fill volumes for the twelve BOPCES sites within the Pukehina-Matata coastal sector are depicted in Figure 4.30, and are based on the calculated beach volumes at each site over the period of profile record available. This shows that erosion is prevalent during

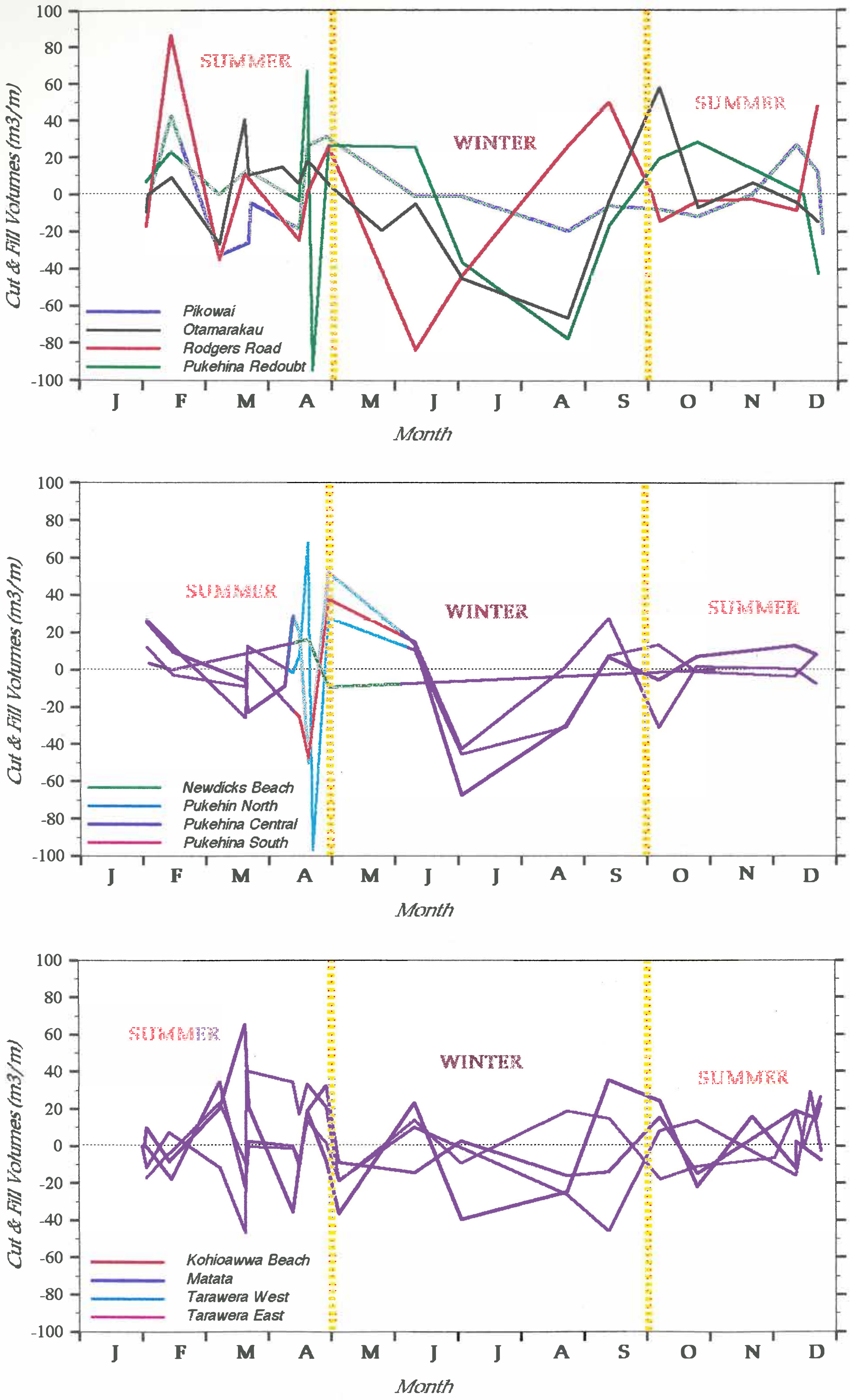


Figure 4.30 Seasonal variation of beach cut and fill volumes for BOPCES sites 19 to 30 inclusive, based on the calculated beach volumes at each site over the period of profile record available.

the winter months with accretion in the summer months (October/November to April/May), consistent with other findings, and provides evidence for correlation with seasonal variations in the wind and wave conditions, as found by Hay (1991).

4.6 Net Volume Changes within the Beach System

Beca, Carter, Hollings & Ferner Ltd. (1992) from estimates of net sediment gains at Pakiri-Mangawhai for both a short-term (two year) period and longer term (13 year) period, found that longer term profile records give a good approximation to the net sediment budget status of beach profiles, with shorter term measurements estimating the gross variation in response to sea-state and weather changes. Hence the longer the period of record the better the estimate of long-term net erosion or accretion of the beach system at each BOPCES site, negating the variable seasonal and cyclic effects of storm erosion and subsequent recovery.

4.6.1 Longer-term Profile Budget

Based on the profile volume changes presented in Table 4.6, the net longer term sediment volume change in the beach system for the Pukehina-Matata coastal sector was determined over the entire record length available at each site. Where possible these net changes were calculated over a 15 year period from 1978 to 1993. An exception to this record length is site 26 whose profile period extends only from 1990 to 1993. Analysis of neighbouring BOPCES sites shows that the Pukehina Redoubt is expected have a similar amount of long-term beach erosion or possibly even more than determined above, which would imply a greater negative net volume change at this site over a 15 year period. Numerous field observations by the author also indicate long-term erosion at this site.

Table 4.6 Estimated net beach volume change between the foredune and mean sea level within the Pukehina-Matata coastal sector, between 1977 and 1993, for BOPCES profile sites. Positive values indicate accretion, negative values erosion.

Site Location	*Net sand volume change* (m^3)
19- Tarawera east	+ 33.8
20- Tarawera west	+ 28.2
21- Matata	+ 30.0
22- Kohioawa Beach	+ 41.6
23- Pikowai	- 7.0
24- Otamarakau	- 35.0
25- Rodgers Road	+ 12.2
26- Pukehina Redoubt	- 61.2
27- Pukehina south	- 33.3
28- Pukehina central	+ 102.4
29- Pukehina north	+ 58.4
30- Newdicks Beach	+ 71.3

The estimated longer-term net change in the volume of sediment within the Pukehina-Matata beach system is presented in Table 4.7.

Table 4.7 Calculated longer-term net sediment budget for the beach system from the foredune to mean sea level, based on the net accumulation or erosion of sediment at BOPCES sites between February 1978 and May 1993. Shoreline length is the distance from halfway between the profile sites on either side of the site, and assumes the net sediment change is the same over this length of coast.

Site Location	*Shoreline Length* (m)	*Averaged Annual Volume Change* (m^3)	*Net Volume over profile period* (m^3)
19- Tarawera east	540	2.22	18,200
20- Tarawera west	2310	3.91	65,200
21- Matata	1750	1.97	52,500
22- Kohioawa Beach	3570	7.98	148,400
23- Pikowai	6025	-0.46	-42,200
24- Otamarakau	4835	-2.28	-169,000
25- Rodgers Road	4160	0.75	50,700
26- Pukehina Redoubt	2895	-18.43	-177,100
27- Pukehina south	2035	-2.18	-67,700
28- Pukehina central	1930	6.72	197,500
29- Pukehina north	1785	3.83	104,200
30- Newdicks Beach	530	4.39	37,700
Total volume of available beach sediments within the Pukehina-Matata coastal sector:			**1,130,600 m^3**
Total net volume change:			**218,500 m^3**
Average volume change (m^3 /m):			**6.75**

The overall net sediment budget for the beach system shows long-term accretion of 218,500 m^3 between February 1978 and May 1993, equating to 6,750 m^3 of sediment accumulation per kilometre of coast. Accounting for the sediment extracted from the beach system between Otamarakau and Pikowai over this period, estimated as 70,000 (Patterson), plus 5,000 (Patterson 3-month extraction, 1991), and 36,000 (N.Z. Railways), would then imply overall accretion of the Pukehina-Matata coastal sector of about +329,500 m^3 for the 1978-1993 period, or 10,180 m^3 per kilometre of coast.

Consideration of the volumes within the 2.4 km mining strip from Otamarakau to Hauone, shows net sediment accumulation within this beach system of about 26,480 m^3 for the 1978-1993 period (equivalent to 11,030 m^3/km). This allows for the sand estimated to have been removed via sand extraction, and agrees reasonably well with the net rate of sediment accretion averaged over the entire Pukehina-Matata coastal sector obtained above. However, the true net change for the Otamarakau-Hauone area during this period indicates an overall substantial net sediment loss to the beach system in the mining strip of about 84,500 m^3, or 35,210 m^3/km.

4.6.2 Shorter-term Profile Budget

Analysis of the net beach volume change from 21-March 1989 to 20-April 1993 was undertaken to determine shorter-term changes in the beach sediment budget for the Pukehina-Matata coastal sector. All profile sites, with the exception of the Pukehina Redoubt site (26), had been surveyed on both these occasions. The results are given in Table 4.8, with an overall net loss of 155,600 m^3 of sediment over this four year period, equating to an annual loss of 38,100 m^3. Accounting for sand extraction rates this would imply natural erosion for the Pukehina-Matata area from 1989 to 1993 of 90,600 m^3, with an annual loss of 22, 180 m^3.

Table 4.8 Calculated short-term net sediment budget for the beach system from the foredune to mean sea level, based on the net accumulation or erosion of sediment at BOPCES sites between 21-March 1989 and 20-April 1993. Shoreline length is as for Table 4.7 above.

Site Location	*Volume Change over profile period* (m^3)	*Averaged Annual Volume Change* (m^3)	*Net Volume over profile period* (m^3)
19- Tarawera east	17.1	4.19	9,200
20- Tarawera west	38.7	9.49	89,500
21- Matata	-33.5	-8.22	-58,700
22- Kohioawa Beach	64.3	15.77	229,900
23- Pikowai	4.0	0.99	24,300
24- Otamarakau	-79.7	-19.54	-385,800
25- Rodgers Road	2.28	0.56	9,500
26- Pukehina Redoubt	-33.4	-8.20	-96,900
27- Pukehina south	-29.7	-7.29	-60,600
28- Pukehina central	-30.0	-7.35	-57,900
29- Pukehina north	82.9	20.30	148,000
30- Newdicks Beach	6.21	1.52	3,300
Total volume of available beach sediments within the Pukehina-Matata coastal sector:			1,173,600 m^3
Total net volume change:			156,600 m^3
Average volume change (m^3 /m):			4.83

As some of the estimated volumes are larger than those calculated for the ~~longer-term volume~~ changes, with a similar sediment flux, it is suggested that the short-term changes are representative of gross amounts and seasonal variations as found by Beca, Carter, Hollings & Ferner Ltd. (1992). The annual natural loss rate calculated here may be misleading, since a significant proportion of this sediment deficit is due to a calculated loss at Otamarakau. It is probable that the profile change at the BOPCES site does not occur over the entire 4.8 kilometres of coast represented by this single profile. Instead it is suggested that the large loss may be an artefact of sand extraction of most of the sand mining directly near the operations plant at Otamarakau, and that the beach itself has experienced no change in the total amount of sediment in the Pukehina-Matata area except for sand extraction causing a deficit in part of the beach system at Otamarakau.

4.7 Summary

- From analysis of the coastal geomorphology, the Pukehina-Matata shoreline appears to have been undergoing gradual erosion since the late Holocene, after an initial accretionary formation phase associated with large sedimentation loads entering the coastal zone during the late Pleistocene developing much of the sandy beaches and dune systems within the study area. However, although sectors of the study area show a potentially disastrous state, long-term erosion on a large-scale has not yet occurred. This is particularly relevant to Pukehina Spit, a substantial housing area and summer holiday resort, more than 60 % of which lies within the delineated coastal hazard zone of Healy (1993).

- In the past 50-70 years the Pukehina-Matata coastal sector has been shown to be fairly stable although there has historically been a tendency for some horizontal coastal erosion of between 0 and 0.2 m per year. However commonly periods of longer-term erosion occur which are followed by periods of accretion, especially along Pukehina Spit.

- In the vicinity of the many beach impounded streams which feed the Otamarakau-Matata region, the beach tends to accrete, whereas the foredune erodes for up to 1.5 km either side, due to stream migration associated with the gross and net littoral drift regime and diabathic sediment transfer. The Waitahanui, Hauone, Pikowai, and Herepuru/Mimihia streams, from observations between 1991 and 1993 and aerial photographic analysis (1943, 1963, 1977, 1981, 1993), all show an overall tendency to migrate in a south-easterly direction along the beach, with stream off-setting greatest in this direction. This suggests a net littoral drift for the Otamarakau-Matata region in a south-easterly direction.

- The Waihi estuary is a large, shallow, bar-bound estuary enclosed by a single barrier spit (Pukehina Beach), with freshwater inflow via a number of channelised streams, and an overall area of 2.4 km^2 of which more than 70 % is aerially exposed. Between 1943 and 1981 the estuary has undergone accretion at its southern margins due to increased drainage of the Pukehina swamp area of the Maketu Basin, and sediment input from streams, principally the Pongakawa and Kaikokopu, feeding the estuary. Comparative aerial photograph analysis of the estuary in 1943 and 1981 shows that the spit on which the Little Waihi motorcamp is situated has accreted, with minimal or no apparent accretion of the northern margins of the estuary. It is also suggested that possible downwarping of the estuary may currently be occurring along a fault bounding the northern margin of the estuary and the Town Point promontory.

- Seasonally the beaches within the Pukehina-Matata coastal sector show typical 'equilibrium beach' type cut and fill cycles, with erosion during the autumn and winter months, and accretion during summer months.

- Based on beach cut & fill volume changes and observational data between 20/4/93 and 23/6/93, it is apparent that the beach volume of the buffer zone along the Pukehina-Matata coastal sector can cope with most single storm events, but it is a series of closely-spaced events between which the beach does not have time to recover and accrete that pose the biggest threat.

- The maximum calculated short-term volume fluctuation, from 1988 to 1993, within the Pukehina-Matata coastal sector varies from 16 m^3/m to 134 m^3/m, with an average variation of 76.2 m^3/m. This maximum beach change is considered to be the envelope of cut and fill, which results from seasonal and yearly erosion-accretion cycles, and indicates the order of magnitude for littoral drift through the beach system, of about 10,000 to 80,000 m^3 in comparison to the known net drift and corresponding envelopes of change at other beach localities within the Bay of Plenty coast.

- Calculation of the net change in sediment volume for the entire beach system within the Pukehina-Matata coastal sector between March 1989 and April 1993, results in a deficit of sediment within the beach system during this period of 90, 570 m^3.

- Superimposed on short-term changes to the beach system are the longer-term net volume changes. Between February 1978 and March 1993 the net change in sediment volume within the beach system from the foredune crest to the beachface (mean sea level) produced a sediment surplus of 218,560 m^3. Inclusion of the volumes of sand removed from the Otamarakau-Hauone area over this period, from sand extraction activities between the beachface and MHWS, showed overall accretion within the study area of 329,500 m^3. This small amount over 32.4 kilometres of coast indicates a beach system which is in a delicate state of equilibrium, with reasonably small volumes of sediment transfer between elements of the beach-dune-nearshore system.

The volumes presented here are analysed and discussed further as part of the littoral sediment budget in Chapter 8.

CHAPTER FIVE:

Sediment Texture

CHAPTER FIVE
SEDIMENT TEXTURE

5.0 Introduction

As the littoral drift regime is a major component of this study, determination of the sediment textural trends both alongshore and offshore is of extreme importance, as well as the need to obtain general information on the sediments of the Pukehina-Matata coastal sector. Various ideas have been developed from the analysis of sediment textural parameters, relating to alongshore variations in sediment texture, and the means by which they can be used to discern littoral drift directions. These ideas are presented as models which may infer sediment transport pathways and can be applied later in developing the littoral sediment budget. The major aims of this chapter are therefore:

(i) Building on the initial work by Healy *et al.* (1977), assess the nature and distribution of the beach and nearshore sediments during an accretionary phase of the beach-dune-nearshore system, in terms of mean grain size, modal grain size, sorting, and skewness.

(ii) Investigate possible origins of the beach-nearshore sediments.

(iii) Elucidate any seasonal effects on the beach sediments in terms of textural alterations to the grain size distribution, by examining two sets of samples, representative of the 'summer' accreted equilibrium profile, and the 'winter' depleted beach profile.

(iv) Establish the fluvial effects on the beach-dune-nearshore system, from collected representative stream and river channel sediments.

(v) Sub-division of the beach and nearshore sediments into groups based on their textural parameters, utilising the *Entropy* computer program.

(vi) Determination of the alongshore sediment transport direction for the study area, from three sediment transport models, the Sunamura and Horikawa (1972) model, the McLaren (1981) model, and the Waihi model.

5.0.1 Previous Work and Interpretations

The characteristics of the beach and offshore sediments along the Pukehina-Matata coastal sector have been briefly described by Healy *et al.* (1977), from dune face, berm face, low tide swash platform, nearshore, and offshore samples collected at BOPCES sites. Concerning the shoreline trends of the area in comparison to the rest of the Bay of Plenty they noted that *"There was a general decrease in grain size in the vicinity of Town Point, however, the grain size increases again towards Otamarakau, especially in the low tide and nearshore zones"*. They found that overall the beach sands are generally coarser in the central Bay of Plenty area from Otamarakau to Whakatane. Which was assessed as relating to the volcanic hinterland as a major sand contributor to the Bay of Plenty littoral system, with possible sand input from the Waitahanui Stream and Tarawera River. Sediments were noticeably more poorly sorted from the Pukehina Redoubt to

Pikowai, with skewness most variable between Pukehina and Whakatane which was suggested as perhaps illustrating the complexity of sediment movement along this stretch of coastline. Selected offshore samples showed areas of very coarse sand at Otamarakau and Pukehina.

Smith *et al.* (1992) described a two kilometre section of the littoral zone between Otamarakau and Hauone based on five sampling sites. Samples in this study were taken from the trough, bar and nearshore seafloor just beyond the bar. Samples may have been taken during an accretionary phase as gravel was only found at one site in small amounts, with a small proportion of silt at all sites. The sediments were described as coarse to medium sands, moderately to moderately well sorted, which are predominantly coarse skewed, with the poorest sorting occurring in the trough. They also mention that the beach sands vary from medium coarse sand to pea gravel depending on the state of the beach, with the sand appearing to overlie the gravel which is exposed during periods of erosion. They suggest that the beach basement material is the stable core of pea gravel inferred as most likely derived from erosion of the Kaharoa Plateau.

5.0.2 Textural Parameter Definitions

In addition to Figure 5.1, below, a brief description of the three main sediment textural parameters; mean grain size, sorting, and skewness, is included here in terms of their usefulness in depicting sediment transport trends.

Mean grain size is perhaps the most important textural parameter to measure, as it is a simple comparative indicator of the weight force that must be balanced by an applied stress before transport by water or wind is possible (Leeder, 1982). Mean grain size will also reflect the availability of different pre-existing sediments and the resistance of particles to weathering and physical abrasion (Friedman and Sanders, 1978). Komar (1976) stated that longshore variations in grain size can be produced in at least three ways: (1) by longshore changes in the wave energy level; (2) by selective rates of transport, the finer grains out-distancing the coarser (dependant on the composition of the sediments); and (3) by selective removal of the finer grains from the beach (carried onshore by winds or offshore by waves), leaving the remaining beach sediment coarser-grained.

Sorting is a measure of the uniformity of the sediment grain size distribution, and represents the standard deviation or range of grain sizes occurring within a sample. 'Poorly sorted' samples represent a wide range of sediment sizes, possibly indicating weaker sediment transport processes leaving a range of sediments in place, and/or sediment input in which the normal sorting process has not had sufficient time to occur. In contrast 'well sorted' samples represent a narrow range of sediment sizes possibly indicating more active sediment transport processes selectively removing some sediment sizes. A range of other degrees of sorting exists between these two extremes. The spatial sorting of beach sediments may be an indicator of longshore sediment transport, with the degree of sorting tending to increase in the direction of net littoral drift (Healy *et al.*, 1977; Healy, 1978).

(a) Grain Size Classes

Millimetres	Phi Units	Udden-Wentworth grain size classes
4		
	-2.0	
2		granule
	-1.0	
1		very coarse sand
	0.0	
0.5		coarse sand
	1.0	
0.25		medium sand
	2.0	
0.125		fine sand
	3.0	
0.0625		very fine sand
	4.0	
0.0310		very coarse silt
	5.0	
0.0156		coarse silt
	6.0	
0.0078		medium silt
	7.0	
0.0039		fine silt
	8.0	
		clay

(b) Sorting Classes

ø Value	Description
< 0.35	very well sorted
0.35 to 0.50	well sorted
0.50 to 0.71	moderately well sorted
0.71 to 1.00	moderately sorted
1.00 to 2.00	poorly sorted
2.00 to 4.00	very poorly sorted
> 4.00	extremely poorly sorted

(c) Skewness

+1.0 to +0.3	very fine skewed
+0.3 to +0.1	fine skewed
+0.1 to -0.1	near symmetrical
-0.1 to -0.3	coarse skewed
-0.3 to -1.0	very coarse skewed

Figure 5.1 Definition diagram of sediment parameters: (a) Grain size, (b) sorting, and (c) skewness. *(source: Folk and Ward, 1957). (where: $2^{-(\phi)}$= mm)*

Skewness provides a measure of the symmetry of sediment size distribution curves (Friedman and Sanders, 1978). Negative (or coarse) skewed samples have a dominance of coarse sediments with a tail towards finer sediment sizes, while fine or positively skewed sediments show the opposite trend. This implies that coarse skewed samples have had the finer sediments winnowed out of them, while the fine skewed samples retain finer sediments possibly indicating that these materials are those that are being more actively transported.

5.1 Textural Parameter Models Implying Littoral Drift

5.1.1 Sunamura and Horikawa Model

Sunamura and Horikawa (1973) proposed that the direction of littoral sediment transport may be determined from longshore variation of both grain size and sorting, each of which should be sensitive to particular beach processes. The use of sediment textural trends in predicting littoral drift directions has been used by a number of coastal sedimentologists (e.g. Sunamura and Horikawa, 1973; Harray and Healy, 1978; Healy, 1978; McLaren, 1981; Bridgwater, 1986; McLaren and Bowles, 1987), and when combined with other data, such as mineralogical trends and geomorphic evidence, may permit a reasonable inference for sediment transport (Figure 5.2).

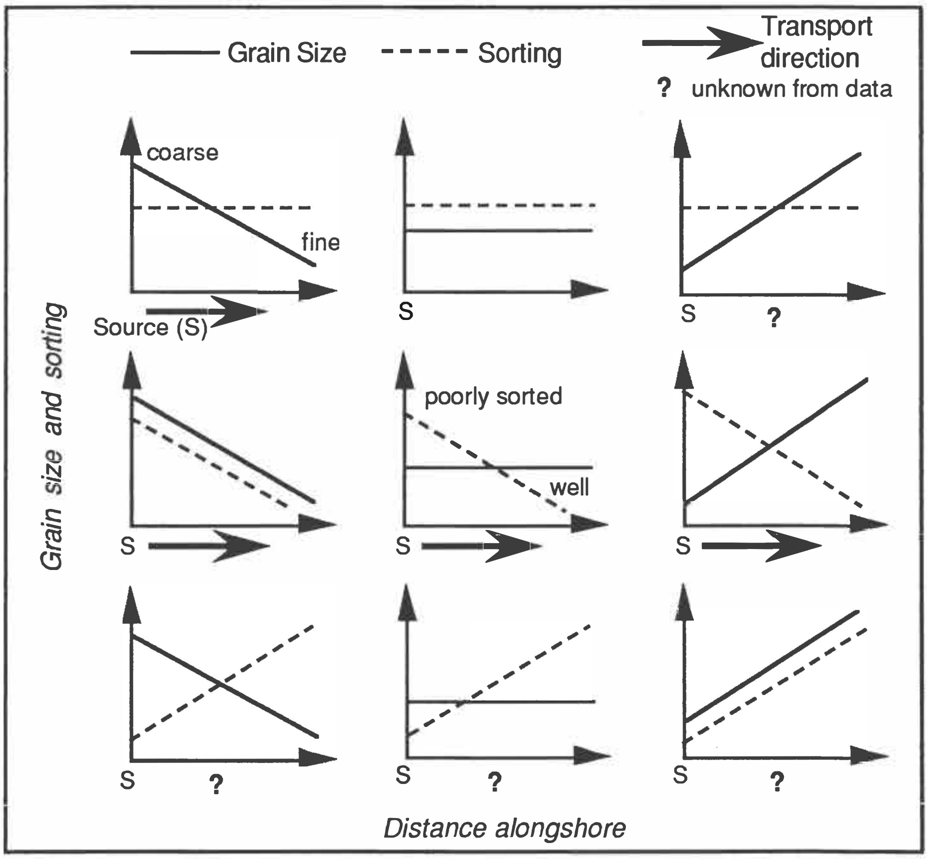


Figure 5.2 Criteria for the inference of sediment transport direction. Shown are the nine different combinations of trends in mean grain size and sorting that may occur from sediment textural data, and the inferred alongshore sediment transport directions for each. Hence certain combinations of M_Z and sorting may indicate littoral drift direction. *(source: Sunamura and Horikawa, 1972)*

5.1.2 McLaren Model

A second model pertaining to the prediction of sediment transport from textural parameters is the 'McLaren model' (McLaren, 1981; McLaren and Bowles, 1985). This model, in a manner similar to Sunamura and Horikawa (1972), uses spatial trends in sediment texture to determine the sediment transport direction. The distributions of sediment in transport are related to their source by a sediment transfer function, which defines the relative probability that a grain within each particular class interval will be eroded and transported. From this model three sediment transport options may exist:

> Case I: If a source sediment undergoes erosion, and the resultant sediment in transport is deposited completely, the deposited sediment becomes *finer, better sorted, and more negatively skewed* than the source (F,B,-).
>
> Case II: The lag remaining after erosion should be *coarser, better sorted, and more positively skewed* (C,B,+).
>
> Case III: If sediment in transport undergoes selective deposition, the resultant deposit can be either finer (Case IIIA) or coarser (Case IIIB) than the source, with better sorting and a more positive skewness (F,B,+ or C,B,+).

These options therefore enable enabling the inference of sediment transport directions from textural parameters. However, a recent paper by Masselink (1992), on longshore sediment textural variation along the Rhone Delta coast, found that in contrast to the known situation the opposite net longshore sediment transport direction was inferred from the McLaren model, and that the model itself is of limited value in determining sediment transport in the nearshore zone. He suggests that the disagreement between the actual and the predicted sediment transport direction is due to three major assumptions of the McLaren model being violated:

- the model assumes uni-directional flow, whereas the longshore transport is often bi-directional;
- the sediment in transport is supposedly derived from a single source. On a beach, the sediment may be derived from several sources, including rivers, eroding beaches, cliffs, dunes, shoreface; and
- the model assumes that the net sediment transport is the primary factor in causing textural trends. However other factors such as wave energy level and cross-shore sediment transport resulting in beach erosion or accretion have an important effect on the sediment characteristics of beach sands (Masselink, 1992).

Nevertheless given these apparent conflictions in the model, an attempt has been made to determine sediment transport pathways for Pukehina-Matata sediments using the McLaren model since it may still prove a useful tool if consistent with other lines of evidence.

5.1.3 Waihi Model

A third model is proposed, based on findings by Harray (1977) and Harray and Healy (1978) for Waihi Beach, on the Bay of Plenty coast, north of Tauranga Harbour, which contains sediments very similar to those found in the Pukehina-Matata coastal sector. The previous two models assume that the sediments along a particular beach are composed of rounded quartz-predominant grains of equal density along the beach. However, for the Pukehina-Matata shoreline the sediments tend to be angular, predominantly composed of plagioclase feldspar (see Chapter 6), and with variable densities (Table 5.1) which depend largely on pumice and rock fragment abundances. Waihi Beach has been demonstrated as the north-western limit of the Bay of Plenty littoral drift system (Harray and Healy, 1978), with littoral sediment transport clearly in a south-easterly direction from Waihi Beach to Bowentown based on numerous lines of evidence. Hence, application of the McLaren and Sunamura & Horikawa models to Waihi Beach in which the littoral drift direction is known, should test both models' applicability to the Pukehina-Matata coastal sector (Figure 5.3) in which the littoral drift direction is not known.

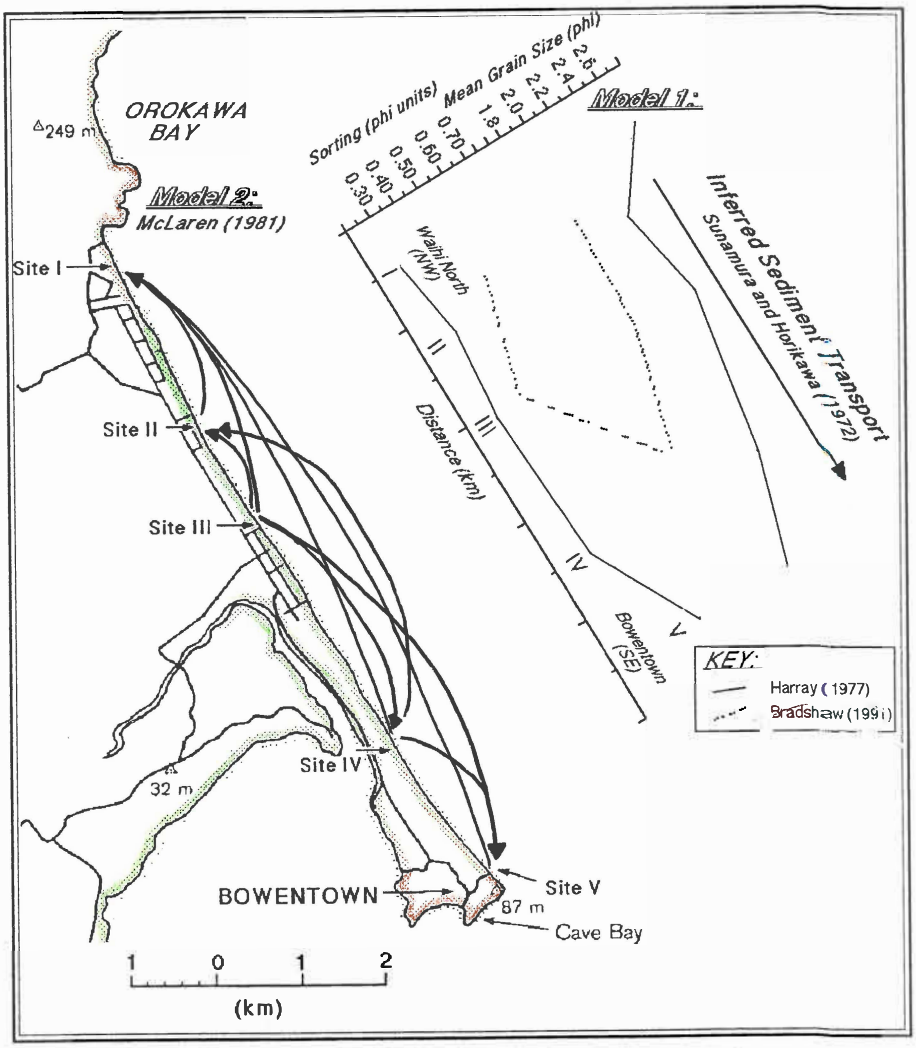


Figure 5.3 Application of the Sunamura and Horikawa (1972) and McLaren (1981) models to Waihi Beach, showing the resultant interpreted sediment transport directions. *Based on textural data from Harray (1977), and Bradshaw (1991).*

From Figure 5.3, there is a general trend of an increase in grain size towards the southern (Bowentown) end of the beach where higher energy conditions and a steeper beach slope prevail (Harray and Healy, 1978). Evidently there is preferential removal of coarse grains from the northern end of the beach and deposition towards the south whereby the angular and variable density of the larger grains are entrained by wave action at the laminar sub-layer between the water and sediment interface. From the McLaren model for Waihi Beach all possible modes of sediment transport are Case I, except from site 4 to 2 (Case IIIB) which is unusual since it implies that at this site sediment is transported and deposited entirely. The possible sediment pathways shown from the McLaren model are inconclusive, although the overall dominance is to the north-west. From site III however the inferred sediment transport is both to the south-east and north-west.

Alteration of the McLaren model to incorporate the nature in which Bay of Plenty sediments are transported in the littoral zone (*viz.* Waihi situation), may therefore give a more accurate means of determining the littoral drift direction along the Pukehina-Matata coast. Thus for the Waihi Beach model, based on information from Harray and Healy (1978), sediment transported from an updrift source should produce a deposit which is *coarser, more poorly or better sorted, and more coarsely (negative) skewed* (C,P,- or C,B,-) than its updrift source which would be *finer, better or poorly sorted, and fine (positive) skewed* (F,B,+ or F,P,+) due to the removal from source of the coarser part of the grain size distribution.

Of the three models proposed the Sunamura and Horikawa (1972) model for inferring sediment transport appears the least complex in approach and has been applied by Bridgwater (1986) on the Mangatawhiri Spit at Omaha, which evidently conforms with data from previous studies (e.g. Schofield, 1975). The McLaren model, while theoretically sound, has practical limitations when applied to the coastal sediments within the Pukehina-Matata study area. The Waihi model may therefore prove to be the most useful model as it has been interpreted for Bay of Plenty beaches which have a peculiar mixture of acid volcanic derived sediments, comprising feldspar, quartz, heavy minerals, shell material, and pumice, which behave differently when in transport compared with sediments composed of entirely rounded quartz grains whose sediment transport nature form the basis of the McLaren model. Inferred net longshore sediment transport directions from the textural data obtained in this chapter are trialled with all three models, with the littoral drift inferences and limitations from each model discussed.

5.2 Sample Collection

A total of 181 samples were collected from the back berm, beach face, and low tide swash zones along the beach; and 74 sporadically from the nearshore and offshore zones at BOPCES sites 19 to 30. The exact locations are given in Healy (1978d), with samples nearshore samples collected in May during the 1992 Bay of Plenty Regional Council Beach Profiling surveys (Dommerholt, in prep., 1993). The beach samples were collected on three separate occasions, in December 1991 (post-erosive, minor accretionary beach conditions, south-westerly winds), April 1992 (prolonged accretionary conditions, calm), and November 1992 (immediately post-erosive conditions, easterly winds). Additionally 17 river samples were collected from the Tarawera River, Kaituna River, Waitahanui, Herepuru, Mimihia, Awakaponga, Hauone, Pikowai, Ohinekoao, Pongakawa, and Kaikokopu streams, taken upstream from any possible tidal and marine influence. Sample collection was by hand for the beach samples and pipe dredge for the nearshore and offshore samples. The offshore samples were collected to a depth of up to 20m. Although this depth is relatively shallow, being some 1.6 to 2.3 km offshore, the closure depth of no significant onshore-offshore movement for the Bay of Plenty is between 6 to 14m water depth depending on wave conditions (Hay, 1991), and thus beyond 15m water depth the sediments are expected to have little interaction with the beach-nearshore system. Locations of the collected samples are given in Figure 5.4.

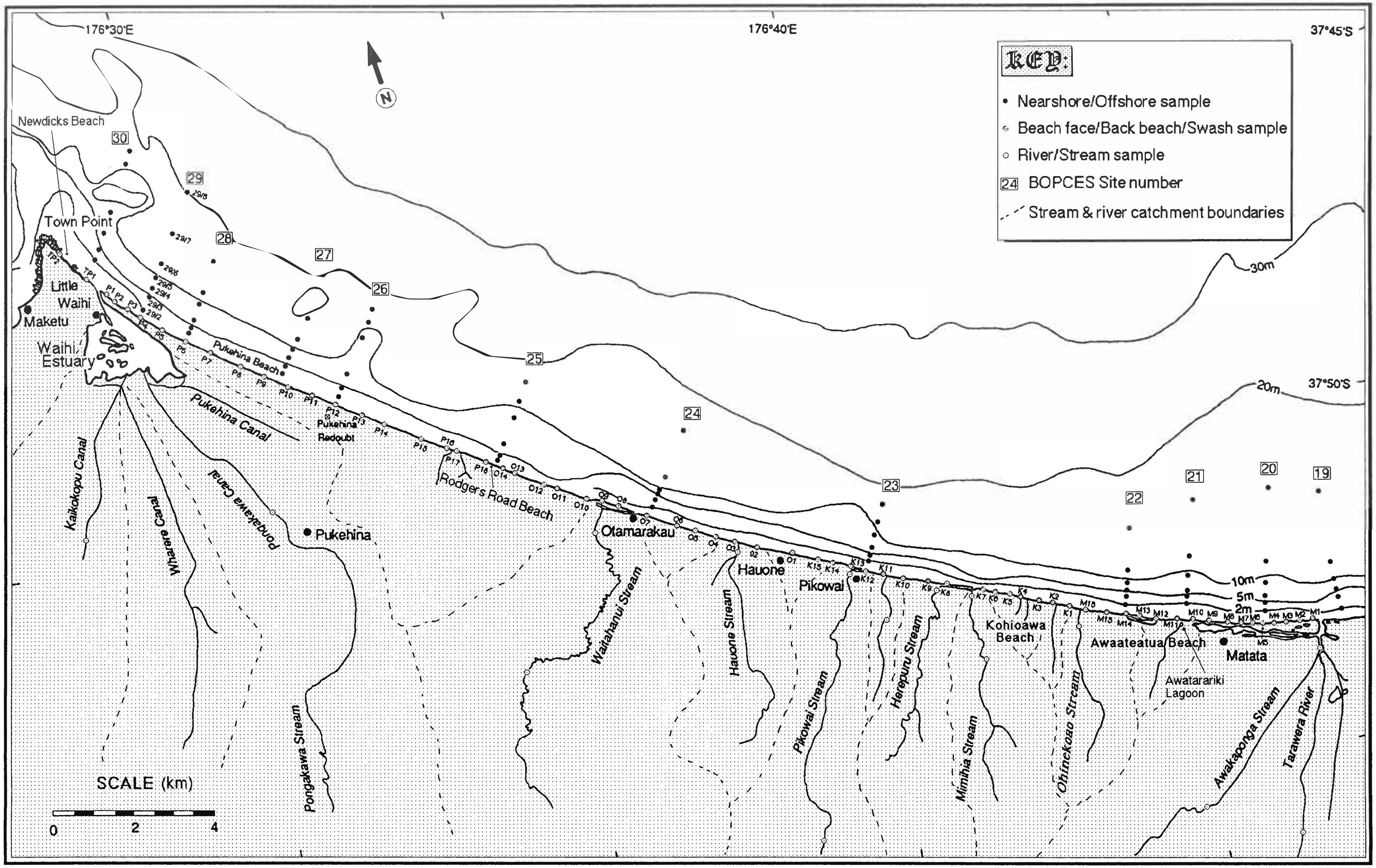


Figure 5.3 Location map of surficial sediment samples collected for sediment textural determination in the Pukehina-Matata coastal sector. Also shown are the stream and river catchment boundaries.

5.3 Sediment Textural Analysis

Samples were analysed using the University of Waikato's Rapid Sediment Analyser (RSA), after first washing samples through -1.5 ϕ and 4 ϕ sieves to remove any salts, muds (finer than 4 ϕ) and coarse material (coarser than 1.5 ϕ). The coarse material was negligible in all but the swash and river samples and some offshore samples, where the coarse fraction was analysed using standard dry sieve techniques and combining the two data sets. Approximately 30-50g of sediment was used in the analysis, since this is shown to induce the least amount of repetition error and is most comparable with the same-sized sample analysed using standard dry sieving techniques (Darlan, 1991).

The main advantage of using the R.S.A over standard mechanical sieves for measuring textural properties is that it provides data based on the hydraulic equivalent behaviour of sediments, particularly useful in determining littoral drift. In this analysis, the generally applied density of 2650 kg.m^{-3} for quartz was used. While this is considered to be approximately representative of Bay of Plenty beach sediments, the presence of rock and shell fragments (e.g. sample 29/7), titanomagnetite, pumice, and volcanic glass shards in large quantities for some samples may be a potential source of experimental error, with sediment density being lesser or greater along the coastline depending on the source of the beach sediments. Studies which calculated the sediment densities for various sediments in the Bay of Plenty-Coromandel region, are shown below in Table 5.1, illustrating the variability in sediment densities. Sediment densities appear highest at the frontal dune and decrease towards the nearshore zone.

Table 5.1 Density variations for some Bay of Plenty sediments. *(source: Darlan, 1991; Dommerholt, in prep.*)*

Sample Locality	*Mean sediment density (kg/m^3)*	*Density relative to quartz (kg/m3) ∞*
Maketu berm face	2689 ± 10	+ 39
*Rodgers Road nearshore (4m water depth)**	2497 ± 10	- 153
Otamarakau dune crest	2747 ± 10	+ 97
Pikowai berm face	2572 ± 10	- 78
Matata beach face	2649 ± 10	- 1
*East Tarawera River (2m water depth)**	2550 ± 10	- 100

∞ density for quartz = 2650 kg/m^3.

Results from the R.S.A are output as normal frequency and cumulative frequency curves, with particle size results given for both graphical and moment method parameters. The moment method parameters were used in this study as they are considered more sensitive to environmental processes than the graphical method (Friedman and Sanders, 1978).

The data obtained from the sediment textural analyses are given in Appendix III.

5.4 Beach-Fluvial-Nearshore Interaction

Overlapping sediment distribution histograms of the beach, stream and nearshore environment can provide valuable information as to the degree of interaction between differing environments. Bradshaw (1991) found that for most barrier spit embayments on the east Coromandel there is a strong overlap of grain size distribution between beach and river sands, supporting the hypothesis that modern barrier spit beach sands are derived from their local catchments.

5.4.1 Fluvial Sediment Texture

The sediment texture of the streams and rivers in the study area (Table 5.2) may therefore give an indication of sediment input to the beach and nearshore region.

Table 5.2 Summary of textural properties for river bed samples associated with the Pukehina-Matata coastal sector.

Sample	Mean Grain Size (φ)	Modal Grain Size (φ)	Sorting	Gravel (%)	Angularity
Tarawera (mid)	-0.37 (vcs2)	1.25	1.83	44	A-SR
Tarawera (estuary)	-0.68 (vcs1)	0.75	1.64	48	A-SR
Awakaponga	-0.30 (vcs2)	0.75	1.68	38	VA-R
Ohinekoao	0.80 (cs2)	1.0	0.98	8	VA-SR
Mimihia (upper)	0.52 (cs2)	1.0	1.08	13	A-SR
Mimihia (lower)	0.81 (cs2)	1.25	0.90	9	A-SR
Herepuru	0.92 (cs2)	1.25	1.28	15	A-SR
Hauone	0.17 (cs1)	1.25	1.72	26	A-SR
Pikowai (upper)	-2.54 (gr)	-4.0	2.13	81	VA-A
Pikowai (lower)	-1.91 (gr)	-4.25	2.39	63	VA-SR
Waitahanui (mid)	-0.49 (vcs2)	0.5	1.67	29	VA-SA
Waitahanui (lower)	1.09 (ms1)	1.5	0.87	7	A-SR
Pongakawa	0.67 (cs2)	0.75	0.66	4	A-SR
Kaikokopu	0.30 (cs1)	1.0	1.85	27	VA-SA

VA = Very angular; A = angular; SA = sub-angular; SR = sub-rounded; R = rounded; VR = very rounded.
gr= gravel; vcs= very coarse sand; cs= coarse sand; ms= medium sand; 1= upper , 2= lower grain size division.

Due to the young age of the catchment material the bedload sediments are predominantly angular, except for those streams where the material is mainly pumiceous, such as the Waitahanui, Mimihia, and Herepuru streams which all flow through the Rotoiti Breccia formation. Sorting tends to be poor, ranging from extremely poor for the Pikowai stream to moderately sorted for the Pongakawa stream. The sediments are predominantly coarse-skewed due to the gravel contents, except for the Pikowai stream which exhibits a high gravel content and upper pebble to upper granule bedload.

The stream and river samples show a natural progression of being coarsest in their upper reaches and finer nearer to the beach.

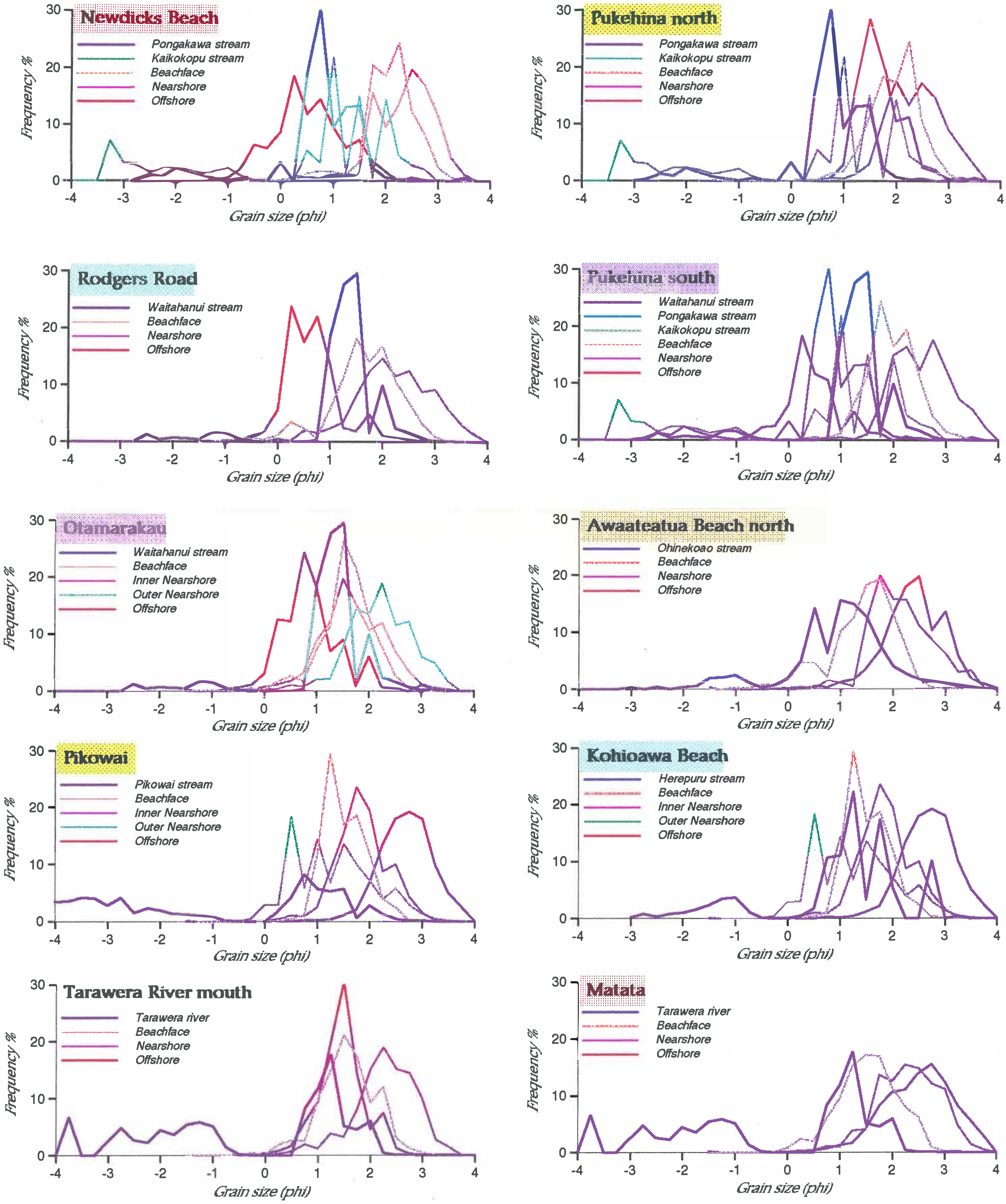


Figure 5.5 Grain size distribution histograms for beach, fluvial and nearshore sediments at various localities, illustrating the degree of interaction between environments.

5.4.2 Distribution Curves

Figure 5.5 illustrates the beach-fluvial nearshore interaction at various localities by using river bed samples of the closest or most representative stream or river, and beachface, nearshore (4 m water depth), and offshore (15 m) samples. All localities except for Rodgers Road, Pukehina Spit north, Pukehina Spit south and Newdicks Beach show a strong overlap of beach and river sediments. The coarse gravel fraction present in the river samples in most cases does not appear in the beach or nearshore zones, and it is assumed from field observations and sediment texture of the swash zone, that this fraction ends up in the low tide swash platform and step regions of the beach. At Pikowai and Kohioawa Beach there is a good overlap between the sediment of the Pikowai and Herepuru streams respectively, and the nearshore. The nearshore sediments at all other localities show only a small overlap with the finer end of the river sample grain size distributions. This may be due to either nearshore sands being derived from sources outside of the local catchments, such as the larger rivers of the Kaituna, Rangitaiki and Whakatane and local cliff erosion, or because they are derived from lower energy fluvial environments within the local catchments, specifically from flood plains or fluvial deltas in estuaries (Bradshaw, 1991).

From Figure 5.5 the Kaikokopu and Pongakawa streams flowing into the Waihi estuary appear to contribute sediment to the region offshore from Pukehina Spit and Newdicks Beach, with some sediment addition to the beach. However the pumiceous nature of the river bed sediments indicates that they may degrade into finer particles before being deposited along Pukehina Spit, and hence alter the grain size distribution curve.

The contributing catchments to the Waihi Estuary are suggested as a sand source by Murray (1978) who cites the following evidence:

(a) the rivers entering the estuary have a high sediment load as shown by the need to regularly dragline the Kaikokopu and Pongakawa River channels, which at the time of this study is still being undertaken at regular intervals of 18 months to 2 years. This sediment is being partially deposited in the estuary, but because of the high river inflows (average flows for the Pongakawa River is given as about 5,100 l/s, and for the Kaikokopu River about 2,800 l/s, with a total discharge into the estuary of about 9,500 l/s) some sediment is transported through the estuary to the littoral system.

(b) the examination of shells on the flood tide delta in the Waihi estuary shows an absence of marine species. This suggests there is little inflow of marine sands into the estuary and therefore the sands present have been derived from sources within the estuary and from rivers.

At Rodgers Road there is some suggestion that the beachface and nearshore sediments are derived from the Waitahanui Stream, although comparison of the fluvial and offshore curves implies very little of the offshore sediments are derived from this stream.

Offshore comparisons of grain size distributions with the river sediments suggests little sediment interaction, except at the Tarawera River mouth, Pukehina Spit and Newdicks Beach localities. The Tarawera River mouth overlap is expected based on the nearshore and offshore grain size patterns. At Newdicks beach and Pukehina Spit two options are apparent. Firstly, as with the Tarawera River it could be an effect of the ebb-tidal delta carrying coarser material out to beyond 12m water depth, although the overlap with the nearshore and beach sands was very minimal. Secondly, and more likely, it could be due to erosion of the Town Point cliff and rock strewn nearshore zone, which is composed of material similar to that found in the streams to the south.

In terms of the interaction between the beach, nearshore and offshore, all localities exhibit reasonable to very strong overlaps between the beach and nearshore sediments. The interaction between the nearshore and offshore is more varied, with only Awaateatua, Pukehina North and Matata showing good overlaps, Pikowai and Tarawera some, and the rest show very little possible sediment exchange. Comparisons of beach and offshore sediment curves, show a similar pattern, with no significant overlap at Newdicks Beach, Rodgers Road, Pikowai and Kohioawa Beach.

For the Tarawera River mouth site it is evident that the beachface curve is a slight translocation of the sand segment of the river curve. The offshore curve shows an extremely good fit with the beachface curve, suggesting interaction. The offshore curve has an increase in the coarser 1.5f mode with a decrease in the finer 2.25 phi mode, while the nearshore only shows an increase in the 2.25 phi mode, which may suggest that from source the majority of the finer material is deposited in the nearshore zone, rather than offshore or at the beachface.

It can be concluded that the source of the beach sands along the Pukehina-Matata coastline is at least partially derived from erosion of local catchment material, which may be supplemented by littoral drift, erosion of submarine reefs in the Town Point-Otamarakau region, Town Point erosion, and possible onshore reworking of pre-Holocene sediments.

5.5 Alongshore Variations in Sediment Texture

5.5.1 Mean Grain Size (M_Z)

The mean grain size trends along the Pukehina-Matata section (Figure 5.6), are similar to those noted by Healy *et al.* (1977), in which the beach sands overall are generally coarser in the central Bay of Plenty area from Otamarakau to Whakatane. This feature may have a number of possible explanations:

(i) The coarseness of the sands may indicate a general source region of input into the beach system from the catchments draining the hinterland;

(ii) The area may be a zone of wave energy focussing with winnowing of finer sediments away from the sector; and

(iii) The beach sands may be nourished from coarser offshore sediments by diabathic exchange.

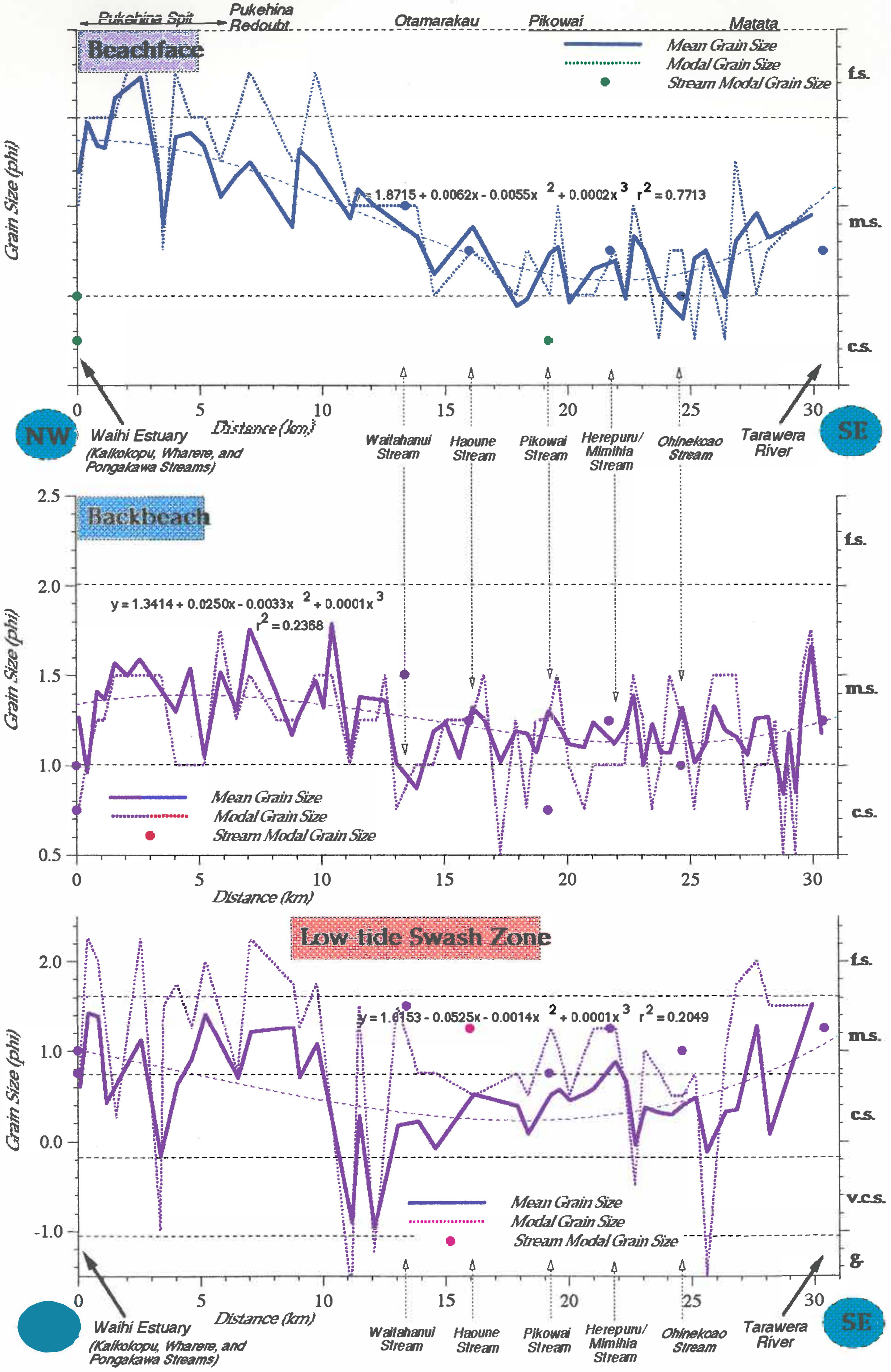


Figure 5.6 Mean and modal grain size variations in the beach sediments along the Pukehina-Matata coast, from the Waihi estuary inlet in the north-west to the Tarawera River mouth in the south-east. The light blue curved dashed line represents a cubic line of best fit through the mean grain size data points, and is indicative of the general trends. The coloured dots are the stream modal grain sizes for the sand mode, given at their corresponding alongshore position. Alongshore distances in all cases are measured from the Waihi estuary.

While the curve of best fit for the textural variables in each plot is statistically inaccurate it does however indicate that there is a strong relationship of longshore variation in mean grain size for the beachface data. By contrast there are only weak correlations in the backbeach and low-tide swash zone plots, hence any trends in the latter two beach environments are only suggestive.

The somewhat chaotic nature of all the grain size plots, which fail to demonstrate a smooth trend, may reflect small variations in sediment input to the littoral zone, and/or variations in the mineral quantities in the surficial sediments effecting the hydraulic behaviour of sediments analysed by the RSA, and/or localised variations in sediment texture caused by the formation of beach cusps present at the time of sampling.

(a) Beachface

Beachface plots tend to be most indicative of alongshore trends (Davis, 1985). Overall, there are finer sediments along Pukehina Spit (medium sand upper) and coarser sediments from Otamarakau to Matata (medium sand lower to coarse sand upper). The trend of finer grain sizes on the Pukehina Spit is common with other barrier spits such as Ohope, Ohiwa (Healy, 1978), and Pauanui (Abrahamson, 1983). The finer grain size for Pukehina Spit is due to a combination of factors. Firstly there is a lack of direct fluvial input along the Pukehina to Rodgers Road sector, indicated from the stream grain sizes (section 5.4) which are dissimilar to those of the beachface in the Pukehina area. No significant stream input occurs until the Waitahanui Stream at Otamarakau, a distinctly coarser sector of beach in which the stream grain sizes on the whole agree within one standard deviation to those of the beachface. Indirectly sediment may come from the Waihi estuary, however, although there is fluvial input into the Waihi estuary from the Kaikokopu and Pongakawa streams, these stream sediments may take some time to work through the estuary before being available to the beach system. Secondly, Pukehina Spit, when subjected to swell and sea waves from the west to north, may be an area of lower wave energy due to sheltering in the lee of Town Point and associated shoals, and wave refraction effects from Motunau and Motiti Islands. Lastly, there are large amounts of pumice and volcanic glass on the beach in this area (see section 6.3) which are rapidly degraded in the littoral zone producing finer grains along Pukehina Spit than for the rest of the study area where the sediments have higher amounts of plagioclase and quartz which are much less easily weathered into smaller particles.

All alongshore surficial sediment plots indicate a decrease in grain size to the east of Otamarakau, and an increase between the Waihi Estuary and Otamarakau. At the point of the Waitahanui stream the sediments are coarsest, suggesting the Waitahanui Stream is a significant contributor to beach sediments within the study area. Healy *et al.* (1977), similarly noted that the M_Z trends indicated a possible sand input from the Waitahanui Stream. The Tarawera River, and Pikowai, Waitahanui, Herepuru, Mimihia, Hauone, and Ohinekoao streams (section 5.4) provide some coarse material to the dune-beach-nearshore system in the Otamarakau to Matata area, which could account for the coarser beachface sediments. The slight inferred fining in grain size that occurs from Matata to the Tarawera River mouth is possibly due to wave refraction from Rurima Island and surrounding reefs during north to easterly wave events creating zones of wave divergence as well as zones of wave focussing along the beach, which has been shown to occur by Healy (1989) and Dunbar (1989).

A coarsening in grain size is noticeable immediately to the east of the Waihi Estuary, along the distal end of Pukehina Spit, possibly illustrating sediment output from the estuary, which has predominantly sand-sized sediments; cliff erosion of the volcanic derived sediment at Town Point, with finer material by-passing the estuary; and differences in wave energy and winnowing of finer material.

(b) Backbeach

The backbeach plot shows similar but less pronounced trends to that of the beachface, since the backbeach is affected by more occasional processes such as storm surge, high tides and wave washover effects, with constant winnowing and sorting by wind.

(c) Low Tide Swash Zone

The low tide swash zone plot exhibits some interesting localised patterns, although the general trend is only suggestive since the standard deviation of error involved (given by the sorting values) is high. At Otamarakau the grain size is considerably coarser (very coarse sand lower class), which may perhaps be related to fluvial input from the Waitahanui stream, and/or sand mining effects which cause a coarsening of the sediment as the better sorted and finer grains on the beach are removed. It is also possible that this locality is the null point or centre for a bi-directional littoral drift system which removes material, particularly finer sediment to the north and south. The decrease in grain size at Otamarakau and central Pukehina Spit may also be the artefact of offshore erosion of reefs and rock outcrops (Chapter 8) bringing gravel material onshore to the swash zone.

5.5.2 Mode (M_d)

The modal grain size is the predominant grain size within a sediment population, and can be indicative of source if the grain size distribution of the source sediments is known. The beachface and backbeach samples tend to be uni-modal, with the majority of the swash sediments bi-modal. The trends in modal grain size approximate those for the mean (Figure 5.6), with finer modes in the Pukehina-Otamarakau sector which for the beachface plot are inconsistent with the stream grain size modes of the Pongakawa and Kaikokopu streams. Conversely coarser modes in the Otamarakau-Matata sector correspond closely to the stream sediment modes of this area. Again this suggests some lack of direct fluvial interaction with parts of the beach system along Pukehina Spit, consistent with the conclusions reached in section 5.4.

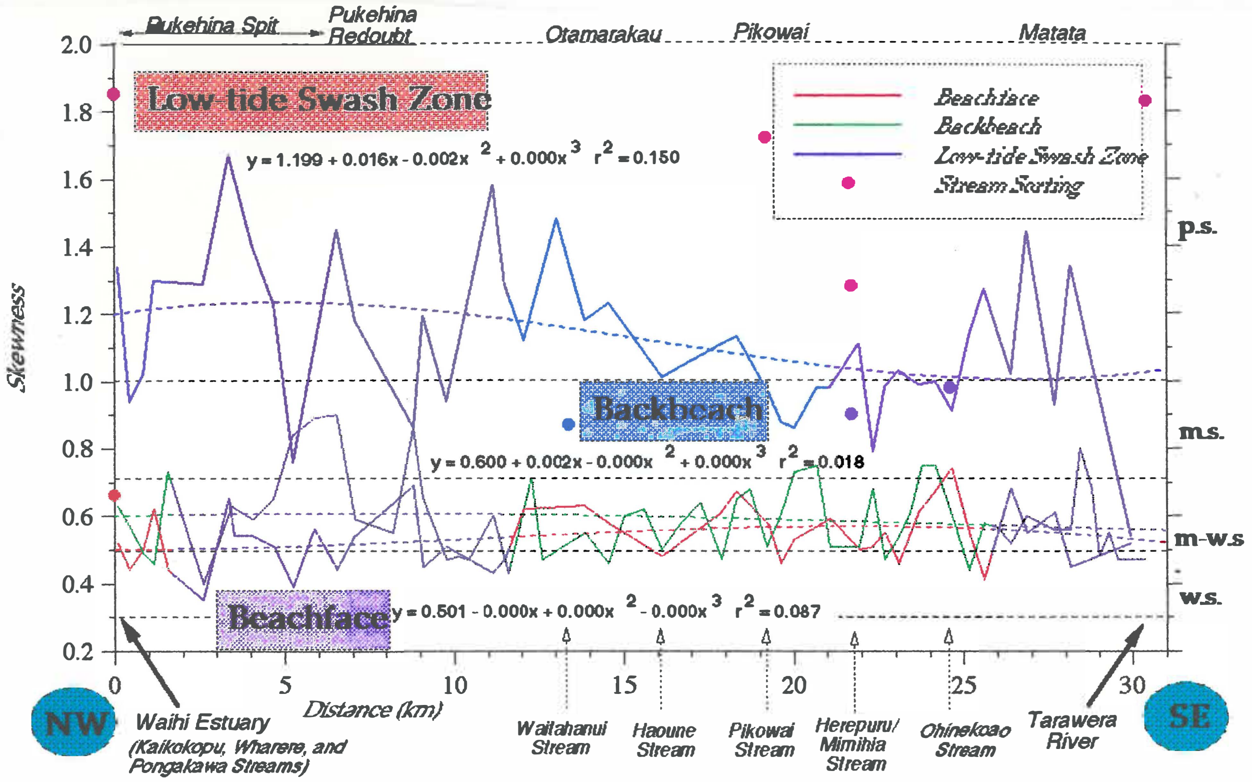


Figure 5.7 Sorting variations in the beach sediments along the Pukehina-Matata shoreline, from the Waihi estuary inlet in the north-west to the Tarawera River mouth in the south-east. The line of best fit is a cubic polynomial curve through the data points. Stream values are denoted by a magenta coloured circle.

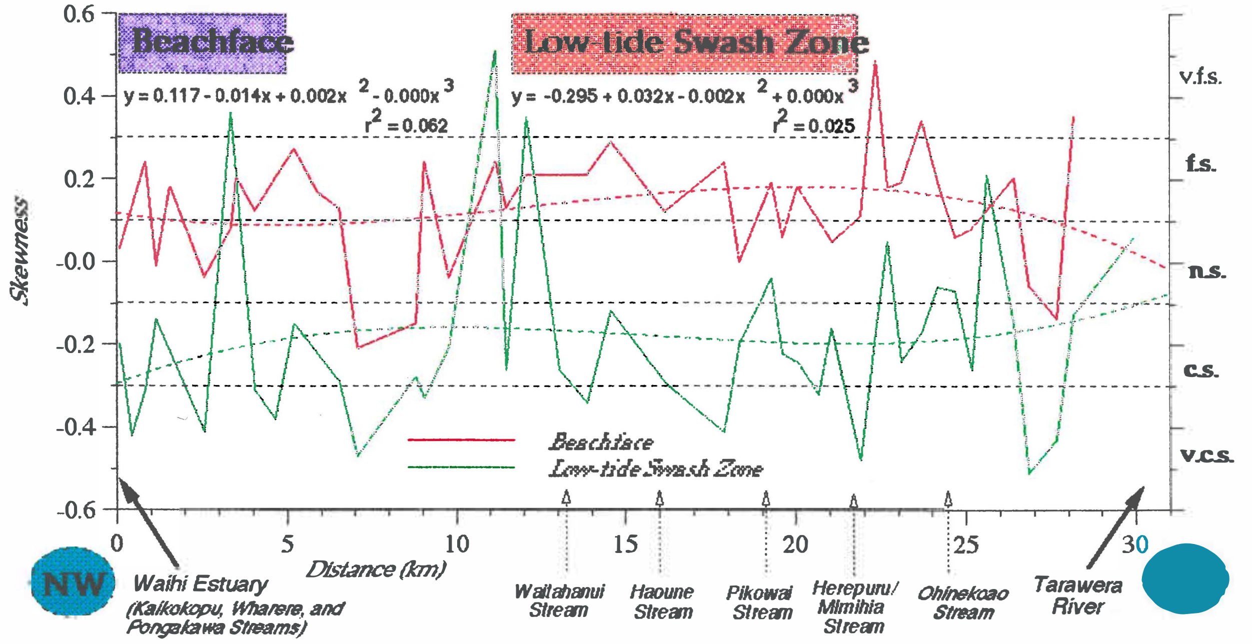


Figure 5.8 Alongshore variations in skewness from the Waihi estuary to the Tarawera River mouth, for beachface and low-tide swash zone surficial sediments.

5.5.3 Sorting (σ)

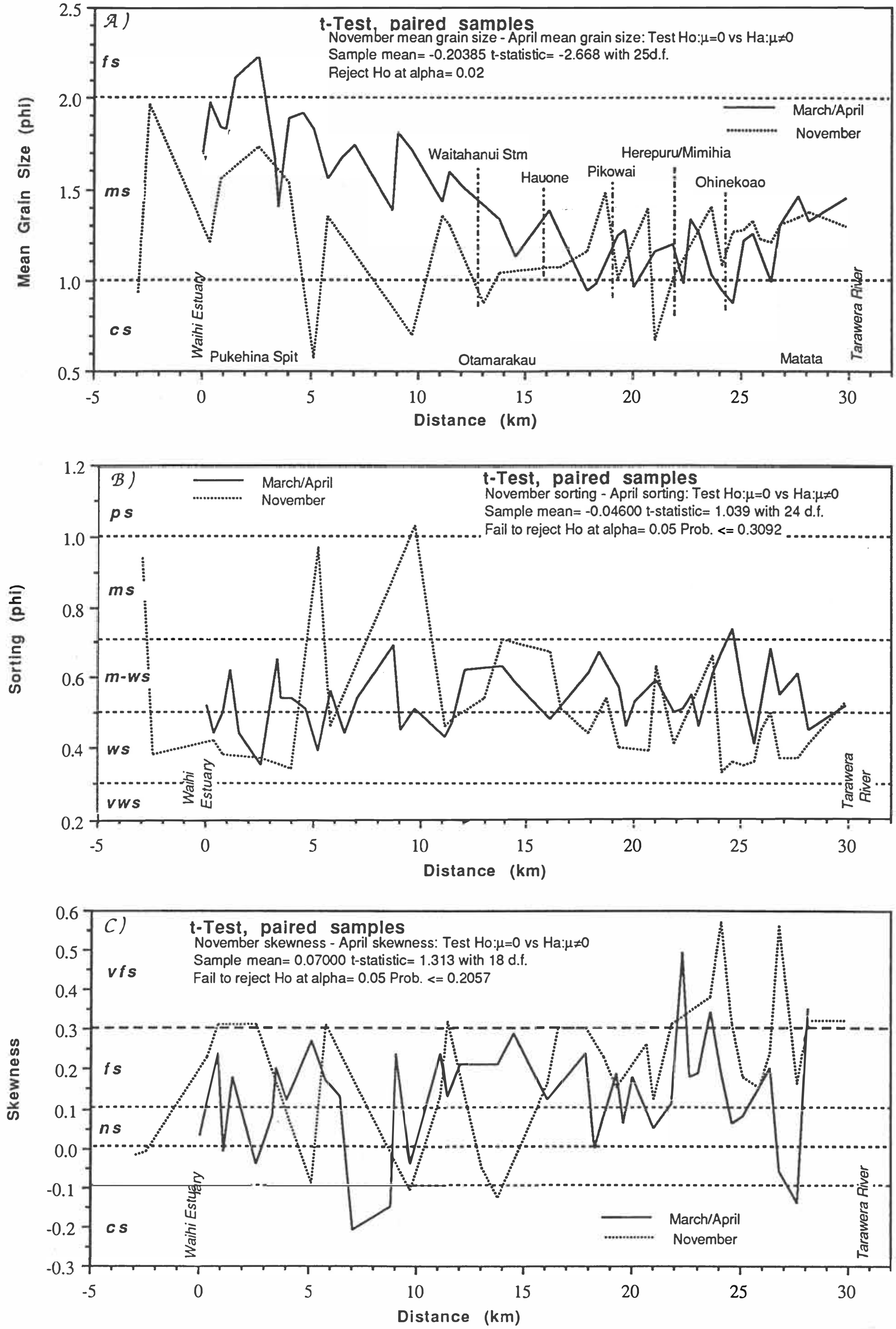
The sorting for all surficial sediments shows a good relationship with mean grain size, and in general the coarser sediments tend to be more poorly sorted than the finer sediments. Figure 5.7 shows that the beach face sands are predominantly well to moderately well sorted, while the backbeach sands are less well sorted by approximately 0.10 phi units. The best fit curves for all three beach environments show a slight but insignificant correlation in the alongshore distribution of sorting values. The low tide swash sediments exhibit a range of sorting values and at best are only moderately sorted, reflecting that this part of the beach system is the coarsest and least sorted under the prevailing reflective beach state at the time. The beach face samples show an inferred trend of increased sorting between Otamarakau and the Tarawera River, with a similar increase in sorting to the west of Otamarakau along the Pukehina Spit. The relatively poorer sorted sediment in the vicinity of the Waitahanui Stream again suggests this to be a local source of the beach sediments.

The other major streams along the coast, in terms of discharge volumes and catchment areas (refer Chapter 9) are in decreasing order the Pongakawa, Kaikokopu, Herepuru, and Pikowai streams, and to a lesser extent Mimihia, Ohinekoao and Hauone streams, each reflecting fluctuations and peaks in the general sorting trends as they add more poorly sorted material to the beach system. The spatial separation of such similar sized streams means that interpreting the offset of peaks of poorer sorting is more difficult, since a peak near or between streams may reflect sediment transport towards the north-west or south-east, and may be influenced by more than one source.

The low tide swash sediments are the most poorly sorted, due to the higher energy experienced in this part of the beach system compared with the beachface and backbeach (Komar, 1976). The large fluctuations from Pukehina to Otamarakau may be due to beach-innershelf diabathic interaction with gravel beds and the erosion of small reefs that occur in the nearshore zone (Chapter 8), with sediments brought onshore by storm waves and long period swell waves.

5.5.4 Skewness

Most of the beachface sands sampled are fine skewed to near symmetrical (Figure 5.8) as is typical of beach environments (Davis, 1985), with the Pukehina Redoubt area showing the only coarse skewed sediments, although the Tarawera River may have some influence on the beachface sediments to the north of the river mouth in the Matata region. The low tide swash sediments are more coarsely skewed overall than the beach sediments, but have similar trends; both are most coarsely skewed at Matata and north of the Pukehina Redoubt where the sediments then become fine skewed in the direction of Otamarakau. At Pukehina Redoubt the excess of coarse grains is possibly due primarily to the onshore movement of coarser material from offshore reefs and relic wave-cut platforms. At Matata this may be due to the effects of the old sand mining operation, focussing at this site (Healy, 1989) (Chapter 7.3).



A) t-Test, paired samples

November mean grain size - April mean grain size: Test Ho:$\mu=0$ vs Ha:$\mu\neq0$
Sample mean= -0.20385 t-statistic= -2.668 with 25d.f.
Reject Ho at alpha= 0.02

B) t-Test, paired samples

November sorting - April sorting: Test Ho:$\mu=0$ vs Ha:$\mu\neq0$
Sample mean= -0.04600 t-statistic= 1.039 with 24 d.f.
Fail to reject Ho at alpha= 0.05 Prob. <= 0.3092

C) t-Test, paired samples

November skewness - April skewness: Test Ho:$\mu=0$ vs Ha:$\mu\neq0$
Sample mean= 0.07000 t-statistic= 1.313 with 18 d.f.
Fail to reject Ho at alpha= 0.05 Prob. <= 0.2057

Figure 5.9 Seasonal alongshore variation in beachface sediments for *a)* mean grain size, *b)* modal grain size, *c)* sorting, and *d)* skewness. Showing that the area north of Otamarakau experiences the greatest seasonal fluctuations in sediment texture. Also given are the results of the paired t-tests for each parameter.

The Rodgers Road to Kohioawa Beach sector, which contains the majority of the streams in the study area, is finely skewed (positive), which may be the result of stream input which has a strong bearing on the beach sediments in this region. Since the streams are bimodal or polymodal (section 5.4), at least two peaks occur on the grain size distribution curve, with the second peak in general being smaller. Hence rather than an addition of fine material, the beach sands, due to the stream input, are interpreted as positively skewed. For the low tide swash sediments the large very finely skewed peaks at Otamarakau and central Pukehina Beach correspond to the coarsest sediments occurring at the same localities. Overall there is no statistically significant trend in sediment skewness for either environment.

5.6 Seasonal Variations

Since Bay of Plenty beaches undergo characteristic seasonal changes (Smith, 1989; Healy *et al.*, 1977), two sets of beachface samples were gathered, one in April and the second in November of 1992 in order to understand if inferred sediment transport directions change with the seasons and wave conditions. In April the beach appeared to be in an accretionary phase, with a well developed berm, steep beachface, and non-existent or variably developed offshore bars typical of the classic 'summer' equilibrium beach profile. By contrast in November the beach had just recently experienced an erosive phase, with a relatively low angled beachface, prominent offshore bar along the entire coast, and an increase in heavy mineral concentrations in the beach sediments, equivalent to the 'winter' profile. Given the differences between the prevailing beach conditions on the two sampling dates, it should be possible to determine seasonal effects on the sediment texture of the beach sediments.

The beach sands in November are coarser overall, better sorted, and more finely skewed than in April (Figure 5.9 and Table 5.3). The main seasonal difference appears to be north of Otamarakau where the beachface sediments in November were some 0.1 to 0.6 phi units coarser. The lower grain sizes and better sorting in this area are the result of the increased wave energy acting on the beachface sediments in November (Hb= 2.5 m; T= 6-8 s) compared to April (Hb= 0.3-0.5 m; T= 10-12 s), with erosive north-easterly generated waves (c.f. SW in April) operating immediately prior to sampling, preferentially removing more of the finer grains, thereby resulting in coarser, better sorted surficial sediments.

Table 5.3 Mean and standard deviations of sediment parameters for November and April beachface sediments, from Datadesk® analyses.

	NOVEMBER SEDIMENTS		APRIL SEDIMENTS	
	Mean Value	*Std. Dev.*	*Mean Value*	*Std. Dev.*
Mean Grain Size	1.23	0.31	1.43	0.37
Sorting	0.49	0.18	0.54	0.097
Skewness	0.21	0.16	0.14	0.14

To determine differences in seasonality of the beachface sediments a statistical test between sediment textural data for both sampling dates was undertaken using the statistical package Datadesk®. The two sampling dates were treated as paired data groups for each sediment parameter, using only those sediment samples taken from the exact same location at each date. A paired t-test was then carried out to find the pairwise differences, used to construct a t-statistic based upon these differences by treating them as if they were a univariate collection of data points.

From the paired t-test the M_Z data shows a strong statistically significant difference between the two sampling dates (p= 0.02, 98 % confidence interval), but for the sorting and skewness data there is no significant difference, i.e. the correlation between the two datasets was lower than the 0.1 probability level, with probability values of p=0.31 and p=0.21 respectively, indicating differences that are statistically non-significant.

From field observations Pukehina Spit experiences frequent morphological change, particularly at the south-eastern (basal) end. Not only does the beach state and profile alter regularly, but also the sediment texture. During periods of erosion and/or spring tides sediment is removed from the beach exposing large patches of gravel and boulder sized volcanogenic rocks up to 40cm in length. These rocks are identical to those found at Newdicks Beach on the southern side of Town Point, and are most prominent from site P9 to P13 covering a kilometre segment of the beach. The gravel patches consist of mainly granule sized greywacke, which are either exposed as the thin cover layer of sand is removed seaward by wave and swash action, or are brought onshore from the nearshore zone where they may exist as gravel beds. These gravel patches, also appear to relocate along the beach between these areas, illustrated in Figure 4.17 (Chapter 4), possibly due to varying angles of wave approach shifting and exposing the gravel either further up or further down the beach. The existence of these gravels may also indicate that the volumes of sand within the beach system are comparatively small in relation to other sectors of beach such as Matata. This is consistent with the attempts made to examine the depth of the sand sized sediments within the Pukehina-Otamarakau area, following an erosive phase (May, 1993). Within this entire area the maximum depth to the gravel layer underneath was only approximately 2 m, with as little as 0.6 m in the vicinity of the Pukehina Redoubt.

5.6 Spatial Distribution Patterns of Surficial Sediments

It was noticeable during field collection and from the mean grain sizes of other Bay of Plenty sediments collected between Waiotahi and Waihi Beach during the 1992 BOPRC Beach Profiling Survey (Dommerholt, in prep) that the beach and nearshore sediments along the Pukehina-Matata coastal sector are generally coarser than all other regions of the Bay of Plenty. This may suggest a higher energy wave environment, possible terrestrial sediment input of coarser material comparative to other parts of the Bay of Plenty, input from palimpest gravels, or input from recent winnowed lag sediments. The former is unlikely based on wave refraction plots of Hay (1991) for the Bay of Plenty, although Town Point and associated shoals do appear to shelter Pukehina Spit from

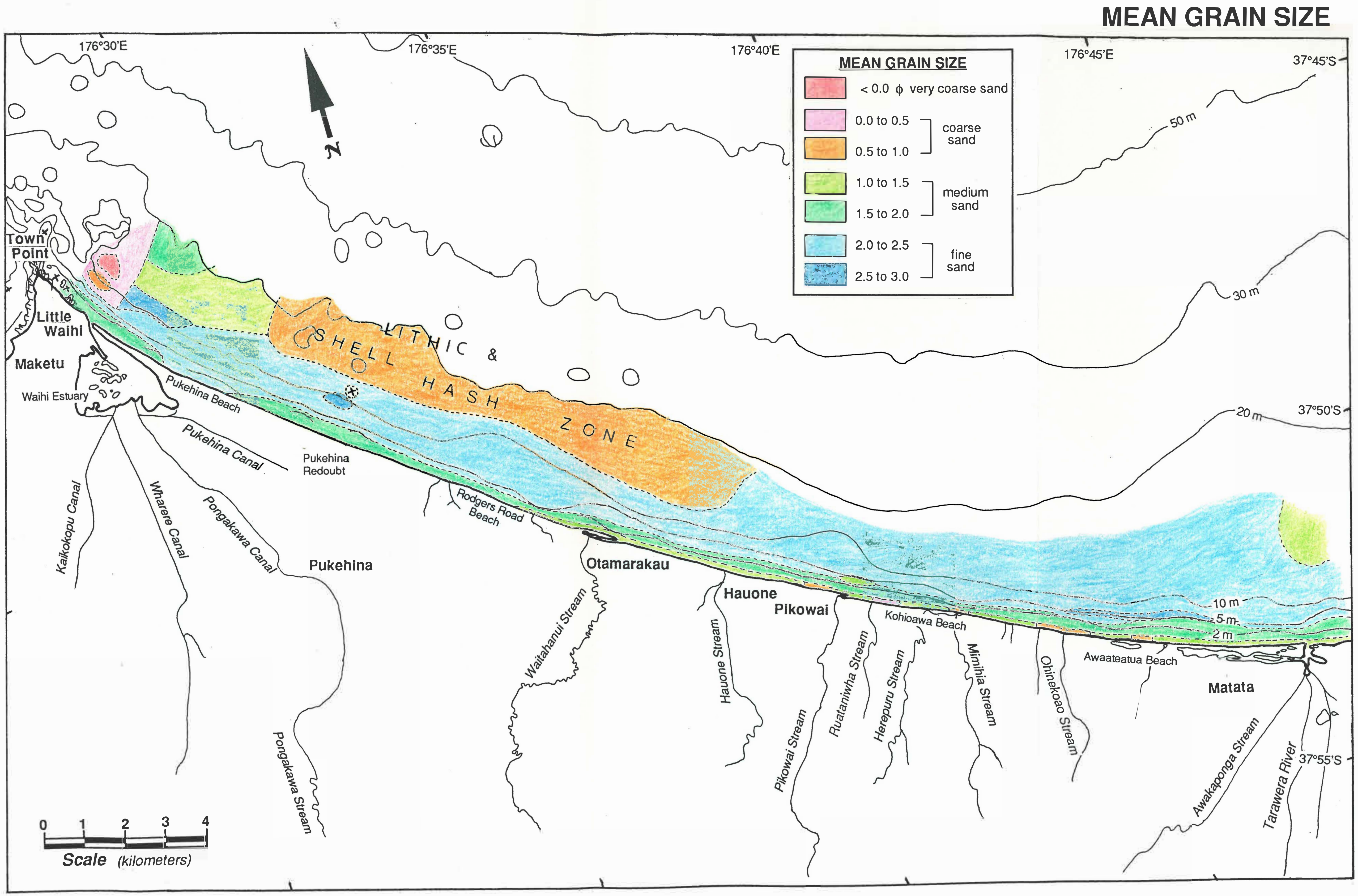


Figure 5.10 Distribution of mean grain size for nearshore surficial sediments along the Pukehina-Matata coastal sector.

north-westerly generated winds and swell.

5.6.1 Grain Size

Mean grain size trends, given in Figure 5.10, show a fairly typical seawards-fining progression, particularly in the south from Otamarakau to Matata, which is similar to that found by Bradshaw (1991) for barrier spit beaches such as Waihi. Beyond 3-4 m water depth, most of the nearshore surficial sediments are composed of fine sands. Three major exceptions to this are highlighted, which reflect an apparent coarsening of sediments offshore from major sediment sources, indicated as the Tarawera river, Waitahanui stream, Waihi Estuary, and possibly Town Point cliffs.

Offshore from the Tarawera River mouth in approximately 15 m water depth a patch of coarser medium sands exist, which is probably an influence of the river and its large sediment load. Similarly a band of coarse sand containing varying amounts of shell and lithic hash material, is present in 13 to 15 m water depth from southern Pukehina Beach to Otamarakau. As noted in the alongshore trends, this area has the coarsest beach sediments in the entire study area, and appears to coincide with irregular submarine outcrops and boulder reefs present on side-scan sonographs and found during diver observations of the seafloor (Chapter 8). An anomaly to this is a patch of fine sand that exists off the Pukehina Redoubt in 8 m water depth, which may surround a submerged rock or reef indicated on hydrographic chart NZ 541, and it may be that the surficial sediments are finer here due to constricted current flows, creating a flat seafloor and characteristic finer sediments. In the vicinity of the Waihi Estuary and Town Point the pattern is more confusing. The offshore region of medium sand sized sediments at northern and central Pukehina Beach, may be the result of the proximity of the Waihi Estuary, with possibly coarser sediments similar to those to the north and south existing further offshore. It is also possible that since there are no submarine rock outcrops in this sector the sediment is derived from areas to the north, south and offshore, and being further from the source is therefore naturally finer. This is further evidenced by the better sorting at this locality compared to adjacent areas. The shell and lithic hash containing sediments present predominantly off southern Pukehina Beach to Otamarakau in 13 to 20 m plus water depths, consist of a variety of volcanogenic rhyolite, greywacke, ignimbrite and conglomerate rock fragments, possibly originating from Town Point and/or submerged rock outcrops, and shell material which shows varying degrees of bioerosion, from non-existent to moderately bioeroded. This may therefore either be an area in which the sediments are fairly static lag deposits, or more likely are reworked continually by long period wave action and coastal currents, since although bioerosion is apparent, encrustation is not. The shell types within these coarse sand-gravel sediments are dominated by *Tawera spissa* (morning star), with immature pipis (*Paphies australis*) found in the Newdicks Beach nearshore region in increasing numbers at shallower depths (Figure 5.11).

In the surf and littoral zones the sediments appear to be coarsest in the vicinity of the streams, with the finest sediments occurring at central Pukehina Beach where the nearshore band of medium sands tapers out. The only noted example of suggested fluvial input to the nearshore system within the

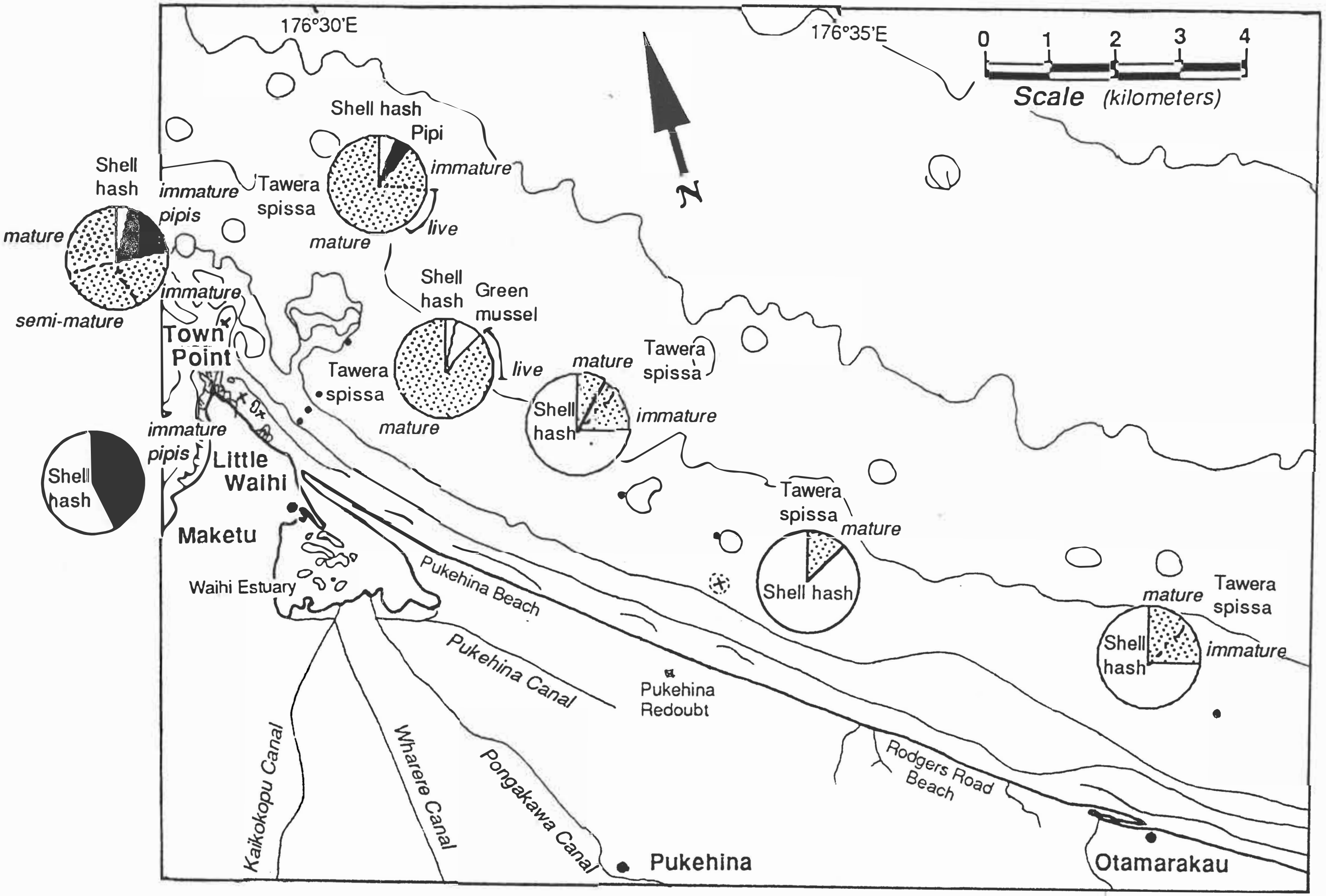


Figure 5.11 Relative compositions of shell material occurring in the coarser surficial sediments found in the Newdicks Beach-Otamarakau area, illustrating the dominance of Tawera spissa, with increased pipi populations close to the Waihi estuary inlet.

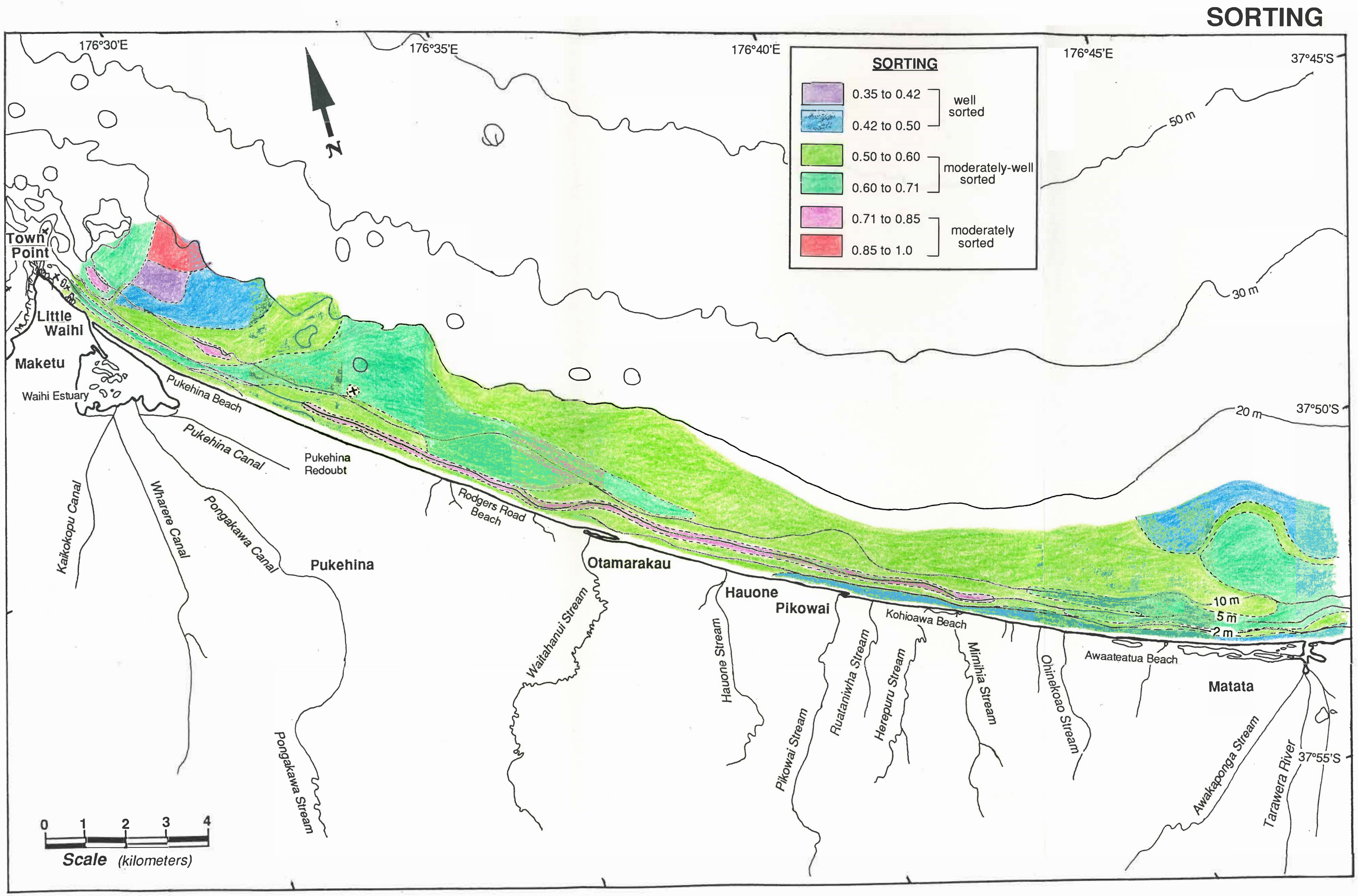


Figure 5.12 Distribution of sorting for nearshore surficial sediments along the Pukehina-Matata coastal sector.

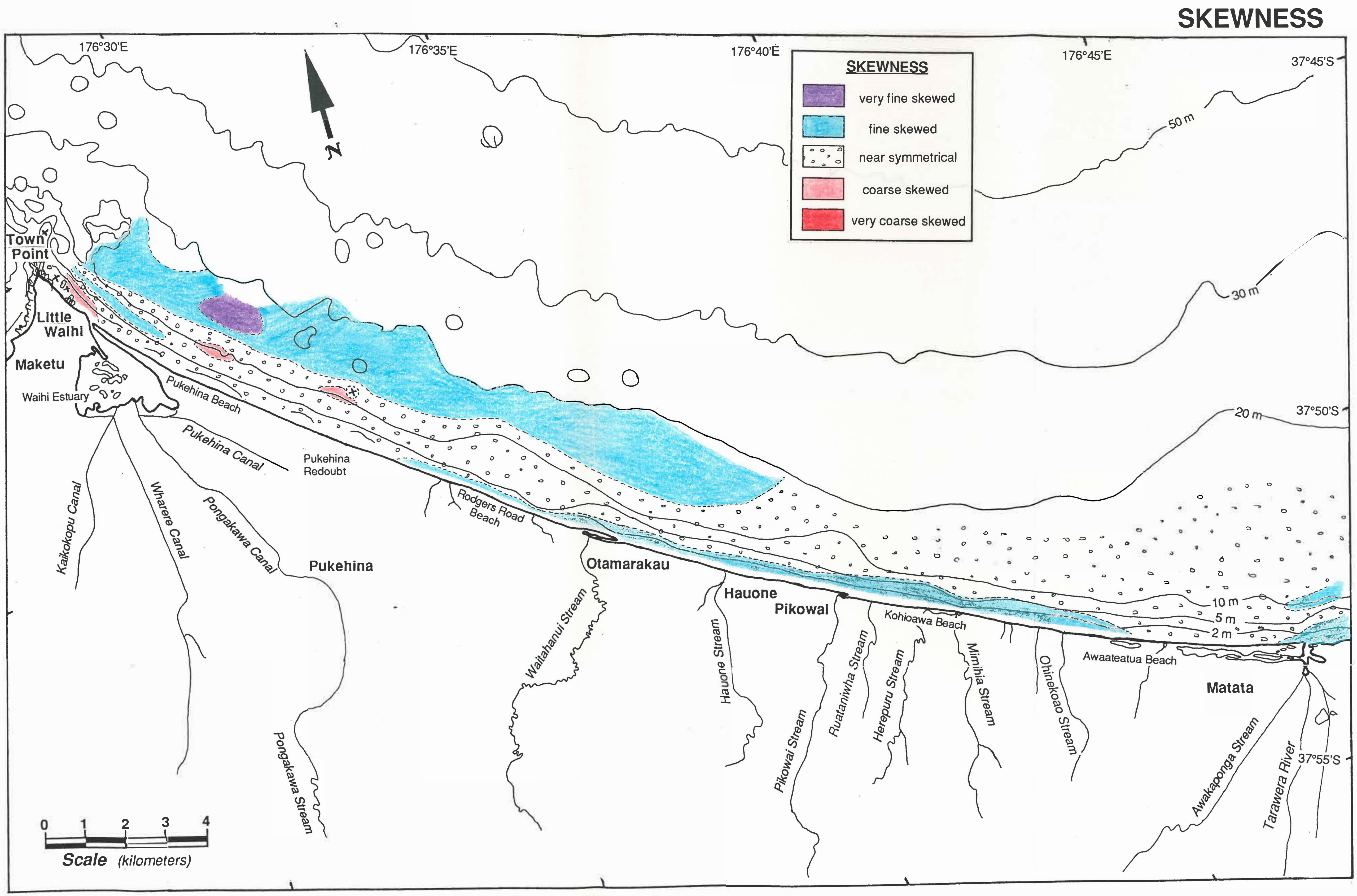


Figure 5.13 Distribution of skewness for nearshore surficial sediments along the Pukehina-Matata coastal sector.

Otamarakau-Matata stream dominated region is offshore from the Pikowai Stream where a patch of coarser medium sands exists in 4 m water depth. The extent of this patch and occurrence of any others is not known due to the relatively broad scale sampling detail, but it is likely that other small patches may be present along the coast corresponding with stream outflows, although the gravelly Pikowai Stream sediments have been shown to be coarser than all the other streams and hence the effect on the nearshore sediment texture is likely to be greater.

5.6.2 Sorting

The surficial sediments of the nearshore are generally moderately-well sorted (Figure 5.12). Since the differences in sorting of the surficial sediments is fairly subtle the number of sorting classes has been expanded to better illustrate trends. Again this region is not as well sorted as other parts of the Bay of Plenty coast, perhaps reflecting its more complicated morphodynamic nature and the factors contributing to the sediment budget in the beach-nearshore system. The sorting patterns correlate reasonably well with mean grain size, in that the distribution variations in grain sizes are illustrated further by variations in sediment sorting.

In the nearshore zone to a depth of 2 m, the sediments are in general moderately-well sorted lower sands, with a decrease in sorting near the Waihi estuary and contrasting well sorted upper sands from Hauone to east of the Tarawera River mouth. In 5 m water depth one of the more noticeable aspects is a narrow band of moderately sorted lower sands from the Pukehina Redoubt to south of Pikowai. This may represent the seaward flank of the offshore bar or platform, which is commonly more poorly sorted (Komar, 1976). Offshore from the Tarawera River mouth there is an area of well sorted upper sediments, with much poorer, moderately-well sorted upper sediments nearer to the river mouth, probably associated with the fluvial sediment load of the river. Around the vicinity of the Waihi estuary a complex and patchy sorting pattern exists which may reflect the influences of both the Waihi estuary and erosion of Town Point sediments, causing areas of better or poorer sorting.

5.6.3 Skewness

The skewness pattern (Figure 5.13) follows the trends established in the grain size and sorting diagrams. In general most of the nearshore and offshore sediments are near symmetrical, with a band of fine skewed sediments occurring in the surfzone region from Rodgers Road to northern Matata. This upper nearshore band, which is absent along Pukehina Spit, the Pukehina Redoubt area, and Awaateatua Beach at Matata, could possibly be due to the streams adding coarse material to the sediments in sufficient quantity that they dominate the grain size distribution, with a small finer tail of sediment. However it is more likely that a small amount of finer material is brought down from the streams in the area and hence gives the sediments a positive skewness, i.e. the presence of the coarser mode dominates over the finer sized mode, so that the addition of the secondary mode yields a positive skewness (Greenwood and Davidson-Arnott, 1972; Komar, 1976).

Two other small bands of fine-skewed sediment are present offshore from the Tarawera River mouth and the Waihi estuary. The lack of coarse (negative) skewed sediments in the Pukehina-Matata region is interesting given that the sediments in general are fairly coarse for the Bay of Plenty. The fine skewed sediments in the offshore region at 12-20m water depth, are coarse and poorly sorted, and presumably have originated from the same source and have been transported, eroded, or deposited under similar conditions. The very fine skewed patch of sediment offshore from the Pukehina Spit is finer than the surrounding sediments, and is a probable depositional area, contributed to from neighbouring material or from finer sediment transported out of the Waihi estuary.

5.6.4 Cross-shore Trends

To examine cross-shore variations, mean grain size was compared with profile morphology (selected profiles Figure 5.14 and all profiles Appendix IV). An immediate feature of the cross-shore profiles is that apart from sites 23, 29, and 30, they all exhibit a coarsening in grain size at their outermost points, with two zones apparent. To the 8-10 m water depth the sites show a fining trend, while beyond this the profiles become coarser. For BOPCES sites 24-28, there is a rapid coarsening of the surficial sediments, which corresponds directly with changes in the profile morphology at 12-15 m water depth. For example BOPCES site 24 has a 1 m drop-off over a very short distance at the 13 m water depth. From SCUBA observations and side-scan sonographs (Chapter 8) this area is a boulder reef of 1-1.5 m diameter boulders. Further north at Pukehina this morphological and textural change is associated with rock outcrops of late Pleistocene pumiceous sediments. From the Tarawera River to Pikowai such reefs and rock outcrops are not apparent, with profiles exhibiting only slight fining or coarsening at equivalent depths. This appears to be due to greater sediment deposition, with less onshore-offshore sediment transport and erosion required to maintain the sediment budget of the beach compared to the northern part of the study area. The coarser deposit present from Town Point (site 30) to Otamarakau (site 24) would also suggest that this area has a small sediment budget.

The Town Point site (30) exhibits rapid fluctuations in texture which again may relate to reefs and boulder outcrops which are common in the nearshore zone around Town Point.

5.7 Statistical Classification of Textural Data

With the number of samples analysed, the use of simple comparisons of grain size distribution histograms, to group and compare similar sediment populations and infer sources, was somewhat limited. The use of a multi-variate classification program (*Entropy*) was therefore employed in statistically analysing 160 selected samples from those collected, to group surficial sediments into classes based on grain size distributions. The program has an upper limit of 250 variables, and hence samples from some environments and those taken at dissimilar sampling dates were neglected in favour of a more comparable data set, thereby restricting the sample variables to 160. Such statistical classification analysis has been used successfully in studying Coromandel shelf sediments (Bradshaw, 1991) and Whangamata estuarine sediments (Sheffield, 1991).

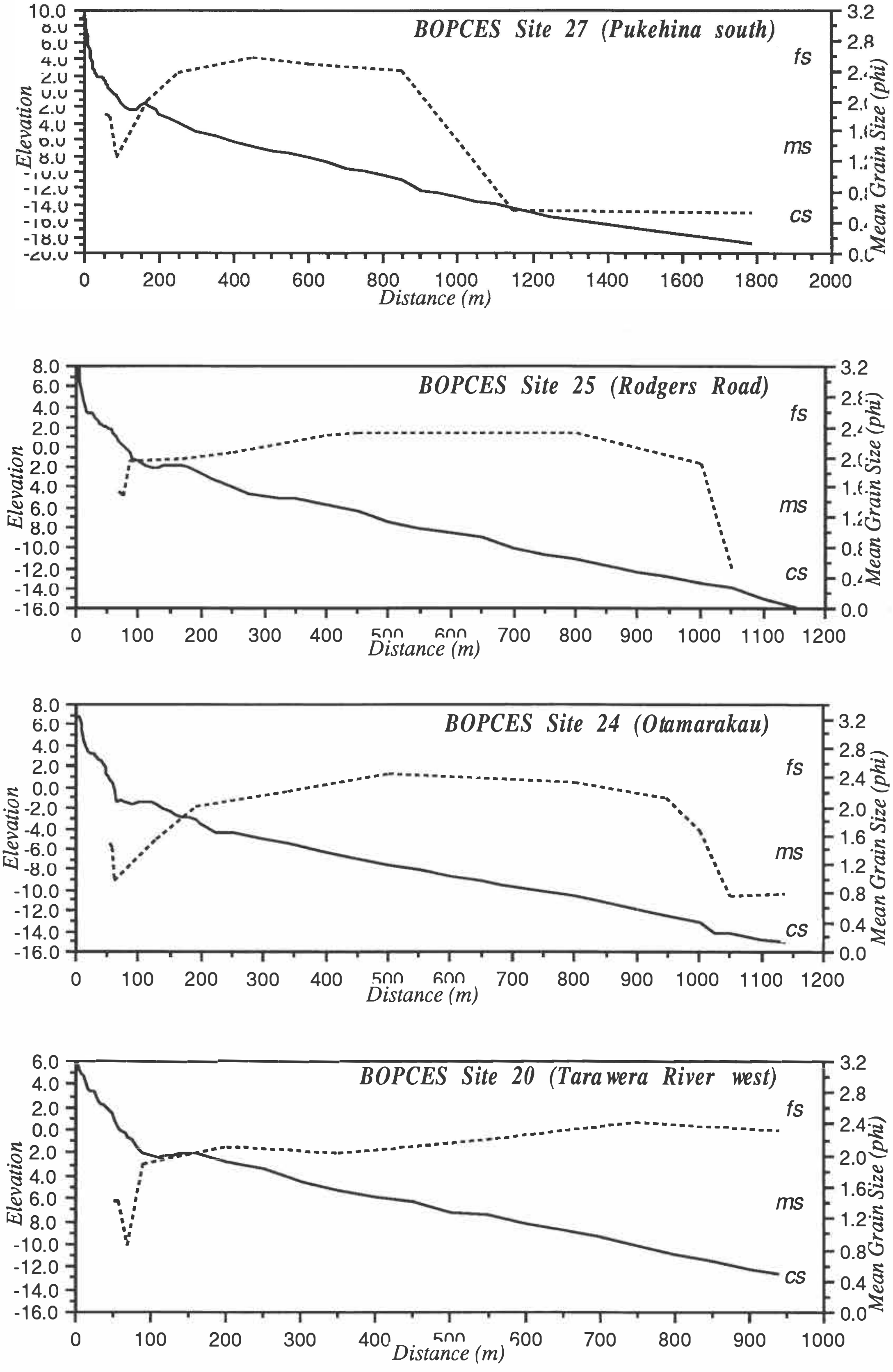


Figure 5.17 Cross-shore variation in mean grain size (dotted line) with distance offshore and corresponding beach-dune-nearshore profile morphology, for selected BOPCES sites. Distance measurements are relative to the profile benchmarks. Grain szie variation is plotted from the upper beachface (MHWM) to the lower nearshore-innershelf.

5.7.1 Entropy Program

Textural data were entered into the *Entropy* program on the University of Waikato's VAX computer system, by placing interval frequency values obtained from the RSA results at 1/4 phi intervals from -3.0 to 4.0 phi. The program then delegates data into groups based on their grain size distribution histograms, and similar grain size, skewness and sorting characteristics. The program calculates an entropy statistic (a measure of the disorder of a system, equivalent to variations in the textural data) for each sample through the formula:

$$H(Y)= \overset{M}{\underset{i=1}{S}} y_i \log_z(1/y_i)$$

<u>where</u>: y_i = the proportion of the ith component in the distribution
M = the number of variables into which the distribution is divided
H (Y)= entropy measure for sample Y.

The program then identifies the best classification of N samples into n classes by maximising the between class entropy across M variables. The optimum classification is recognised when the between class entropy (i.e. variation) begins to increase at a decreasing rate with the addition of each new class. Details of the original computer algorithm are given in Johnstone and Semple (1983), but no information is provided on using the actual program (a brief working example of the programme is given in Appendix V).

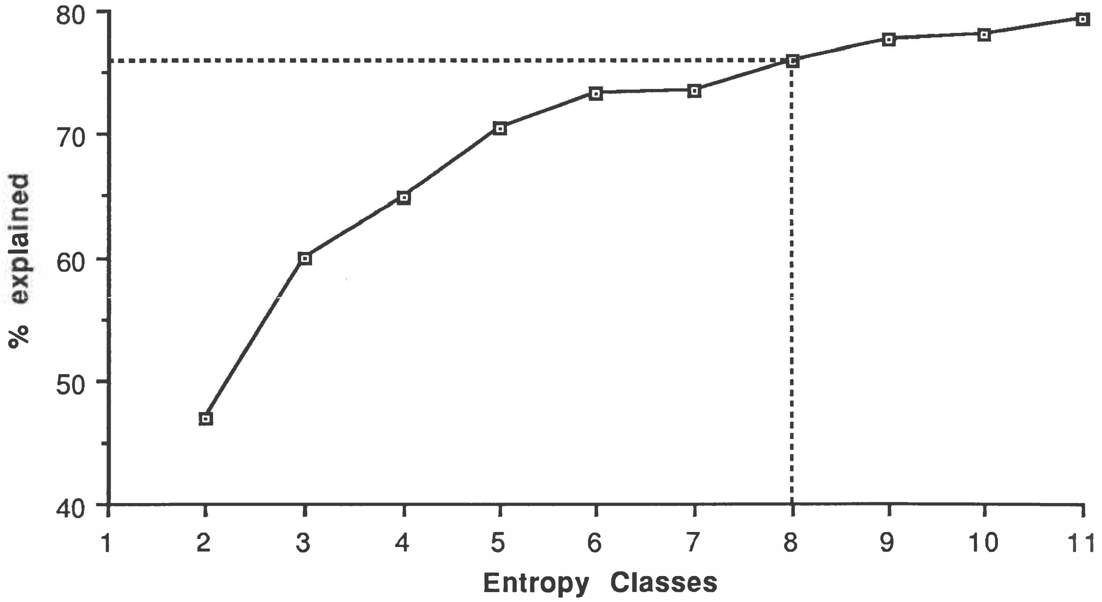


Figure 5.15 Depiction of the number of different entropy classes into which the textural data can be classified, and the amount of variation in the data matrix explained by each classification.

Results of the program are illustrated in Figure 5.15, from which a classification of 8 groups or entropy classes explaining 75.8 % of the matrix variability was obtained. At this point additional entropy classes do not result in a significant increase in the amount of data variation explained, with eight classes sufficient to provide patterns and trends in the textural data. Note that the data which is unexplained by the programme in one of the eight entropy classes (24.14%) is therefore placed into the closest representative class.

Plots of mean grain size against sorting (Figure 5.16) show that the different entropy classes are not clearly defined by their mean grain size as was found by Bradshaw (1991) for his east Coromandel shelf samples. Instead it appears to be a combination of mean grain size and sorting, shown by the overlapping nature of some of the entropy classes. Skewness (Figure 5.17) appears to have only a small effect on defining the entropy groupings, especially in classes 1, 2 and 4 which have a tightly defined mean grain size but a large skewness scatter. There is however a tendency for sediments to become more finely skewed in the coarser grained classes.

Table 5.4 summarises the textural characteristics of the eight classes. Classes 1 and 2 are medium sands, classes 3, 4, and 5 fine sands, and classes 6, 7, and 8 coarse sands. Correspondingly classes 2 and 4 tend to be well to moderately-well sorted sediments, 1 well to poorly sorted, 3 and 6 moderately-well sorted, 5 moderately-well to moderately sorted, 7 poorly sorted, and class 8 moderately to poorly sorted. The average grain size distributions of each of the eight entropy classes are illustrated in Figure 5.18.

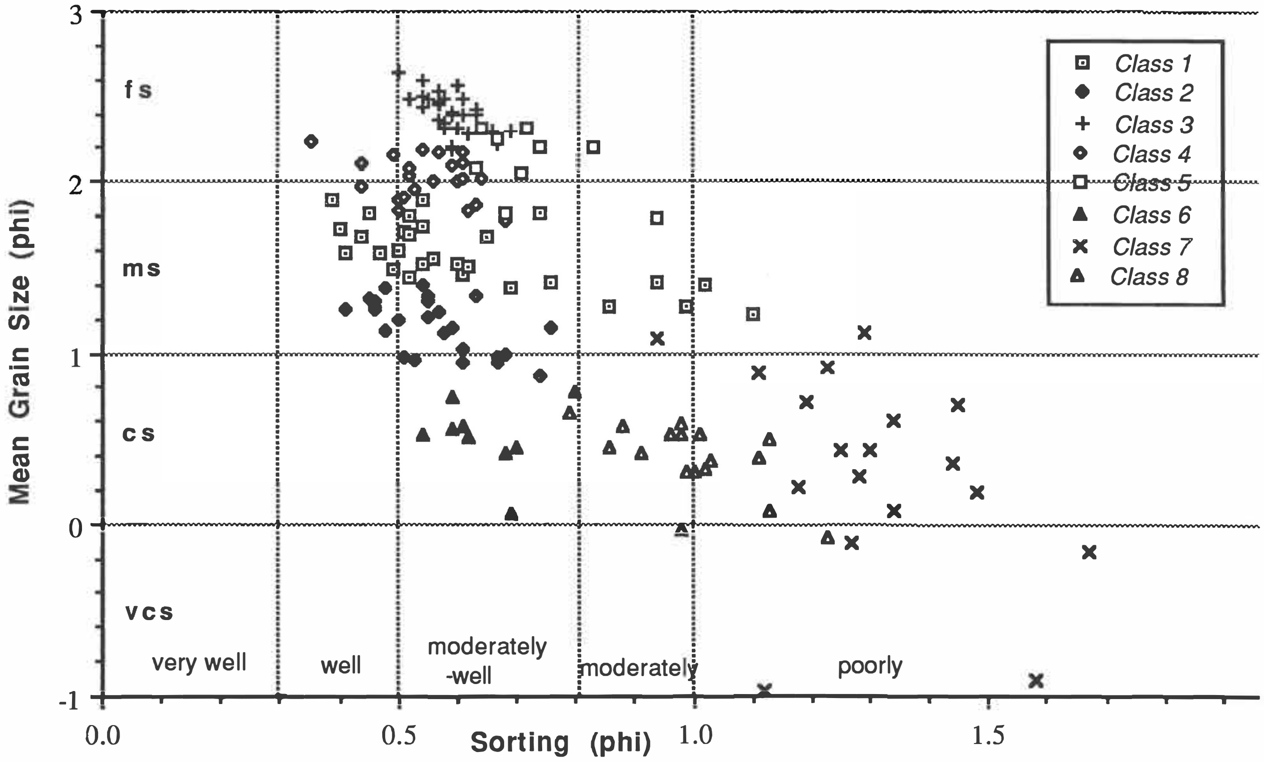


Figure 5.16 Mean grain size plotted against sorting for surficial sediments from the eight entropy classes. This shows that although the entropy classification is based on mean grain size, sediment sorting is an important secondary factor, since sorting for each class is over a greater or lesser defined range. Sediment sorting is best within the upper medium to lower fine sized sand range, with a tendency for sediments to become increasingly better sorted as grain size decreases.

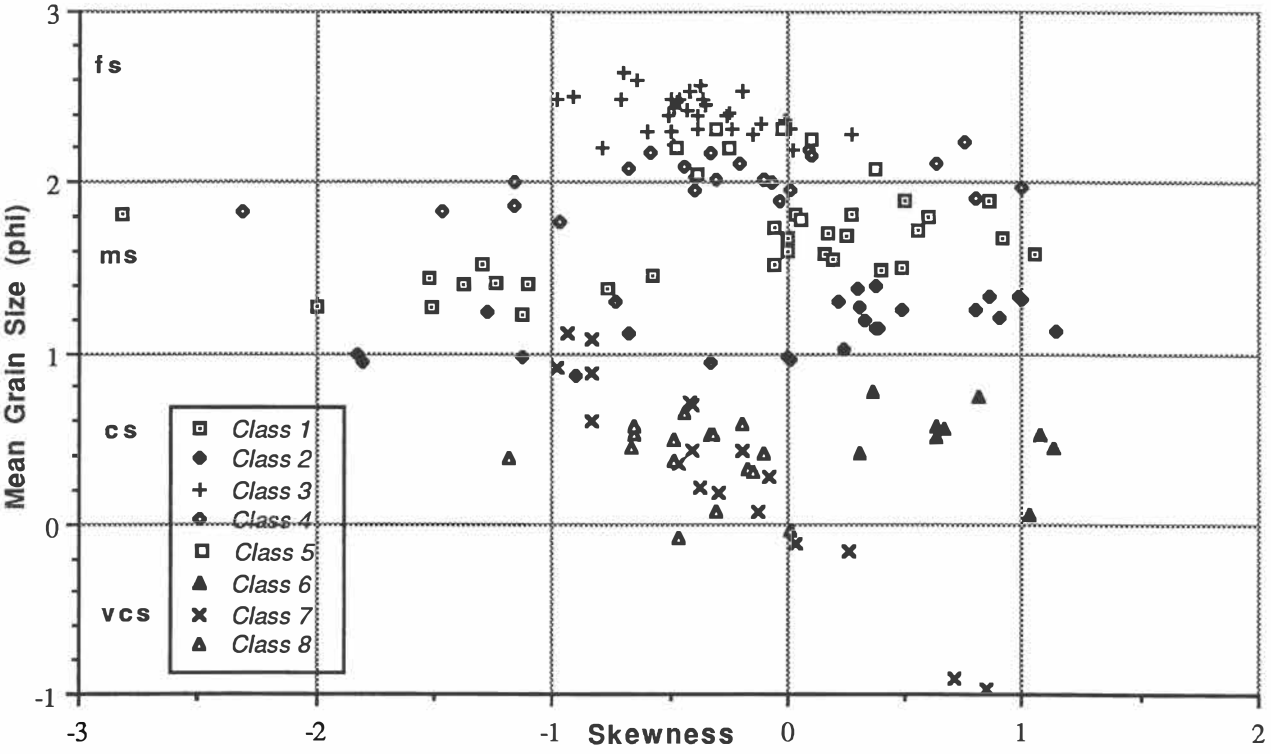


Figure 5.17 Mean grain size plotted against skewness for the eight entropy classes. This shows that skewness is also an important secondary factor in the classification of most of the entropy classes, particularly classes 3, 5, 6 and 7.

Table 5.4 Summary of the mean textural properties for each of the eight different entropy classes, using averaged observations for each data set in the class.

Entropy Class	*Mean Grain Size (ϕ)*	*Sorting (ϕ)*	*Skewness*	*Gravel (%)*	*CaCO3* (%)*
1	ms *upper* (1.56)	mod.-well	near	1.0	3
2	ms *lower* (1.16)	mod.-well	near	0.9	8
3	fs *lower* (2.41)	mod.-well	near	0.1	6
4	fs *lower* (2.02)	mod.-well	near	0.2	5
5	fs *lower* (2.11)	mod.	near	0.0	6
6	cs *upper* (0.51)	mod.-well	near	0.6	14
7	cs *lower* (0.32)	poorly	coarse	23.2	10
8	cs *lower* (0.38)	mod.- poorly	coarse	10.2	5

* from Section 6.4 near= near symmetrical, coarse= coarse skewed.

Figure 5.19 shows the distribution of the various entropy classes along the Pukehina-Matata nearshore zone. The use of the entropy programme brings to light several points of interest which were not evident in the spatial distribution patterns of the surficial sediments. The beach sands, which as shown previously are intimately connected with the nearby river and stream environment, are defined by class 1 in the region from Newdicks Beach to Otamarakau, except for some finer grained sediments (class 4) along the Pukehina Spit which are perhaps interacting with the surf

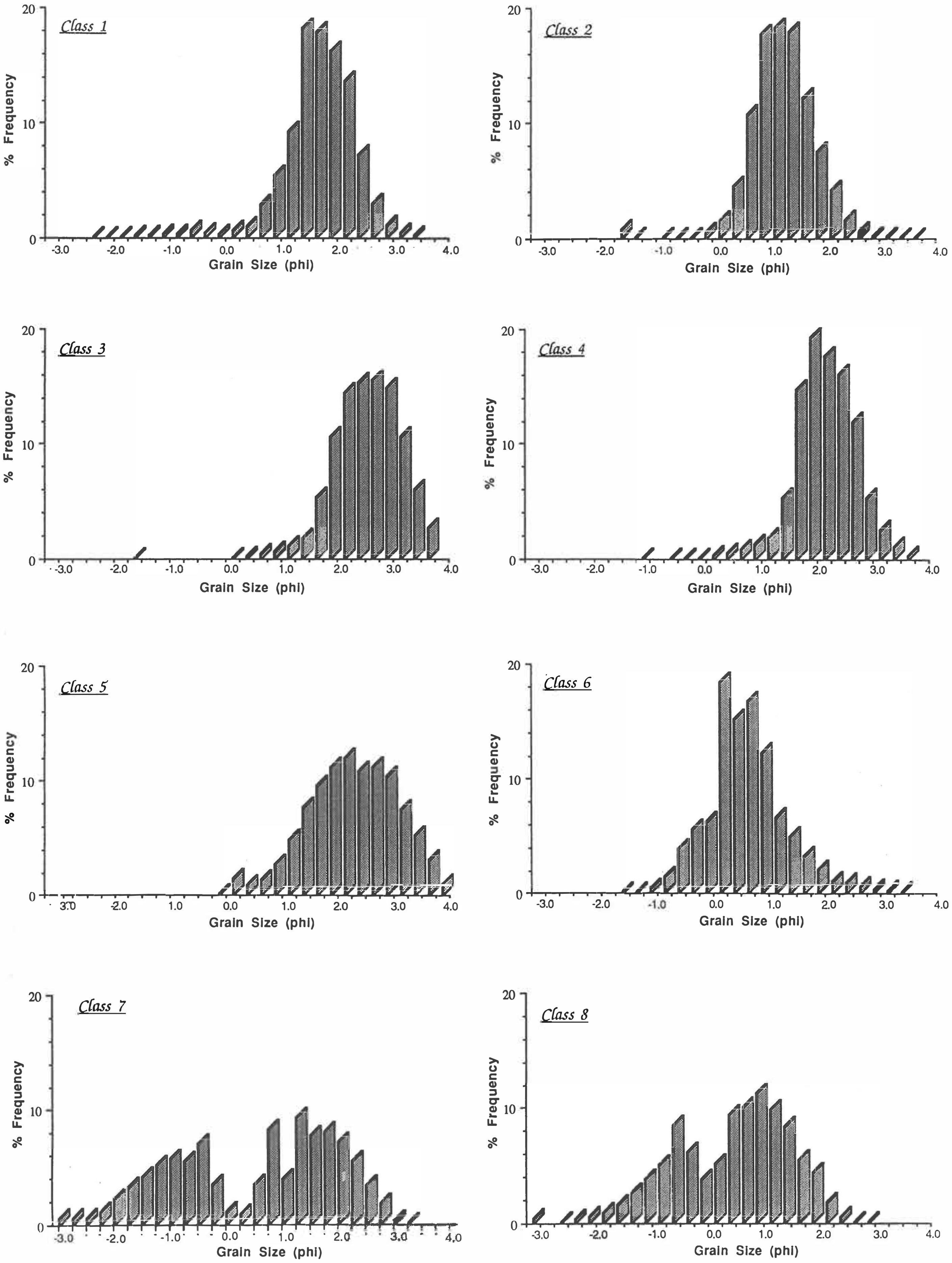


Figure 5.18 Grain size frequency distribution histograms for each of the eight different entropy classes.

zone area. Interestingly, from the Waitahanui Stream mouth at Otamarakau to just before the Tarawera River mouth, the beach sediments are all class two, reflecting their coarser nature, probably due to the streams that occur within this area but are absent further north. The class 1 sediments in the Otamarakau-Matata region are then found to occur immediately further seaward of the class 2 sediments within the surfzone. This suggests that the beach and upper littoral zone are composed of texturally similar sediments along the entire Pukehina-Matata coastline, with sediment addition to the beach from the streams in the Otamarakau-Matata area altering this general trend.

In the nearshore zone the pattern is approximately similar along the entire sector, although from Otamarakau to Matata this pattern is translocated slightly further offshore (Class 1 sediments then class 4, followed by class 5 and then class 3 sediments in increasing distance offshore). This pattern of offshore fining in grain size had been shown to occur for other barrier beach coastlines in the Bay of Plenty, such as Waihi (Bradshaw, 1991). For Newdicks Beach beyond 5 m water depth, and Pukehina south to Otamarakau beyond 14 m water depth, the sediments are entropy class 6, suggesting that they originate from a similar source. The prominence of this class at shallower depths at Newdicks Beach, may infer erosion of the Town Point shoals as a sediment source for the offshore area. However since the offshore reefs and submarine outcrops along Pukehina Spit and Redoubt are suggestive of similar geologic material to Town Point, based on diving observations and the low reflectivity of bedrock material on side-scan sonographs (Chapter 8), it seems probable that these may be one of the main sources of sediment for the Pukehina to Otamarakau offshore zone, and may therefore represent the same entropy class.

5.8 Inference of Net Sediment Transport

5.8.1 Sunamura and Horikawa (1972) Model

The inferred alongshore net sediment transport based on the model of Sunamura and Horikawa (1972), appears from Figure 5.20 to be bi-directional, based on the sediment transport directions interpreted from generalised sediment textural trends (particularly the beachface plots), and Figure 5.1.

Depending to some extent on seasonal effects and wave conditions, from Figure 5.20 the Sunamura and Horikawa model would suggest that sediment moves in a south-easterly direction from Otamarakau to the Tarawera River mouth, and to the north-west along Pukehina Spit from at least the Pukehina Redoubt. Between the Redoubt and the Waitahanui Stream entrance near Otamarakau the net longshore drift may be either minimal, with other processes taking precedence, such as onshore-offshore (diabathic) transport operating to move sediment, or littoral drift within this area is variable depending on the beach-dune-nearshore conditions operating, which would therefore determine the 'centre point' of the inferred bi-directional littoral drift.

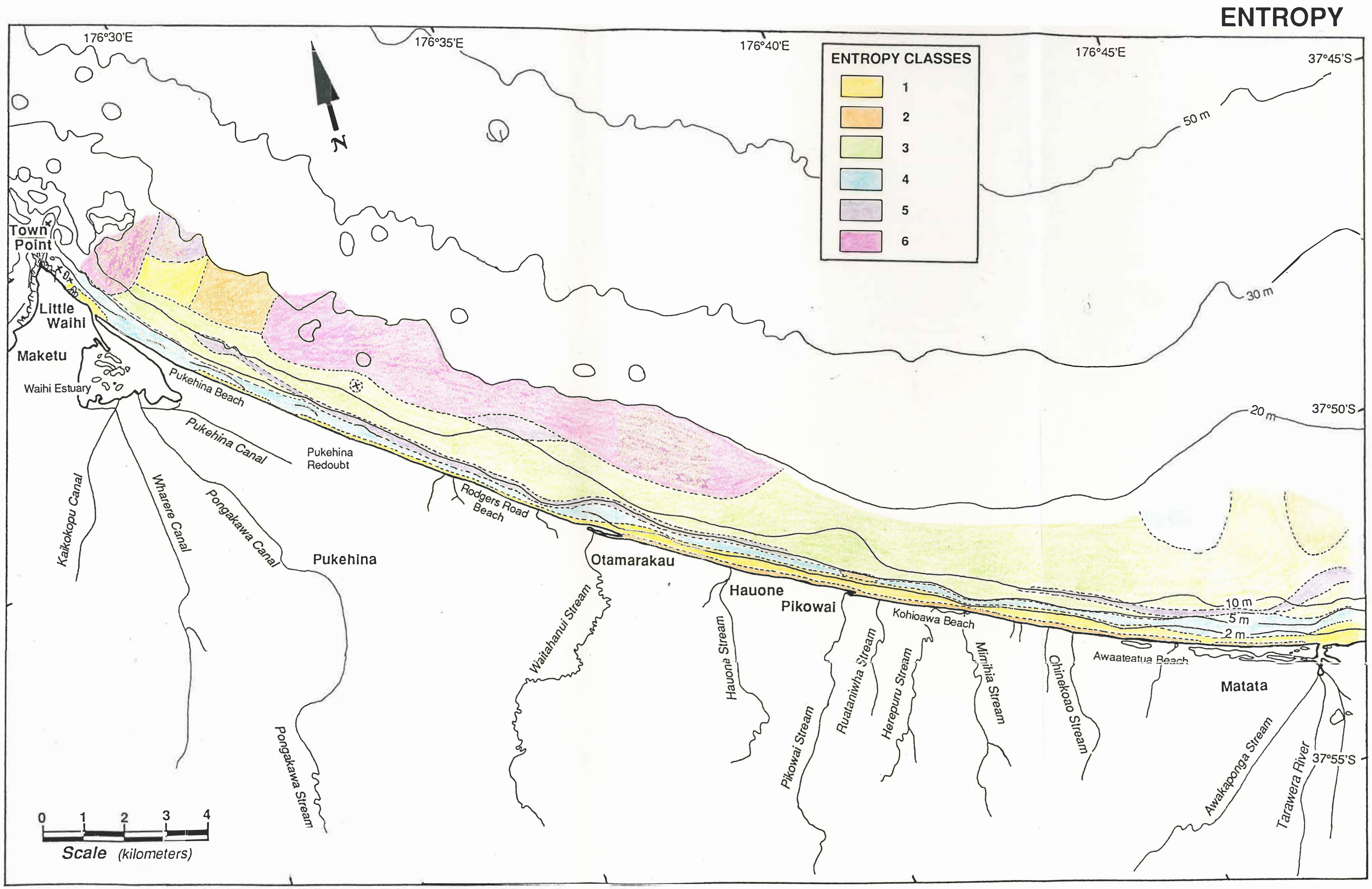


Figure 5.20 Distribution of the six entropy classes for surficial sediments in the nearshore as delineated by the ENTROPY programme

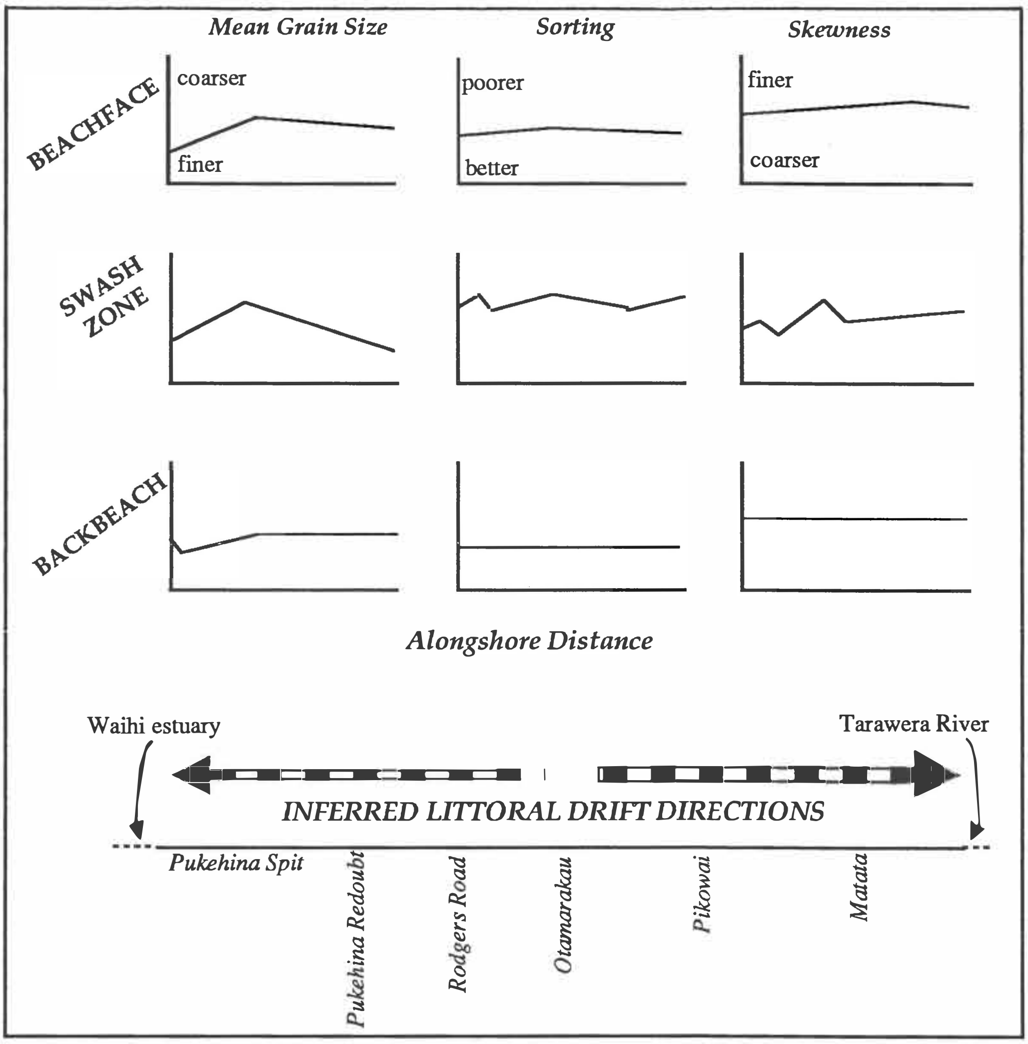


Figure 5.20 Generalised schematic spatial trends in textural parameters for the Pukehina-Matata coastal sector based on interpretations of the alongshore sediment textural results (Figs. 5.6 & 5.7). The bottom figure shows the inferred sediment transport directions based on these trends and the Sunamura and Horikawa model (Fig. 5.1).

5.8.2 McLaren (1981) Model

The McLaren model when applied to the sediment textural data should suggest areas of sediment source and sink, although the model does rely on a deposit being derived from a *single* source. For much, if not all of the study area, there are several probable sources of the beach sediments, which could therefore imply one of three possibilities (McLaren, 1981). First, the trend may indicate the dominant source, which is thus of use; secondly, the multiple sources invalidate the trend so that a single source can not be determined, which again is useful; and the last possibility is that a mixture of two or more sediment sources may produce an incorrect but reasonable trend. Given these limitations, particularly applicable where streams introduce new sediment into the alongshore beach system, matched pair comparisons were made between possible sources and possible sinks or deposits of beachface sediments along the Pukehina-Matata coastal sector (Table 5.5a and 5.5b). This approach is similar to that used by McLaren (1981, p.615-616) who inferred possible sources and sinks of sediments using data from 7 beachface locations taken on the Yakutat Foreland, Alaska.

Table 5.5a Sediment trend matrix for beachface sediments (November, 1992) at 19 representative locations along the Pukehina-Matata beach as for Fig.5.4. Each matched pair of sediment samples consists of three values, mean grain size, sorting, and skewness respectively relating the deposited sediment (at right) to the possible sediment source (top). F = finer than, C = coarser than; B = better sorting, P = poorer sorting; - = finer skewed, + = coarser skewed; and an equals sign indicates the same value. Italicised boxes indicate trends that are impossible between a deposit and its source sediment based on the McLaren model.

SED. DEPOSIT	**SEDIMENT SOURCE**																		
Sample Locality	TP1	P2	P6	P9	P11	P18	O12	O8	O7	O3	K15	K13	K12	K8	K1	M15	M11	M8	M2
TP1		F B -	*F P -*	*F P -*	F B +	F B +	F B -	F B +	F B +	F B -	F B -	F B -	F B -	F B -	*F P -*	*F P -*	*F P -*	F B -	F B -
P2	*C P +*		*C P -*	*C P -*	F B +	F B +	C B +	F B +	F B +	F B +	F B -	*C B =*	*F P -*	F B +	*F P -*	*C P +*	*C P -*	*C P -*	C B -
P6	C B +	F B +		*F P +*	F B +	F B +	F B +	F B +	F B +	F B +	F B +	F B +	F B +	F B +	*F P -*	*F P +*	*F = -*	F B -	F B +
P9	C B +	F B +	*C B -*		F B +	F B +	F B +	F B +	F B +	F B +	*F B =*	F B +	F B +	F B +	F P -	F B +	F B -	F B -	F B -
P11	*C P -*	*C P -*	*C P -*	*C P -*		C B +	*C P -*	*C P -*	*C P +*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*
P18	*C P -*	*C P -*	*C P -*	*C P -*	*F P -*		*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*	*F P -*	*C P -*	*C P -*	*F P -*	*C P -*	*C P -*
O12	*C P +*	*F P -*	*C P -*	*C P -*	F B +	F B +		F B +	F B +	F B -	*F P -*	*C B -*	*F P -*	F B +	*F P -*	*F P -*	*C P -*	*C P -*	F B -
O8	*C P -*	*C P -*	*C P -*	*C P -*	F B +	F B +	*C P -*		C B +	*C B -*	*C P -*	*C = -*	*C P -*	F B -	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*
O7	*C P -*	*C P -*	*C P -*	*C P -*	F B -	F B -	*C P -*	*C P -*		*C P -*	*C P -*	*C P -*	*F P -*	*F P -*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*
O3	*C P +*	*C P -*	*C P -*	*C P -*	F B +	F B +	*C P +*	*F P +*	F B +		*C P -*	*C P -*	*F P +*	*F P +*	*C P -*	*C P -*	*C P -*	*C P -*	*C P -*
K15	*C P +*	*C P +*	*C P -*	*C P =*	F B +	F B +	C B +	F B +	F B +	F B +		C B +	*F P +*	F B +	*F P -*	*F P +*	*C P -*	*C P -*	*C B -*
K13	*C P +*	*F P =*	*C P -*	*C P -*	F B +	F B +	*F P +*	*F = +*	F B +	F B +	*F P -*		*F P +*	F B +	*F P -*	*F P +*	*F P -*	*F P -*	*F P -*
K12	*C P +*	*C P -*	*C P -*	*C P -*	F B +	F B +	C B +	F B +	C B +	C B +	*C B -*	*C B -*		F B +	*C P -*	*C P -*	*C P -*	*C B -*	*C B -*
K8	*C P +*	*C P -*	*C P -*	*C P -*	F B +	C B +	*C P -*	F B +	C B +	*C B -*	*C P -*	*C P -*	*C P -*		*C P -*	*C P -*	*C P -*	*C P -*	*C P -*
K1	C B +	C B +	C B +	C B +	F B +	F B +	C B +	F B +	F B +	F B +	C B +	C B +	F B +	F B +		C B +	C B +	C B +	C B +
M15	C B +	F B -	*C B -*	*C P -*	F B +	F B +	C B +	F B +	F B +	F B +	F B -	*C B -*	F B +	F B +	*F P -*		*C B -*	*C B -*	*C B -*
M11	C B +	F B +	*C = +*	*C P +*	F B +	F B +	C B +	F B +	F B +	F B +	F B +	C B +	F B +	F B +	*F P -*	*F P +*		C B +	F B +
M8	*C P +*	C B +	*C P +*	*C P +*	F B +	F B +	F B +	F B +	F B +	F B +	F B +	C B +	*F P +*	F B +	*F P -*	*F P +*	*F P -*		*F B =*
M2	*C P +*	*F P +*	*C P +*	*C P +*	F B +	F B +	*C P +*	F B +	F B +	F B +	*F P +*	C B +	*F P +*	F B +	*F P -*	*F P +*	*C P -*	*C P =*	

Table 5.5b Sediment trend matrix for beachface sediments (April, 1992) at 19 representative locations along the Pukehina-Matata beach as for Fig.5.4. Each matched pair of sediment samples consists of three values, mean grain size, sorting, and skewness respectively relating the deposited sediment (at right) to the possible sediment source (top). F = finer than, C = coarser than; B = better sorting, P = poorer sorting; - = finer skewed, + = coarser skewed; and an equals sign indicates the same value. Italicised boxes indicate trends that are impossible between a deposit and its source sediment based on the McLaren model.

SED. DEPOSIT	**SEDIMENT SOURCE**																		
Sample Locality	TP1	P2	P6	P9	P11	P18	O12	O8	O7	O3	K15	K13	K12	K8	K1	M15	M11	M8	M2
TP1		*C* *P* -	*C* *P* -	F B -	*F* *P* -	*F* *P* -	*F* *P* -	F B -	F B -	*F* *P* -	F B -	F B -	F B -	F B -	F B -	F B -	F B -	*F* *P* -	*F* *P* -
P2	F B +		*C* *P* +	F B +	*F* *P* +	F B +	F B +	F B -	F B +	F B -	F B +	F P +	F B +	F B +	F B +	F B +	F B +	F B -	F B +
P6	F B +	F B -		F B -	F B -	F B -	F B -	F B -	F B -	F B -	F B -	F B -	F B -	F B -	F B -	F B +	F B +	F B -	F B -
P9	*C* *P* +	*C* *P* +	*C* *P* +		*F* *P* -	F P +	F P -	F = -	F B -	*F* *P* =	F B -	F B +	F B -	F B +	F B -	F B +	F B +	*F* *P* -	*F* *P* +
P11	C B +	*C* *B* -	*C* *P* +	C B +		F B +	F B +	F B -	F B +	F B +	F B +	F B +	F B +	F B +	F B +	F B +	F B +	F B -	F B +
P18	*C* *P* +	*C* *P* -	*C* *P* =	*C* *B* -	*C* *P* -		*F* *P* -	F B -	F B -	*F* *P* -	F B -	F B -	F B -	F B -	F B -	F B -	F B +	*F* *P* -	F B -
O12	C B +	*C* *B* -	*C* *P* +	C B +	*C* *P* -	C B +		F B -	F B +	F B +	F B =	F B +	F B +	F B +	F B +	F B +	F B +	F B -	F B +
O8	*C* *P* +	*C* *P* +	*C* *P* +	C = +	*C* *P* +	*C* *P* +	*F* *P* +		F B +	*F* *P* +	F B +	F B +	F B +	F B +	F B +	F B +	F B +	*F* *P* +	*F* *P* +
O7	*C* *P* +	*C* *P* -	*C* *P* +	*C* *P* +	*C* *P* -	*C* *P* +	*F* *P* -	*C* *P* -		*C* *P* +	*F* *P* -	F B +	*F* *P* +	*F* *P* +	F B +	*F* *P* +	*F* *P* +	*F* *P* -	*C* *P* +
O3	C B +	*C* *P* -	*C* *P* +	C B +	*C* *P* -	C B +	*F* *P* -	C B -	F B -		F B +	F B +	F B -	F B +	F B -	F B +	F B +	*F* *P* -	C B +
K15	*C* *P* +	*C* *P* -	*C* *P* +	*C* *P* +	*C* *P* -	*C* *P* +	*F* *P* =	*C* *P* -	C B +	*C* *P* +		C B +	*C* *P* +	*C* *P* +	= B +	*C* *P* +	*C* *P* +	*C* *P* -	*C* *P* +
K13	*C* *P* +	*C* *P* -	*C* *P* +	*C* *P* -	*C* *P* -	*C* *P* +	*F* *P* -	*C* *P* -	*C* *P* -	*C* *P* -	*F* *P* -		*C* *P* -	*C* *P* -	F = -	*C* *P* -	*C* *P* +	*C* *P* -	*C* *P* =
K12	*C* *P* +	*C* *P* -	*C* *P* +	*C* *P* +	*C* *P* -	*C* *P* +	*F* *P* -	*C* *P* -	*C* *B* -	*C* *P* +	F B -	F B +		F B +	F B =	*F* *P* +	*C* *P* +	*C* *P* -	*C* *P* +
K8	*C* *P* +	*C* *P* -	*C* *P* +	*C* *P* -	*C* *P* -	*C* *P* +	*F* *P* -	*C* *P* -	*C* *B* -	*C* *P* -	F B -	F B +	*C* *P* -		F B -	*C* *P* -	*C* *P* +	*C* *P* -	*C* *P* +
K1	*C* *P* +	*C* *P* -	*C* *P* +	*C* *P* +	*C* *P* -	*C* *P* +	*F* *P* -	*C* *P* -	*C* *P* -	*C* *P* +	= *P* -	C = +	*C* *P* =	C P +		*C* *P* +	*C* *P* +	*C* *P* -	*C* *P* +
M15	*C* *P* +	*C* *P* -	*C* *P* +	*C* *P* -	*C* *P* -	*C* *P* +	*F* *P* -	*C* *P* -	*C* *B* -	*C* *P* -	F B -	F B +	*C* *B* -	C B +	F B -		C = +	*C* *P* -	*C* *P* +
M11	*C* *P* +	*C* *P* -	*C* *P* -	*C* *P* -	*C* *P* -	*C* *P* -	*F* *P* -	*C* *P* -	*C* *B* -	*C* *P* -	F B -	F B -	F B -	F B -	F B -	F = -		*C* *P* -	*C* *B* -
M8	C B +	*C* *P* -	*C* *P* +	C B +	*C* *P* +	C B +	*F* *P* -	*C* *B* -	C B +	C B +	F B +	F B +	F B +	F B +	F B +	F B +	F B +		C B +
M2	C B +	*C* *P* -	*C* *P* +	C B -	*C* *P* -	C B +	*F* *P* -	*C* *B* -	C B -	F B -	*F* *P* +	F B -	F B =	F B -	F B -	F B -	F B +	*F* *P* -	

Figures 5.21a and 5.21b show the possible linkages from source to deposit or partial deposit based on the sediment trend matrix for April and November which may determine seasonal, as well as overall sediment transport directions. It should be noted however that only 19 samples were used, so that while these were chosen on the basis of the previous sediment textural trends, some possible sediment transport pathways may occur which are not represented in the diagrams. The most likely area in which this may occur is between the Pukehina Redoubt and Otamarakau where the linkages shown are probably more simplistic than the actual situation.

Those linkages which are obviously incorrect from other textural analysis are neglected. For example in Figure 5.21a, it is improbable that the Tarawera River (represented by site M2) is providing source sediment for Pukehina Spit and Town Point, given that there is no relationship for areas between these regions. It is possible that linkages between sediment locations are merely a reflection of the beach state and conditions at the time of sampling and may change throughout the year, however based on field observations both situations seem to be the dominant two prevailing conditions for the Pukehina-Matata coastal sector. The McLaren model compares the mean grain size, sorting and skewness in one relationship, suggesting several interesting possibilities in terms of sediment transport in the area.

November

The Tarawera River appears to be a source for the beach sediments to the north of its mouth as far as the Awatarariki Lagoon, north of Matata (M11). K1, located just north of the Ohinekoao Stream is a possible area of deposition for all other localities and may be a sink for sediment brought to the south-east by the littoral drift system and from a counter littoral drift supply bringing sediment from the Tarawera River north along Awaateatua Beach. The Waitahanui Stream also seems to deposit material to the north and south, providing one of the main sources of littoral sediment. The beach at the Pukehina Redoubt (P11) shows that it may be a possible source of sediment for the entire Pukehina Spit, implying a net littoral drift to the north-west along this region.

April

The possible sediment pathways for the April situation (Figure 5.21b) show some distinct differences. Firstly the Tarawera River (M2) supplies sediment only as far as central Matata (M8); this is probably the result of the fairly stable accretionary situation which prevailed at the time coupled with a north-westerly wind direction, which would have allowed for the littoral drift system to move less interrupted in a south-easterly direction down the coast along Awaateatua Beach than in November. This is further illustrated by the possible sediment pathways from K12, K8, K1 and M15 all ending up at M2 by way of Case I type transport. Added to this is the shifting of sediment from Otamarakau (O7) onwards, in a general south-easterly direction from site to site down the beach, which matches well with the alongshore mean grain size and sorting trends.

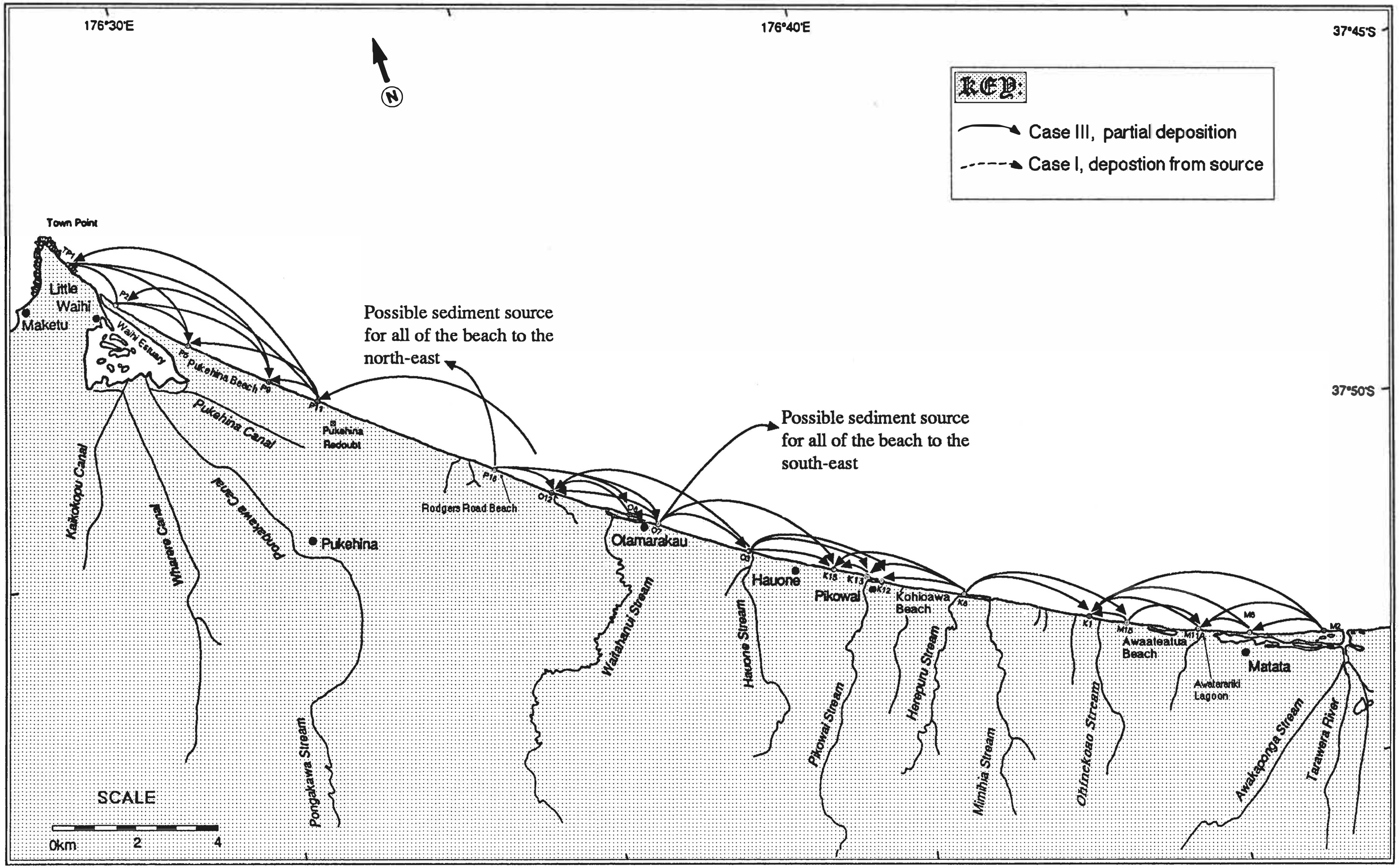


Figure 5.21a Locations of the beachface samples used in the McLaren model, and possible sediment pathways based on the November sediment trend matrix.

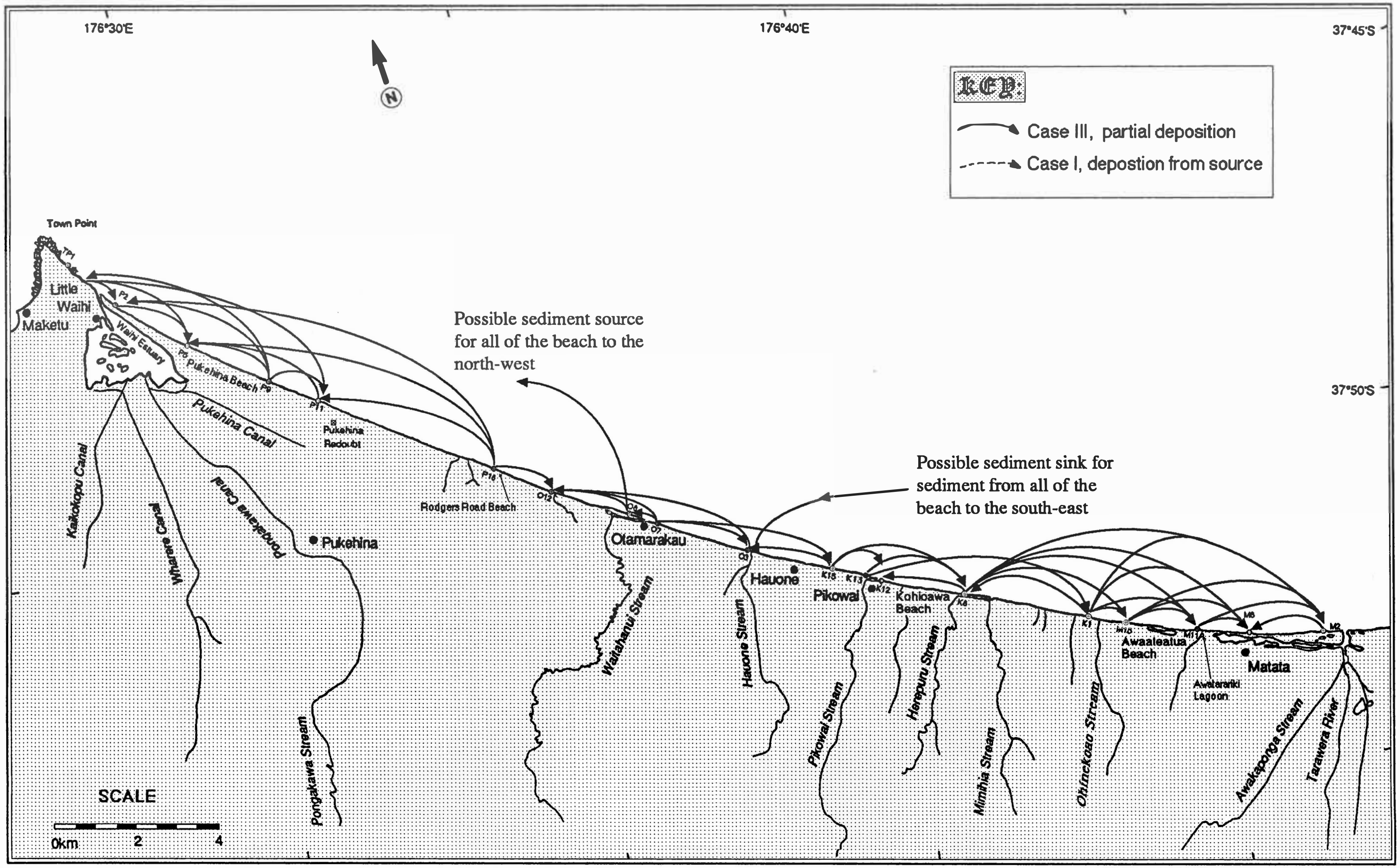


Figure 5.21b Locations of the beachface samples used in the McLaren model, and possible sediment pathways based on the April sediment trend matrix.

The possible sediment sinks or deposit areas which do not act in turn as a sediment source, differ slightly from those that may occur in November. Along Pukehina Spit, central (P6) and southern (P9) Pukehina Spit were the deposit areas based on the November sediment matrix, whereas in April Pukehina central (P6) and P2 & P11 were the sediment sinks. In both cases the suggested source for much of the Pukehina beach sediments is at Rodgers Road Beach (P18), south of Newdicks Beach (TP1), and P11 in November and P9 in April. The shift in location of the last two sites, again ties in well with field observations and evidence, which suggests that if southern Pukehina Beach is a sediment source area then the exact starting point for sediment nourishment to the northern part of the beach varies depending on the beach state, wind and wave conditions, and the interaction between the nearshore zone and the beach.

Other sites of possible sediment accumulation are at O12, 2.5 km north of Otamarakau, which in both situations receives sediment from the Waitahanui stream (O7 & O8) to the south and from the beach system at Rodgers Road Beach (P18). Similarly, K12 may also be a site for sediment accumulation in both situations, although being sited by the Pikowai Stream, this site should theoretically be a sediment source area. The probable reason for the difference is that the other sites along this region are located near streams themselves, so that K12 may be only a local sediment deposit area as a result of beach-fluvial interaction. Also due to stream wandering, the K12 site in April was located on the northern side of the Pikowai Stream mouth.

From both Figures 5.21a and 5.21b the main sediment transport pathways are Case III type sediment transport, which is similar to examples used by McLaren (1981). However, in the April situation there are more Case I type pathways than in November. Since Case I is finer, better sorted, and more negatively skewed, it should represent total deposition of sediment in transport from source, without any intermediary deposition during transport, which again may illustrate the different beach conditions prevailing in the April situation compared with November. McLaren (1981) suggests that because beachface sediments undergo continuous movement through the action of breaking waves and swash, Case I is unlikely to occur in this environment and could therefore be reasonably rejected. Even so the Case I type is distinct to some extent from Case IIIA & B, and while not truly representing total deposition from source may still suggest a viable possible sediment pathway.

Table 5.6 Relative percentages of possible sediment transport pathway directions along the Pukehina-Matata coastal sector for the two sampling dates.

	Town Point to Otamarakau		*Otamarakau to Matata*	
	North-west	South-east	North-west	South-east
NOVEMBER	31 %	10 %	18 %	41 %
APRIL	33 %	12 %	23 %	32 %

Sediment transport in the longshore direction, which constitutes in part the littoral drift regime, generally appears to be in a north-westerly direction from Otamarakau to the Waihi estuary, and south-easterly from Otamarakau to Matata, shown by the inferred sediment pathways between beachface localities, and summarised in Table 5.6.

The sediment trend pathways are also useful in suggesting probable areas in which erosion or accretion may be occurring. Hence, it is likely that at P18 erosion is occurring at all times in order to act as a sediment source area. P6 conversely would be an area of accretion. Further south, along Kohioawa and Awaateatua Beaches the areas of sediment erosion and accretion tend to vary according to the beach conditions, so erosion in one particular area is possibly not occurring all year round. Comparisons with the results of historical aerial photographic analysis (Chapter Four), show that Rodgers Road (P18) historically is an area of sediment accretion, which may imply that the area is receiving sediment from the nearshore zone since the sediment trend matrix shows no sediment input from the beaches on either side. If this is the case then the sediment input from offshore must be sufficient to supply much of the Pukehina Redoubt area as well as beach accretion at Rodgers Road.

Application of the principles behind the McLaren model could also be used to infer possible transport directions in the nearshore and offshore. The finer, better sorted, more negatively skewed sediments offshore from northern Pukehina Beach (Sites 29 and 28), compared with the surrounding sediments indicates that this is an area of deposition, probably resulting from Waihi estuary outflows. Similarly the decrease in grain size and increase in sorting in a seaward direction especially from Pikowai to the Tarawera River mouth, indicates removal of fine material in an offshore direction, leaving coarser material closest to the beach and surfzone. While these conclusions are logical, they do lend some validity to the McLaren model.

5.8.3 Waihi Model

The Waihi model is a variation on the McLaren model in an attempt to apply local conditions to a more universal model. Hence, a Case IV type sediment transport may occur based on the situation that is found along Waihi Beach (Harray and Healy, 1978), in which sediment transported from source may become *coarser, better or poorer sorted, and more negatively skewed* (due to the addition of coarser sized grains), while the resultant source sediment is *finer, better or poorer sorted and more positively skewed*. Using this Case IV transport scenario and the sediment trend matrices of Table 5.5a &b, possible sediment pathways are shown in Figure 5.22. From these results it appears that the Waihi model does not work well at all. This is illustrated by a number of conflictions. Firstly, the streams introduce coarse material into the littoral system, so for example O7 (Otamarakau) should not be a site for sediment deposition, rather as shown by the McLaren model it is a site which supplies sediment to downdrift localities. Secondly, at site P11 (Pukehina Redoubt), the beach is shown by the Waihi model to be a major sediment sink area, which should therefore be undergoing accretion, field observations and evidence from Chapter 3 however show that the area is eroding. The abundance of pumice along some parts of the Pukehina-Matata coast, particularly Pukehina Spit (see Chapter 6), should result in better sorted beach sands rather than more poorly sorted, as the pumice is weathered rapidly and moved offshore as fine sediment.

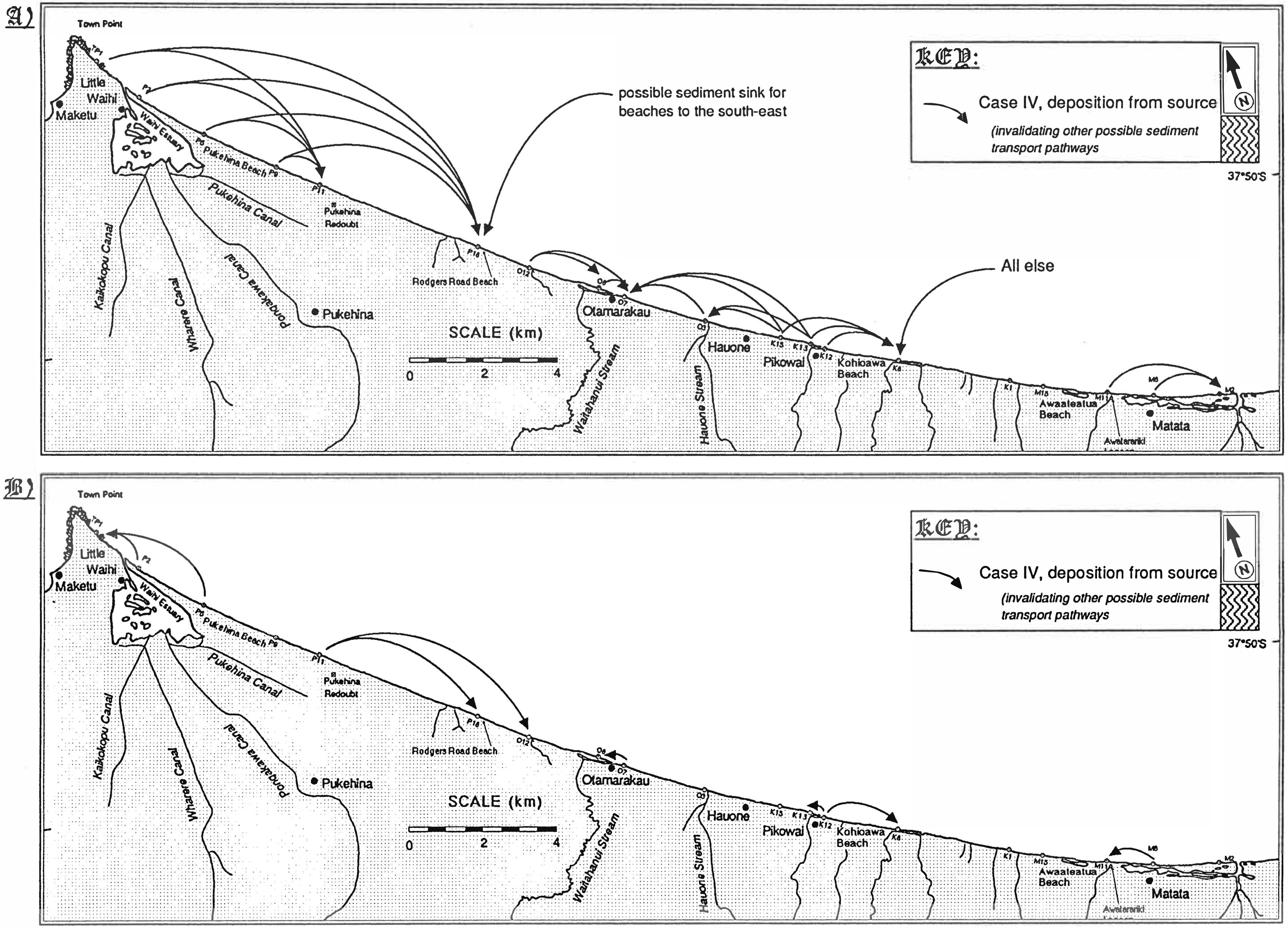


Figure 5.22 Possible sediment transport pathways for the Waihi model, using the *a)* November, and *b)* April sediment trend matrices.

The McLaren model does allow for a deposit to become either finer or coarser than source and better sorted. For a barrier beach in which sediment is continually transported along the beach in the littoral drift system this should hold true. The reason that the deposited sediment is coarser and poorer sorted at southern Waihi Beach is that Tauranga Harbour may add material so that the system does not act as a typical barrier beach. Hence, the Waihi model may only be applicable along Pukehina Spit and Town Point.

5.8.4 Inferred Sediment Transport from Healy et al. (1977) Data

As an additional comparison the McLaren model was applied to beachface data from Healy *et al.* (1977) for 12 sites within the Pukehina-Matata coastal sector (Figure 5.23).

From Figure 5.23 BOPCES site 21 is suggested as a sediment source region to the beach between Rodgers Road and east of the Tarawera River mouth, which is not implied from Figures 5.21a or 5.21b. This difference can be attributed to the sand extraction that was taking place at this site at the time of sediment sampling. The sediment pathways suggested in general are consistent with those found previously, with the Pukehina Redoubt suggested as a major sediment source region, Rodgers Road a sediment sink, northern and central Pukehina Spit sediment sinks, and Otamarakau both source and sink supplying sediment to the beaches to the north-west.

Table 5.7 Sediment trend matrix for beachface sediments at BOPCES sites contained in the Pukehina-Matata coastal sector, from data contained in Healy *et al.* (1977). Symbols are as for Tables 5.5a and 5.5b.

SED. DEPOSIT	**SEDIMENT SOURCE**											
Sample Locality	30	29	28	27	26	25	24	23	22	21	20	19
30		F P +	F P -	F P -	F B +	F P +	F B -	F = +	F P +	F B +	F B +	F P -
29	C B +		F P +	F = +	F B -	F p +	F B -	F B +	F P +	F B +	F B +	F P +
28	C B +	C B -		C B +	F B +	F P +	C B -	F B +	F B +	F B +	F B +	F P +
27	C B +	C = -	F P -		F B +	F P +	C B -	F B +	F P +	F B +	F B +	F P -
26	C P -	C P +	C P -	C P -		F P -	C P -	F P -	F P -	F B =	F P +	F P -
25	C B -	C B -	C B -	C B -	C B +		C B -	C B +	C B +	F B +	F B +	C B -
24	C P +	C P -	F P +	F P +	F B +	F P +		F P +	F P +	F B +	F B +	F P +
23	C = -	C P -	C P -	C P -	C B +	F P -	C B -		F P -	F B +	F B +	C P -
22	C B -	C B -	C P -	C B -	C B +	F P -	C B -	C B +		F B +	F B +	C P -
21	C P -	C P -	C P -	C P -	C P =	C P -	C P -	C P -	C P -		F P +	C P -
20	C P -	C P -	C P -	C P -	C B -	C P -	C P -	C P -	C P -	C P -		C P -
19	C B +	C B -	C B -	C B +	C B +	F P +	C B -	F B +	F B +	F B +	F B +	

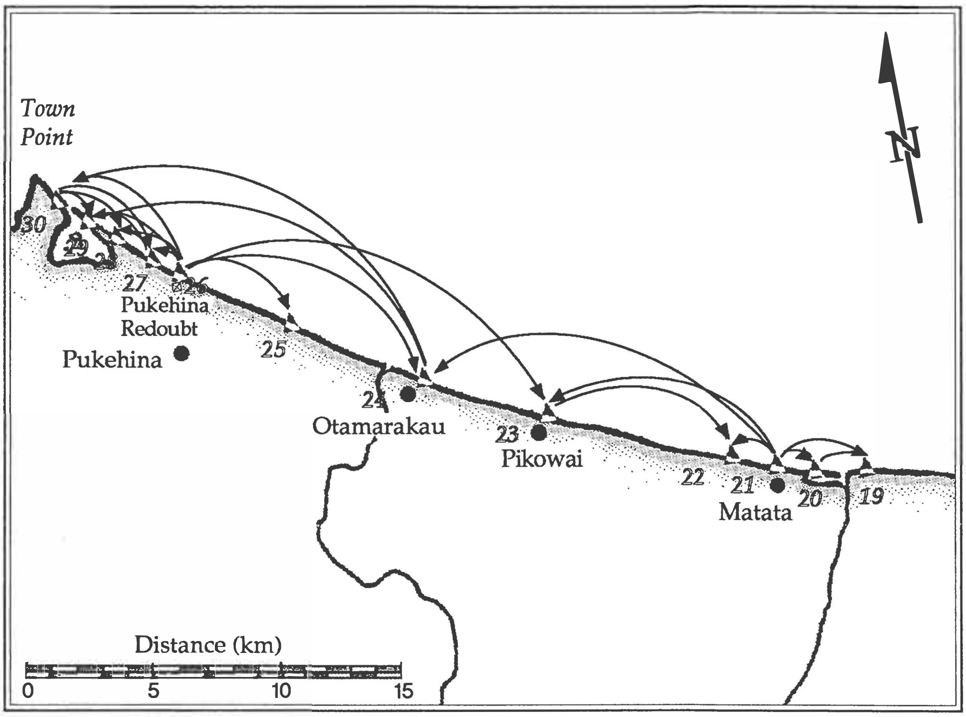


Figure 5.23 Possible sediment transport pathways inferred from the McLaren model, using sediment textural data from Healy *et al.* (1977).

5.9 SUMMARY

The beach and nearshore regions of the Pukehina-Matata coastal sector contain some of the coarsest surficial sediments in the Bay of Plenty.

- The stream and river sediments are predominantly coarser and more poorly sorted than those found on the beach, with the low-tide swash zone sediments implying that the coarsest fraction from the streams is deposited in this environment. The degree of fluvial interaction with both the beach and nearshore sediments is variable. All areas of the Pukehina-Matata coastal sector show a strong overlap of beach and river sediments, with the exception of Pukehina Spit, Pukehina Redoubt and Newdicks Beach. Nearshore-fluvial interaction shows only weak partial overlaps apart from at Pikowai and Kohioawa Beach. Similarly the interaction between the offshore zone and river sediments is noticeable only at the Tarawera River mouth, northern Pukehina Spit, and Newdicks Beach localities.

Comparisons of the grain size distribution curves at selected sites, suggests that the source of the beach sands is a least partially derived from erosion of local catchment rocks, which may be supplemented by littoral drift, erosion of submarine reefs in the Town Point-Otamarakau region, and possible onshore reworking of pre-Holocene sediments.

- Along Newdicks Beach and Pukehina Spit to the Pukehina Redoubt, the beach sediments are medium to fine grained, moderately-well to well sorted sands. These appear to be reworked terrestrially derived material from both the Waihi Estuary and sediment from the Pukehina Redoubt to Otamarakau area, with small quantities of sediment available from localised cliff and nearshore erosion at Town Point of conglomeritic and ignimbrite material which is transported south along Pukehina Spit.

From Otamarakau to Matata, the beach sediments are medium to coarse grained, moderately to moderately-well sorted sands. Compared with the sediments in the Pukehina area these sediments are derived significantly more from fluvial input from the Waitahanui, Pikowai, Herepuru, Mimihia, Hauone and Ohinekoao streams, and from sediment dispersion at the mouth of the Tarawera River along Awaateatua Beach to Matata.

Between the Pukehina Redoubt and Otamarakau, the beach sediments are coarse to medium grained, moderately to moderately-well sorted sands. The derivation of these sediments is not well known. It appears that the Waitahanui Stream provides some sediment, and can be positively traced perhaps 2 km from its mouth. It is suggested that some of the Pukehina Redoubt-Otamarakau material is derived from active reworking of offshore material including possible erosion of submarine rock outcrops, which may be added to by littoral drift movement from north of Town Point, 'deflected' past Pukehina Beach.

Longshore variations in sediment textural parameters was found to be most apparent in beachface sediments with the coarsest surficial sediments found near Otamarakau and the finest along Pukehina Spit.

- The nearshore sediments in the region show an overall offshore fining trend, with sediments becoming more poorly sorted and more coarsely skewed in an offshore direction. Imposed on this general pattern is a distinctive area of coarser sediment in 12-20 m water depth from Town Point to Otamarakau, with the odd patch of slightly coarser sediment at a similar depth offshore from the Tarawera River, as well as small localised patches of coarser or finer surficial sediments, such as found immediately offshore from the Pikowai Stream.

- Beach sediments exhibit some degree of seasonal change, where different beach states, and wind and wave conditions prevail. It appears that mostly this occurs north of Otamarakau, while between Otamarakau and the Tarawera River mouth there is little change, perhaps due to the constant influx of fluvial sediments to the beach along this area, and differing wave refraction patterns in the Pukehina area with wave approach, causing greater surficial sediment changes in the northern part of the study area. Additionally the exposure of gravel patches along the Pukehina Spit and Redoubt sectors as the covering layer of sand is removed significantly alters the grain size distribution. From the two beachface sediment datasets collected, April and November, constituting two extremes of beach conditions, statistically significant seasonal variations were found in alongshore grain size plots using paired t-tests, while statistically insignificant variations existed for sorting and skewness.

- Cross-shore variations in grain size can be correlated in part to changes in profile morphology, particularly in BOPCES sites from Otamarakau to Town Point, where grain size rapidly coarsens at the 12-15 m water depth, associated with submarine offshore rock outcrops in the nearshore zone which possibly are remnants of the Late Pleistocene wave cut terraces formed prior to the last sea-level rise of 6,000 yrs.

- Statistical classification of textural data using *Entropy* showed that the beach sediments are similar along the entire coastal sector, although a coarser band of sediments occurs within the Otamarakau-Matata region again relating to fluvial inputs. Other patterns in the distribution of entropy-classified sediments are consistent with the spatial distribution of the nearshore surficial sediment parameters, specifically mean grain size and sorting, which are the two textural parameters most important in determining the entropy classes.

- From the inferred sediment transport models of Sunamura & Horikawa (1972) the Pukehina-Matata textural data infers bi-directional alongshore transport to the north-west and south-east from a centre point near Otamarakau. The north-west directed littoral drift along Pukehina Spit is thought to be in part due to the lee effect created by the Town Point promontory combined with wave refraction reducing the influence of north and north-easterly generated waves, thereby creating a more complex current pattern than that which occurs further down the coast.

The McLaren (1981) model was trialled for both November and April sampling dates using textural beachface data to produce possible sediment transport pathways from sediment source to sink based on relative mean grain size, sorting, and skewness values between 19 sites. Overall it was found that there was a trend for sediment transport to the south-east from Otamarakau to Matata, and to the north-west to Pukehina, although this depends slightly on the beach and wave conditions.

Textural data from Healy *et al.* (1977) for the 12 sites contained in the study area produced possible sediment transport pathways consistent with those already found from this study. The only exception was Rodgers Road which is suggested to be a sediment sink rather than source. This relates more accurately with historical erosion-accretion trends showing the area from Rodgers Road to the south-east to be slightly accreting. However to the north-west from Rodgers Road to Pukehina Redoubt the beach is apparently eroding consistent with the McLaren model and the idea that this region is a sediment source. Other inferred source sectors of the study area are Otamarakau, Kohioawa Beach, and southern Pukehina Spit (basal end). Conversely inferred sectors of the beach which may act as sediment sinks are northern (distal end) and central Pukehina Spit, Newdicks Beach, and Matata.

A third model, the Waihi model, an adaption of the McLaren model to the sediment transport behaviour of Bay of Plenty sediments, suggests sediment transport pathways inconsistent with other lines of evidence and has been noted as being of little use in determining littoral drift directions.

Confirmation of the sources for different nearshore and beach deposits advocated above can only be made following a detailed examination of their mineralogy, which is addressed in Chapter 6, and nearshore morphology (Chapter 8).

CHAPTER SIX:

Sediment Composition

CHAPTER SIX
SEDIMENT COMPOSITION

6.0 Introduction

Interpretation from sediment textural analyses may give some possible indications concerning sources and littoral transport directions. However these require substantiation with additional lines of evidence. It has been demonstrated for example, by Judge (1970), and Miller (1981) for Poverty Bay, that mineralogical trends may be extremely useful in determining littoral sediment sources and sinks, and may also delineate the net long-term littoral movement.

Within the Bay of Plenty, examples such as Christopherson (1977) for Whiritoa Beach (Chapter 3), show that the sediment provenance of beach sands can be determined by comparing their mineralogical assemblage to catchment geology within the local area. The typical mineral assemblages and abundances that may occur in the geologic materials (Chapter 2) within the Pukehina-Matata area are given in Table 6.1. Although these abundances are generalised values they do give some indication of the likely minerals present in sediments derived from a given geology. However in some cases the Rhyolitic Ash values are likely to vary since it includes both ignimbrite and tephra material, and the percentages and occurrence of the various minerals will depend on each individual tephra member or ignimbrite flow, and the volcanic source centre involved.

Table 6.1 Typical general assemblages of minerals weathered from selected parent rocks. Values indicate approximate percentages of minerals. *(source: N.Z. Soil Bureau, 1978)*

MINERAL	*Greywacke*	*Rhyolite*	*Rhyolitic Ash*	*Andesite*	*Andesitic Ash*	*Basalt Scoria*
Quartz	35	30	VL	L	VL	-
Acid feldspar	40	30	30	5	-	-
Andesine	10	-	-	40	40	20
Acid-intermediate glass	1	30	60	5	30	-
Basic glass	-	-	-	-	-	20
Chlorites	5	-	-	-	-	-
Muscovite	5	-	-	-	-	-
Biotite	5	1	-	5	5	5
Hornblende A	1	1	-	10	10	-
Hornblende B	1	-	1	-	-	-
Hypersthene	-	1	1-3	5	5	-
Enstatite	-	-	-	-	-	5
Augite-Diopside	1	-	1	5	5	10
Epidote	1	-	-	-	-	-
Pumpellyite	P	-	-	-	-	-
Olivine	-	-	-	1	-	5
Calcite	1	-	-	-	-	-
Apatite	1	-	P	P	-	-
Garnet	1	-	-	-	-	-
Tourmaline	1	-	-	-	-	-
Sphene	P	-	-	-	-	-
Rutile	-	-	P	P	-	-
Zircon	1	-	-	P	-	-
Ilmenite	-	-	P	1-5	1-5	1-5
Magnetite	-	1	1	1-5	1-5	1-5

VL= very low, L= low, P= present   Hornblende A= green & brown hornblende, Hornblende B= cummingtonite.

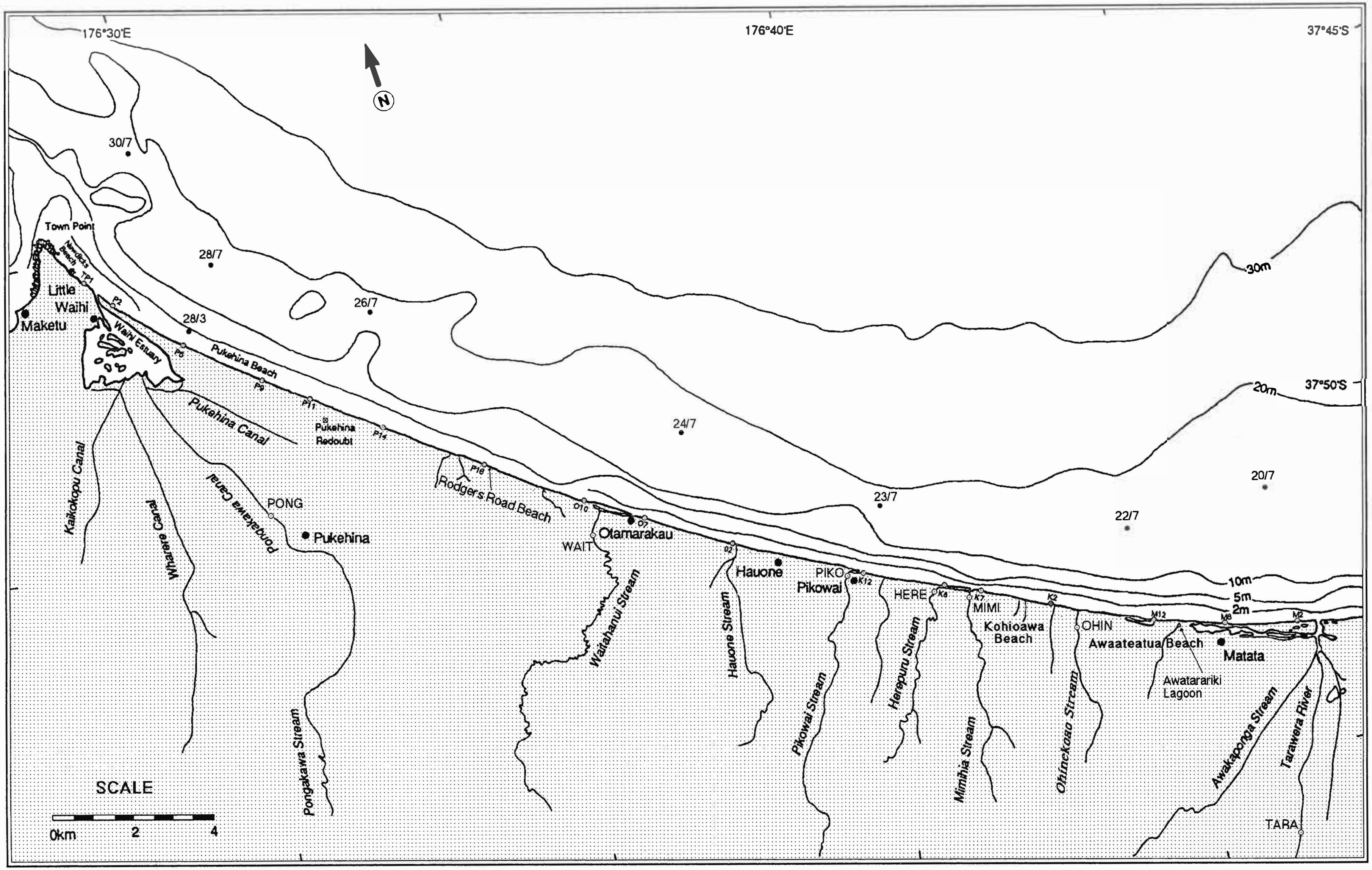


Figure 6.1 Location map of the surficial sediment samples (32) used in the mineralogical analyses. Samples are as for Chapter Five, and described in Figure 5.4.

This chapter therefore attempts to further evaluate the sources of sediment to the Pukehina-Matata beach-dune-nearshore system by analysing the light and heavy mineralogy of representative beach, nearshore and stream surficial deposits. In addition the carbonate contents of the sediments, and analysis of the low-tide swash zone gravels is included.

6.1 Methodology

6.1.1 Carbonate

Calcium carbonate is a component of coastal sediments, contributed to by marine organisms, and in high carbonate areas such as the Hauraki Gulf can compose up to 80 % (Smith, 1991). The percentage calcium carbonate in samples was determined by taking an oven dry 10 to 20g split and adding 1N HCl acid. The sample was then washed, dried and reweighed to determine the weight loss due to $CaCO_3$ dissolution by the acid.

6.1.2 Mineralogy

A total of 34 samples were selected from site locations used for the textural analysis aspect of this study, with cross-shore variations limited in favour of a complete analysis of variations and trends in the mineralogy along the coast. Fluvial samples were selected representing the major streams or rivers that could have an effect on the littoral sediments: Waitahanui, Hauone, Pikowai, Herepuru, Mimihia, Ohinekoao, Pongakawa, Kaikokopu streams, and the Tarawera and Kaituna rivers. Beach samples (17) were gathered from the beach face to a depth of 5 cm, being TP1, P2, P6, P9, P11, P14, P18, O10, O7, O2, K12, K8, K7, K2, M12, M8, and M2. The eight nearshore samples used were from BOPCES sites 30, 28, 26, 24, 23, 22, and 20 at or near 15 m water depth. One sample was also taken from BOPCES site 28 in 4 m water depth as an upper nearshore comparison. The location of all mineralogy samples is shown in Figure 6.1.

Standard laboratory methods for sample preparation were used following Lewis (1984), with each sample washed, dried, and then mechanically split by sieves to retain the -1 to 4 phi fraction (entire 'sand' fraction). While it is usual for mineralogical analyses to be undertaken on a restricted grain size, commonly the fine sand fraction (2-4 phi), a more non-restricted grain size was used for several reasons:

(i) the provenance indicated by the addition of coarse modern terrigenous material as a sediment source to the beach system may be neglected if only the fine sand range was employed, due to the minerals present in the coarser fractions being ignored.

(ii) mineral proportions are strongly dependant on grain size (Griffith, 1967). The Pukehina-Matata sediments are particularly coarse and have minimal proportions of sediment greater than 3 phi. Thus using the entire sand range should give more realistic mineralogical results for the Pukehina-Matata coastal sector. For example, more resistant minerals such as quartz, should be

more prominent in the coarser part of the grain size distribution histogram than feldspar crystals which are relatively more easily weathered, and would occur in higher concentrations in the finer fractions.

(iii) the heavy minerals in the Pukehina-Matata sediments are not restricted to the 2-4 phi size range as is the case in most heavy mineral studies (e.g. Bradshaw, 1991; Judge, 1970), with their occurrence dependant on the overall grain size distribution and modal grain size.

(iv) using the entire sand fraction is more relevant for later sediment budget determinations.

The 'sand' split was treated with HCl to remove the carbonate component from samples, determined separately in section 6.2. Splits were then impregnated with araldite resin and prepared as thin sections for determination of bulk mineralogy, by point counting 400 grains per slide (Appendix VI).

Heavy minerals were extracted from the sand split using tetrabromoethane (TBE), after initial attempts with a Frantz magnetic separator gave heavy splits which contained high numbers of lithic and pumice fragments while neglecting some non-magnetic heavy minerals. After separation with TBE, detrital mounts were made in araldite resin. A standard petrographic microscope was then used to identify the heavy minerals present, with approximately 300 grains being examined and point counted from each sample. Results obtained from the heavy mineralogical analysis are given in Appendix VIB, with the general sediment composition by weight of the carbonate, light, and heavy mineral fractions, presented in Appendix VIC.

Due to the difficulty in distinguishing between quartz and feldspar under a standard petrographic microscope, and the time consuming nature of feldspar staining techniques, a cathodoluminescence (CL) microscope was also employed to aid in the identification of some of the light minerals. Additional preparation of slides for CL required polishing for approximately 30 minutes with alpha alumina powder.

The cathodoluminescence microscope involves bombarding samples with energetic electrons, which cause different minerals to produce characteristic visible radiation (Marshall, 1988), and hence different colours depending on the mineral species, providing a quick and accurate means of distinguishing various minerals, particularly feldspar (yellow) from quartz (violet). Details of the application of CL to beach sediments is given in Bradshaw (1991) who applied this technique in the analyses of east Coromandel sediments.

6.2 General Sediment Composition -Results

The general spatial composition by weight of the beach, river and nearshore sediments, determined separately from carbonate and mineralogical analyses, is shown in Figure 6.2. With the corresponding alongshore sediment compositions given in Figure 6.3.

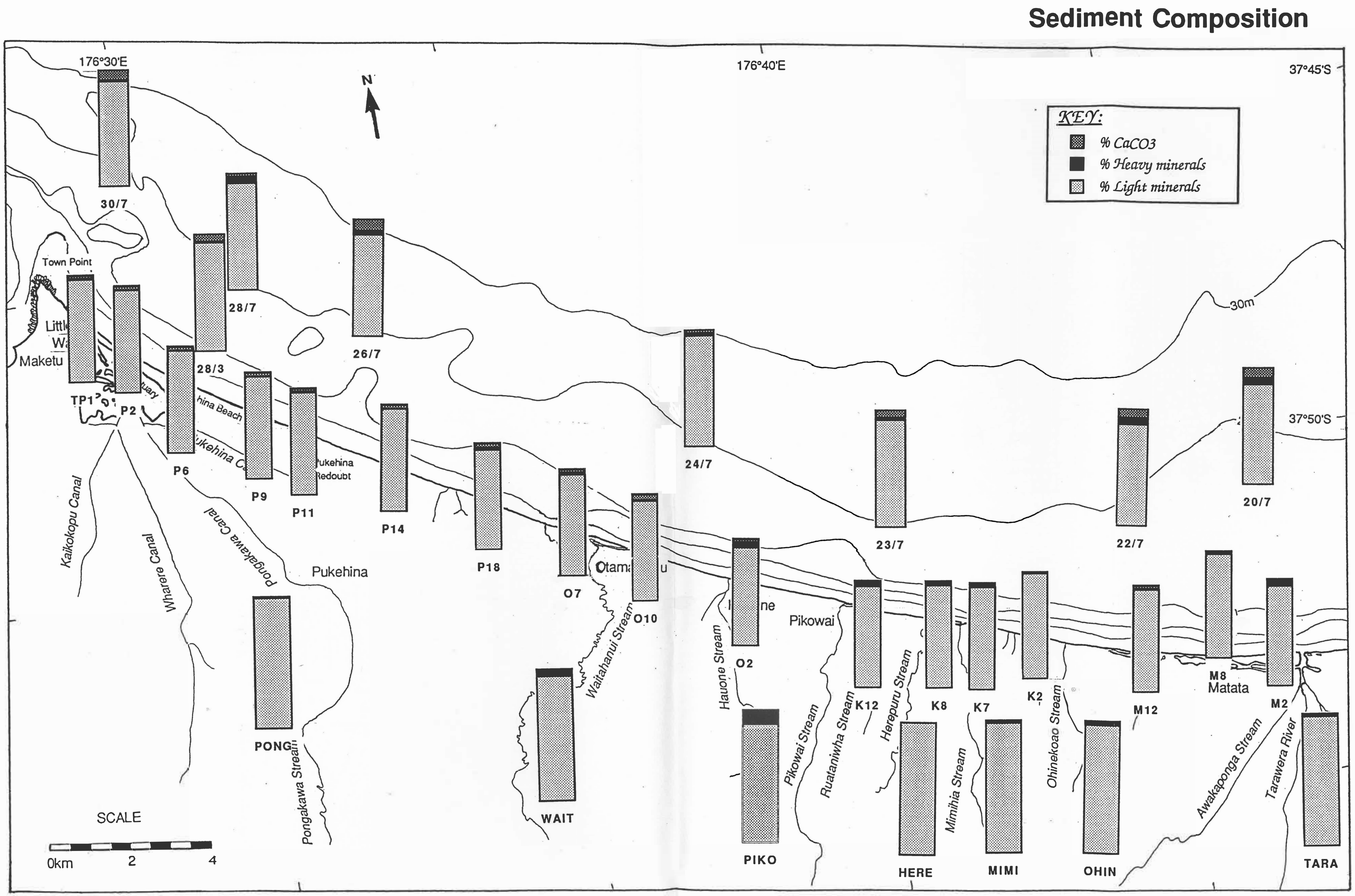


Figure 6.2 Sediment composition by weight of selected beachface, stream, and nearshore surficial sediments within the Pukehina-Matata coastal sector. Sample numbers are the same as those from Figure 6.1; e.g. PONG= stream sample, P2= beach sample, 28/7= nearshore (15 m water depth) sample. For the nearshore samples the sample numbers depict the actual sample location, for the beachface samples the mid-point of the mineral bars, while the stream positions are mostly schematic.

Carbonate abundances are highest from Town Point to Otamarakau, with low declining amounts towards Matata and the Tarawera River mouth.

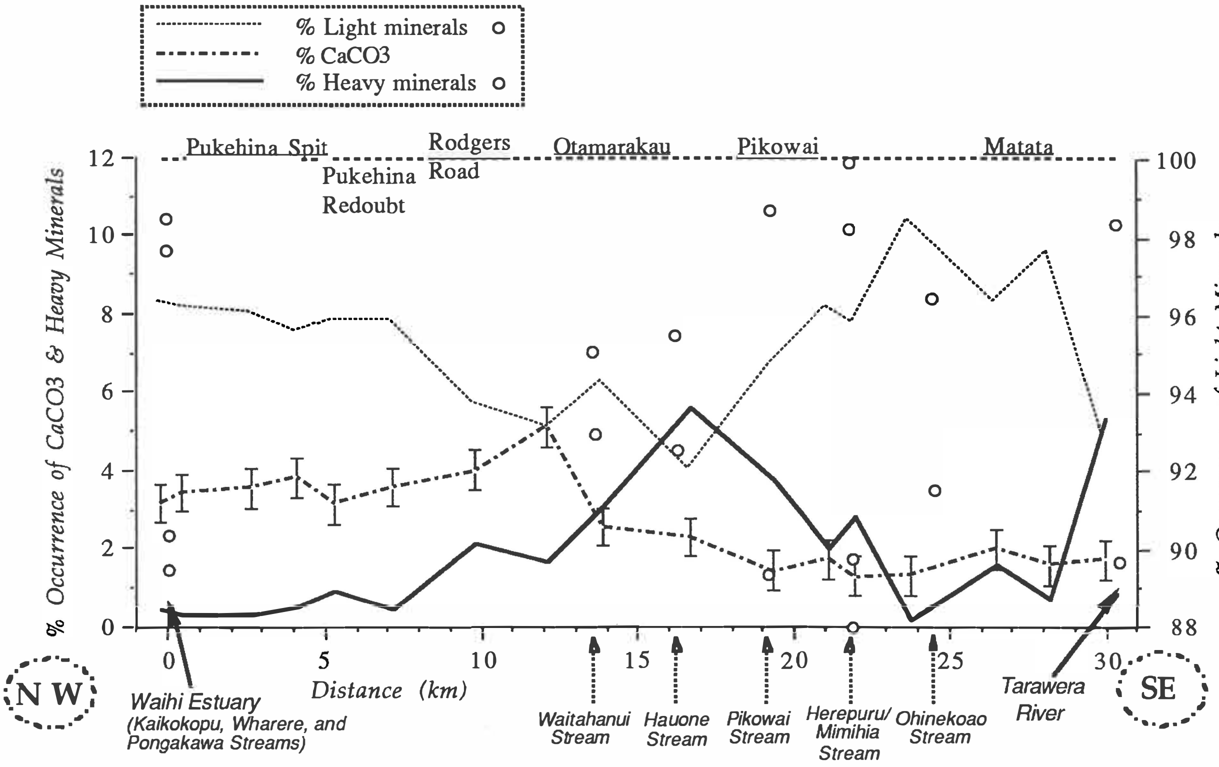


Figure 6.3 Composition by weight of the light minerals, heavy minerals, and carbonate ($CaCO_3$) in the beachface surficial sediments. Also shown are the stream and river values denoted by a white circle (light minerals) and black circle (heavy minerals), and standard errors for each alongshore value.

Light minerals constitute the majority of the beach sediments (92.1 to 98.5 %), due to the high input of quartzo-felspathic sediments from TVZ derived material. The pattern tends to show the reverse of the heavy mineral trend.

Heavy minerals constitute a small part of the total sedimentary suite for most sediments. The beach sands contain 0.2 to 5.6 % heavy minerals, compared with 1.2 to 6.0 % for offshore sediments, and between 0.02 % (Herepuru Stream) to 10.6 % (Pikowai Stream) in the streams. The overall trend is an increasing abundance of heavy minerals from the Waihi estuary towards Otamarakau, culminating in a peak at Hauone. Towards Matata abundances decrease with small peaks where streams contribute to the beach sediments, such as the Pikowai and Mimihia streams. The influence of the Tarawera River in terms of the large amounts of sediment delivered to the beach system is shown by the increase in heavy minerals near its mouth. Similarly the offshore sediments in this region have relatively high heavy mineral contents. An abundance or increase in heavy minerals at a particular beach locality may infer erosion as opposed to an input of sediment from a stream or other source. For example the peak just north-west of Matata in the vicinity of the old sand extraction site, is probably due to wave focussing at this point, shown to occur by Healy (1989) and Dunbar (1989), dependant on wind, wave and beach conditions.

6.3 Carbonate %

6.3.1 Beach

Figure 6.4 shows the alongshore variation in the percentage $CaCO_3$ in the beachface sediments. Overall the beach sediments exhibit low carbonate levels of between 1.1 to 5.3 %, comparable to values found by Bradshaw (1991) for eastern Coromandel. In relation to shellfish numbers in the study area, the Bay of Plenty Regional Council's Coastal and Estuarine Ecology Monitoring Programme (1990/91) recorded the lowest mean species richness, for open sandy coasts in the Bay of Plenty, at beach sites between Pukehina and Thornton (BOPRC, 1993). This is believed to be a combination of coarser sediments and a steeper beach gradient resulting in a harsh, high energy environment, which places a limitation on the number of species which can survive there (BOPRC, 1993). This is consistent with the lower carbonate content found in the coarser surficial sediments in the south-eastern sector of the study area from Hauone to Matata, and may also be due in part to the constant addition of fluvial material within this area.

The trends in % carbonate in the beach sands show an inverse relationship to mean grain size, with relatively higher percentages from the Waihi estuary to Otamarakau, and a marked decrease towards the Tarawera River, reaching a low at Kohioawa Beach north of Matata. This agrees with a shellfish species diversity and abundance limited to a certain extent by the sediment texture.

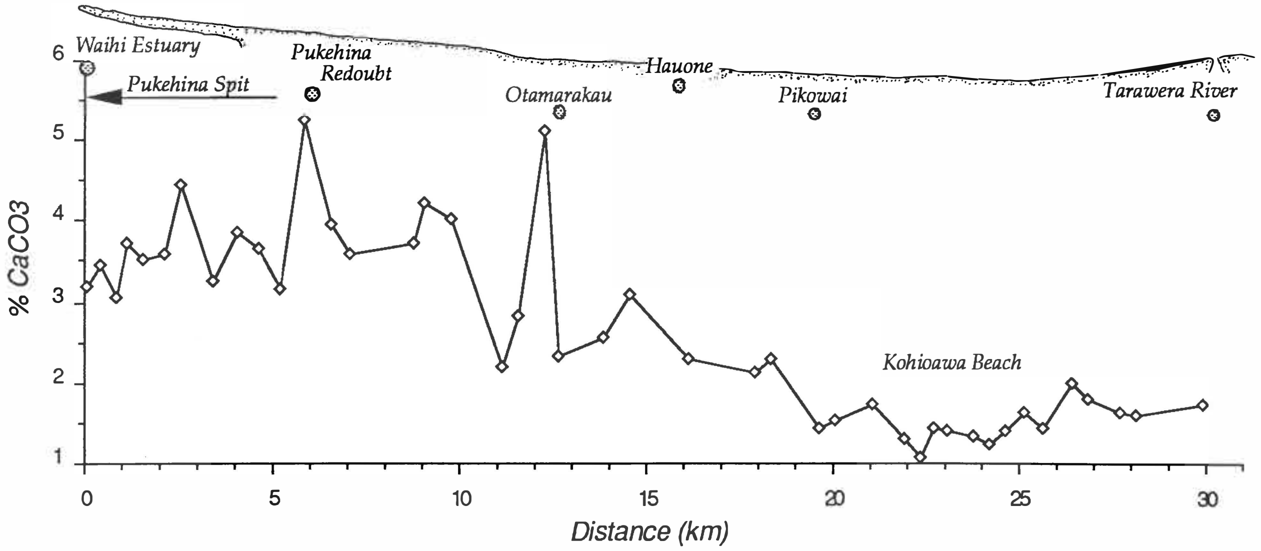


Figure 6.4 Carbonate content in beachface surficial sediments along the Pukehina-Matata coastal sector, showing higher levels from Pukehina to Hauone and contrasting low values in the southern part of the study area from Pikowai to the Tarawera River mouth.

Bradshaw (1992) found that for the barrier spit beaches of the eastern Coromandel, such as Waihi and Pauanui carbonate levels were in the vicinity of 5 to 8%, except where offshore reefs or islands occurred. It appears Pukehina Spit is similar with higher amounts of carbonate on the barrier spit compared with the open sandy beaches to the south. From brief inspections of the foreshore study area the shell species in the region from Town Point to Otamarakau are much more varied and in

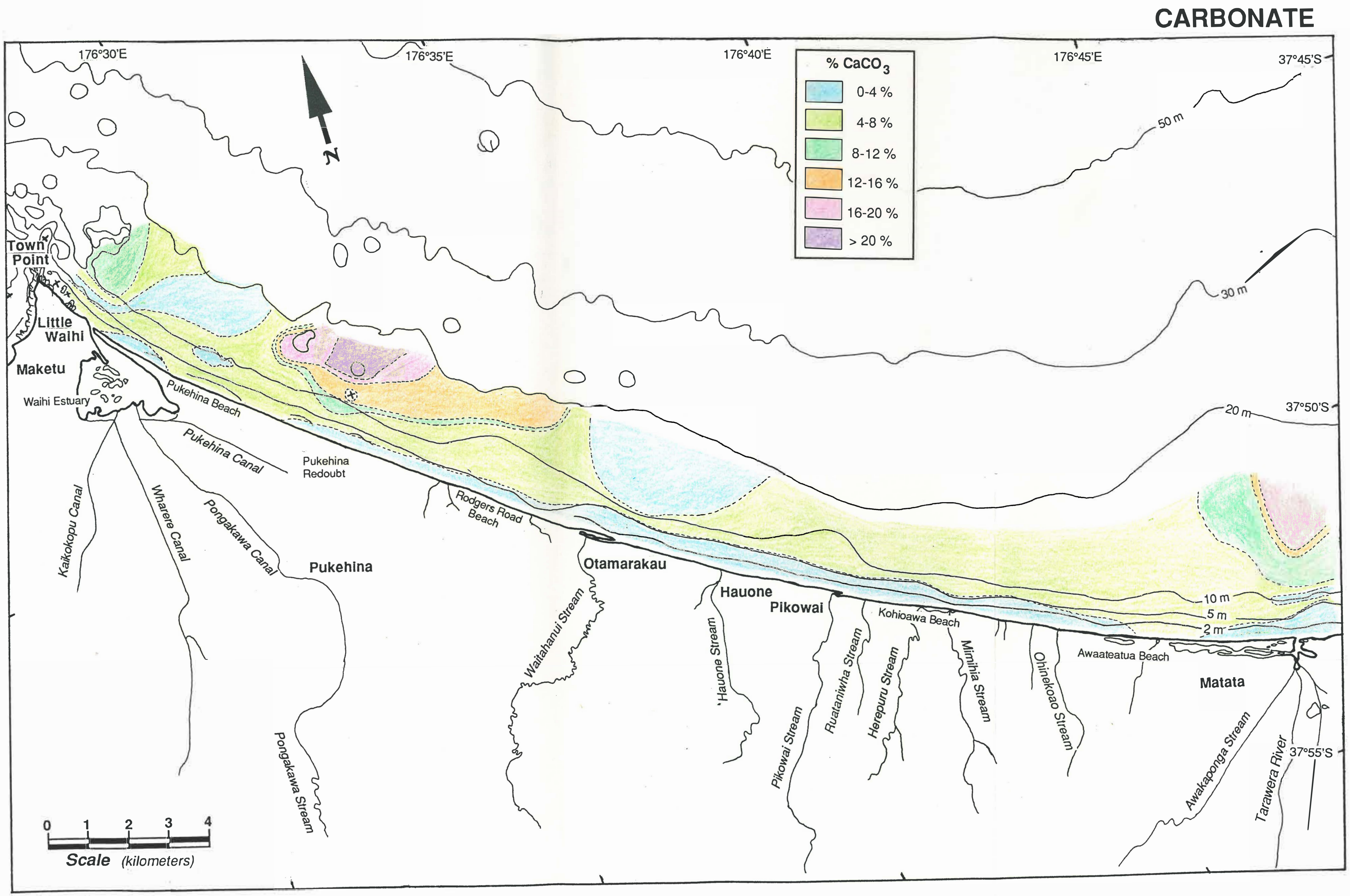


Figure 6.4 The nearshore carbonate pattern for surficial sediments in the Pukehina-Matata coastal sector.

greater abundance than for the area to the south. This appears to be due to the Waihi estuary contributing pipis (*Paphies australis*), and cockles (*Chione stuchburyi*) to the beach system, and the nearshore submerged rocks in the area which provide a habitat for species not found in the coarser sand beaches towards Matata.

6.3.2 Nearshore

The area around Waihi estuary and Town Point rather surprisingly has little carbonate material, with two localities offshore from the Pukehina Redoubt and the Tarawera River, the only areas of significantly higher $CaCO_3$ levels (Figure 6.5). The first may have a higher amount due to the presence of a reef indicated on hydrographic charts (NZ 541), which would allow for more abundant amounts of epifauna to live on the rocky substrates and then be incorporated into the sediments of this area. The second region around the Tarawera River mouth consists of shell hash material which appears to be considerably less bioeroded and weathered than the shell material found offshore between Otamarakau and southern Pukehina. The lack of significant carbonate material around Town Point is more surprising due to both its close proximity to the Waihi estuary and the common occurrence of boulder reefs and associated rocky substrates. It is probable that the coarser grain size within this nearshore region limits species abundance, and/or this area is contributing to the littoral sediment budget and is not stable enough to permit great amounts of colonisation by marine organisms.

6.4 Results of Mineralogical Analysis

The major components identified in the light fraction were plagioclase feldspar (predominantly albite), volcanic glass, quartz, and lithic fragments. The heavy minerals are dominated by hypersthene, and in some samples opaque minerals (those minerals which appear black when viewed in thin section under plane polarised light). Other heavy minerals identified include augite, green hornblende, brown hornblende, biotite, cummingtonite, apatite, zircon, olivine, and aegerine. These results are consistent with the sand mineralogy for nearby Maketu estuary, which is dominated by minerals of volcanic origin (Murray, 1978), and contains geologically similar sediments to the Pukehina-Matata coastal sector. The most common minerals found were volcanic glass, quartz and plagioclase, with lesser amounts of hornblende, augite and hypersthene (Murray, 1978).

Table 6.2 Physical Properties of the Pukehina Beach to Matata Mineral Components. (A) Light minerals, (B) Heavy minerals. *(source: Denham, 1960, and Allaby and Allaby, 1991)*

Mineral	*Hardness*	*Specific Gravity* (kg/m^3)	*Crystal Form*
(A)			
Quartz	7	2.65	hexagonal prisms, but poor cleavage
Rhyolitic Glass	-	2.3	structureless; granular
*Alkaline Feldspar**	6	2.6	stubby to elongate prisms
*Plagioclase Feldspar**	6-6.5	2.6-2.75	bladed to tabular

(B)			
Hypersthene	5-6	3.5	large, tabular, elongated
Augite	6	3.3	small to med., stubby prismatic-granular
Aegerine	6	3.5	small, prismatic
Hornblende	5-6	2.9-3.3	medium, columnar-bladed
Cummingtonite	5.5	3.3	large to medium, bladed
Biotite	2-3	2.7-3.3	large to medium, flaky cleavage
Magnetite	5.5-6.5	4.9-5.2	small, granular
Ilmenite	5-6	4.5-5.0	small, tabular
Apatite	5	3.1-3.3	v. small, hexagonal needle-like prisms
Zircon	7.5	4.6	small, prismatic
Olivine	6-7	3.2-4.4	prismatic to granular

* Feldspars are divided into two main solid solution series: alkaline feldspars (K-feldspar to Na-feldspar; and plagioclase feldspars (Na-feldspar to Ca-feldspar). The plagioclase series is: Albite (Na-feldspar) occurring in acid igneous rocks, Oligoclase, Andesine intermediate igneous rocks, Labradorite basic igneous rocks, and Anorthite ultrabasic igneous rocks and metamorphosed limestones (Allaby and Allaby, 1991). They can be distinguished under thin section from alkali feldspars by crystal twinning. The main alkali feldspar is orthoclase (K-feldspar), present in acid plutonic rocks and metamorphics, although anorthoclase occurs in acid volcanics (Deer *et al.*, 1966; Briggs, 1988).

Comparison of the mineralogy of various pumiceous lithologies within the Matata-Otamarakau coastal cliffs (Healy and Ewart, 1965), shows a dominance of glass, with crystals of plagioclase, quartz, hornblende, magnetite, and hypersthene in decreasing abundance (Table 6.3). The pumiceous sediments analysed from the cliffs lie geologically between marine sandstone strata and Late Quaternary tephras. As much of the Pukehina-Matata coastal sector is composed of the sediments found in these coastal cliffs, the mineralogy should at least typify the general geology of the pumiceous lithologies in the region.

Table 6.3. Modal analyses of pumice samples from coastal cliff deposits in the Matata-Otamarakau region. (modified after Table B-I, Healy and Ewart, 1965). Where LWF= Little Waihi Formation, UPD= Undifferentiated Pumiceous Deposits, MIgn.= Matahina Ignimbrite; tr= trace.

Collection Locality *	*Equivalent Unit Lithology*	Glass	Quartz	Plagio-clase.	Hyper-sthene.	Horn-blende.	Mag-netite.	Total crystal content
Member e	upper LWF	86.1	6.0	7.0	<0.1	0.7	0.2	13.9
Member g	mid LWF$^{\infty}$	83.0	2.6	13.3	<0.1	0.9	0.2	17.0
Member h1	mid LWF	88.1	2.0	8.8	<0.1	0.9	0.2	11.9
Member h2	mid LWF	84.9	4.7	9.0	-	0.9	0.5	15.1
Member i$^{\#}$	lower LWF	99.7	-	0.3	-	-	tr	0.3
Member k1	upper UPD	99.2	-	0.8	-	-	<0.1	0.8
Member m	distal MIgn.	94.8	0.4	4.4	-	0.4	<0.1	5.2

** As referred to in Figure 2.4 (Chapter 2), $^{\infty}$ redeposited unit, $^{\#}$basal lapilli.*

6.4.1 Light Minerals

The major light mineral in the beach-nearshore sands is plagioclase, with varying amounts of quartz, glass, alkaline feldspar, and lithics (Figure 6.6), relating to the volcanogenic sources of sediment for various parts of the shoreline. The shoreline distributions of the various light minerals are given in Figure 6.7, along with a cubic or quadratic curve of best fit. The best fit curves tend to simplify the actual situation, and suggest that coupled with the dynamic nature of the

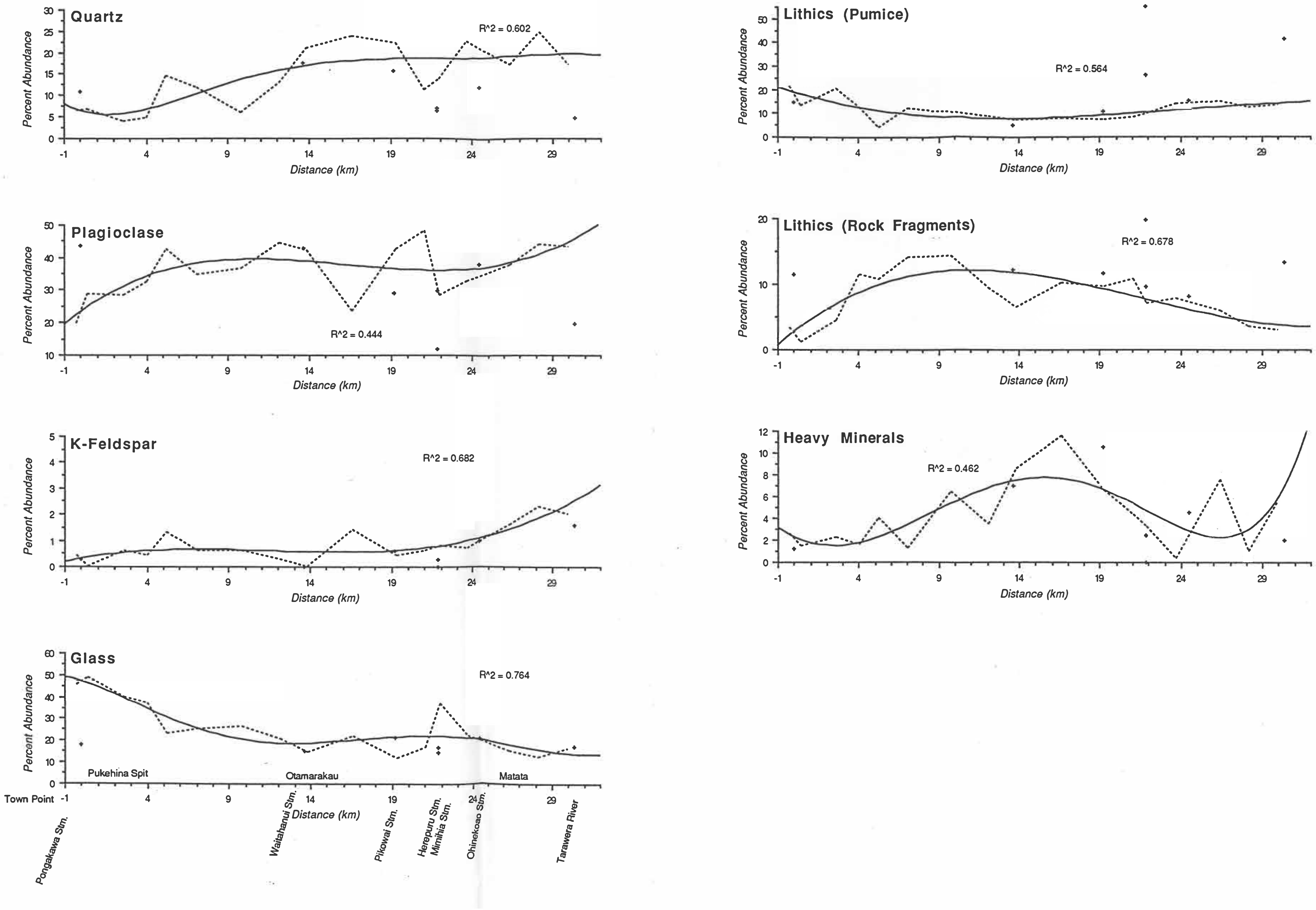
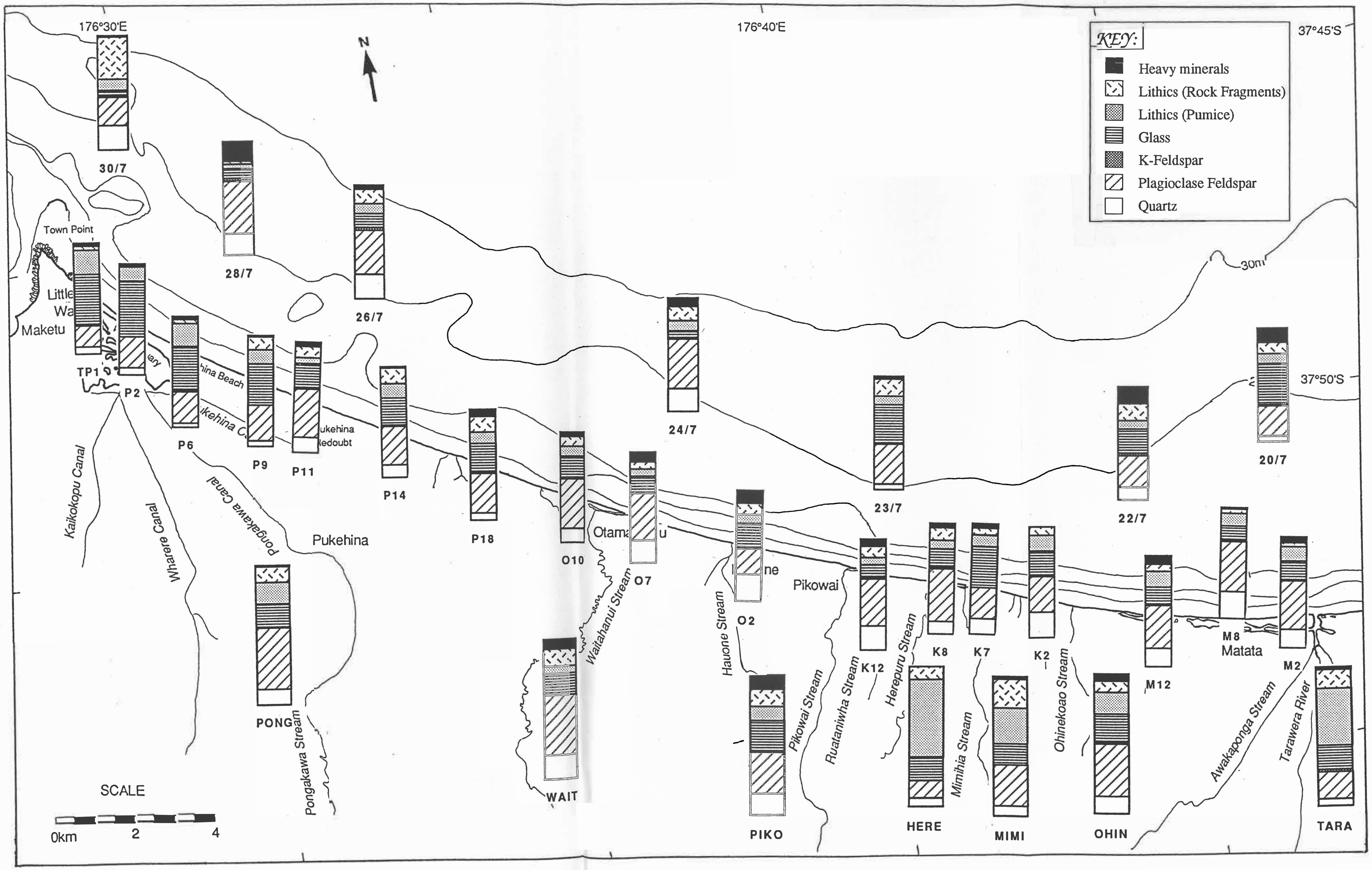


Figure 6.6 Alongshore bulk mineralogy plots of selected beachface surficial sediments within the Pukehina-Matata coastal sector. Crosses denote representative stream values. Also given is a cubic or quadratic line of best fit through the data points, indicating the simplified trends of increasing or decreasing mineral content.



Light Mineralogy

Figure 6.7 Detailed light mineralogy of selected samples for the beach-nearshore system of the Pukehina-Matata coastal sector, samples as for Figure 6.2.

coastal environment there are several point and line sources for each mineral, rather than a single point source, in which a linear line of best fit would be more applicable. Additionally the dominance of a particular mineral species, results in lower amounts of all other light mineral components. For example the lack of plagioclase and quartz along Pukehina Spit is probably an artefact of the high amounts of volcanic glass, although it is possible that there is a relatively smaller sediment input to the beach system in this area of these minerals.

The shoreline distributions of quartz, plagioclase feldspar, and alkaline feldspar exhibit a generalised increase in percent abundance from Town Point to the Tarawera River. Quartz shows significant input from the Waitahanui and Pikowai streams, and the Tarawera River. The peak corresponding to the Pukehina Redoubt area is probably due to sediment input from pumiceous and conglomeritic reefs and outcrops offshore in 10-20m water depth (Chapter 8). The low quartz abundance on the Pukehina Spit may be due to either little input of quartz containing sediment, and/or the abundances are masked by the large amounts of pumice and volcanic glass also present.

Plagioclase feldspar exhibits a similar trend to quartz except that there are high amounts of plagioclase along the beach in the north from the basal end of Pukehina Spit to Otamarakau. The large amounts of plagioclase are consistent with sediment derivation from the Okataina Volcanic Centre whose eruptives constitute the majority of the study area. Sources are therefore numerous, although there is a large input from the Tarawera River in terms of the volume of sediment delivered to the coast (Chapter 9).

K-Feldspar is in low abundance along the entire area due to it being derived predominantly from igneous plutonic and metamorphic rocks, which very rarely occur in the local geology. The main source is indicated as the Tarawera River, although some minor input does appear to come from the Hauone, Pikowai and Ohinekoao streams, and possibly the submarine outcrops offshore from the Pukehina Redoubt.

Glass shows the opposite trend to K-feldspar with a general decrease from Town Point to the Tarawera River mouth. The peak at the Herepuru/Mimihia stream mouth may be related to the large volumes of pumice in the Herepuru Stream. The predominance on Pukehina Spit is possibly due to pumiceous sediments being brought onshore from offshore submarine erosion, and from fluvial input of sediments carried out of the Waihi estuary. Since glass is soft and therefore rapidly degrades in the littoral zone, a constant sediment input must be occurring from a local source in the Pukehina Spit area. However at the time of sampling the beach was in a well developed accretionary phase, with low wave energy which would have caused the glass (and pumice) to be degraded rather less than normal, with a higher proportion of the glass material remaining on the beach rather than being carried offshore.

Glass constitutes a large proportion of the minerals in the geologic materials of the Pukehina-Matata area (Table 6.3), and is therefore a major component of the beach-dune-nearshore sediments, even allowing for the significant amounts which are rapidly weathered out of the littoral zone. However as implied shown by Figure 6.8, glass is expected to be more abundant in the finer grained sediments along Pukehina Spit.

Pumiceous sediments comprise much of the hinterland, consisting of the Rotoiti Breccia, late Quaternary tephra deposits, Little Waihi Formation, and undifferentiated pumice deposits, which are easily eroded and abundant in the stream sediments. The pattern of shoreline distribution is similar to glass, with much of the pumice material rapidly degraded into fine sediments and transported offshore.

Rock fragments are low along Pukehina Spit, with a large peak at the Redoubt-Otamarakau region and a steady decrease towards the Tarawera River, although the Pikowai Stream in particular supplies some rock fragments to the beach.

The heavy mineral trend shown is similar to that determined from the general sediment compositions determined by weight (Figure 6.3) with a main peak in the Otamarakau-Hauone area. This indicates a possible source from the Waitahanui, Hauone, and Pikowai streams, or erosion associated with natural processes such as wave focussing. Alternatively it may represent the effects of sand mining at Otamarakau failing to replenish the downdrift region of the study area. The peak at Matata may similarly represent the effects of previous sand extraction, although this ceased some 5 years before sampling and is more probably due to wave focussing which is known to occur at this site (Healy, 1989). The other smaller peaks at Rodgers Road and Pukehina Redoubt are consistent with the ideas formulated using the McLaren model in section 5.7.2, of sediment source regions for other parts of the beach.

6.4.1.1 Ratios of Bulk Mineral Contents and Grain Size Ratios

Mineral contents, as suggested above, may be effected by the grain size distributions of the surficial sediments (Griffith, 1967). Figure 6.8 shows that there is a strong linear relationship between mineral abundances and the sediment grain size for most of the minerals. Quartz abundances increase as the mean grain size becomes *coarser*, whereas glass shows a corresponding increase as the grain size becomes *finer*. Other weaker relationships are apparent for plagioclase feldspar, K-feldspar, and heavy minerals which all increase as the grain size becomes coarser, while pumice shows a similar but weaker trend to glass. Rock fragments appear to be the exception and have no relationship to mean grain size.

Given the above the trends, the alongshore ratio of mineralogical abundance to mean grain size was determined (Figure 6.9). The alongshore trends again infer sediment input from fluvial sources, indicated by the fluctuations in the ratio of mineral % to grain size.

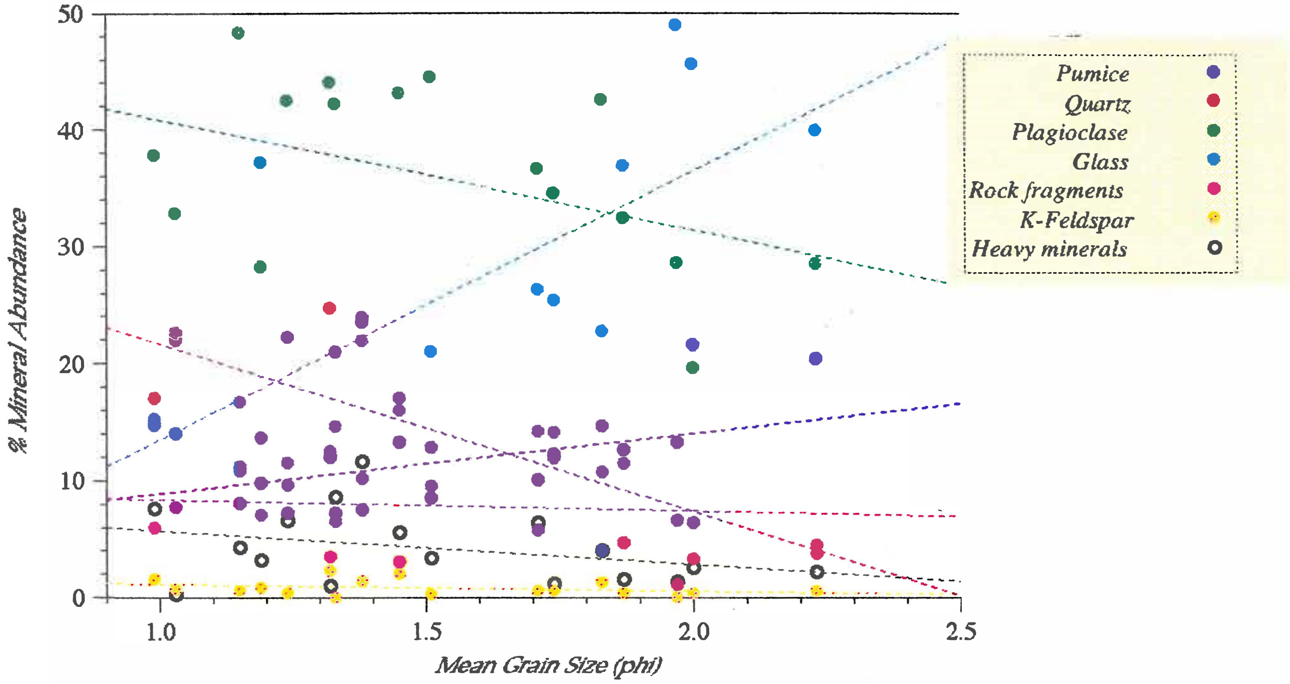


Figure 6.8 Plot of percentage mineral abundance against mean grain size for the bulk mineralogy components of the surficial beachface sediments. Also given are the linear lines of best fit (same colours as for samples), showing a strong trend of increased glass content in the finer grained sediments, and higher quartz in the coarser grained sediments, reflecting both the source and contrasting weathering of these minerals.

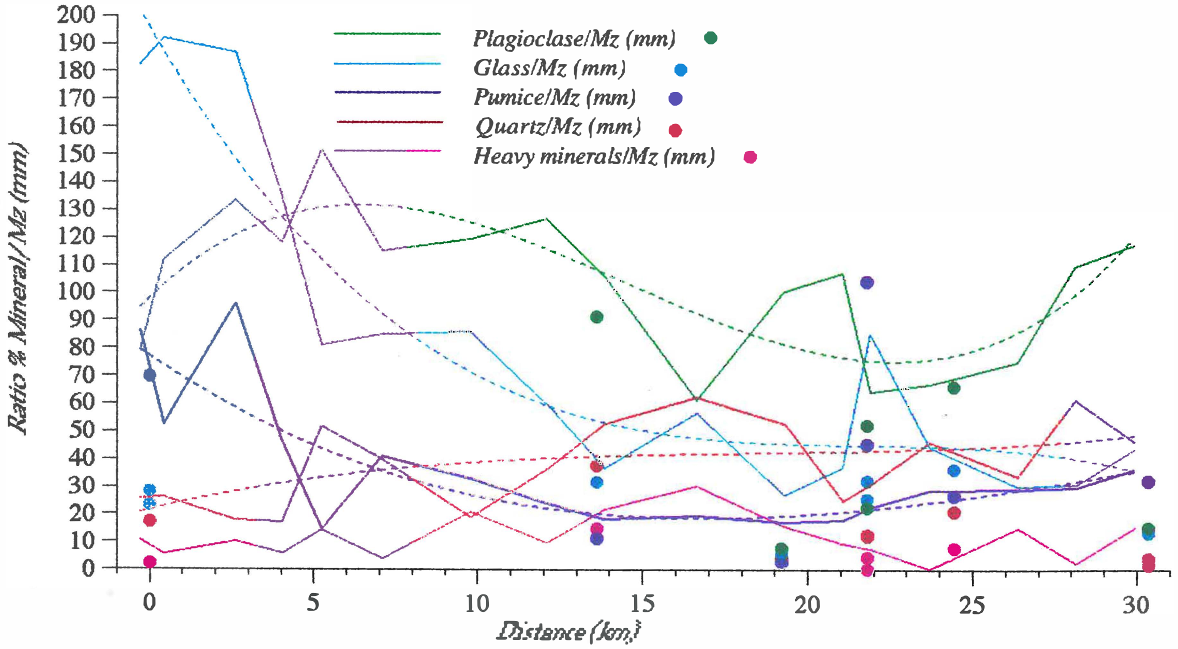


Figure 6.9 The alongshore ratio of bulk mineral content to mean grain size in surficial beachface samples of the Pukehina-Matata coastal sector. The coloured circles correspond to stream values, showing their relative sediment contributions to the beach system.

Pumice and glass are easily transported due to their light densities, and are degraded rapidly in the littoral zone. The relatively high amounts found along Pukehina Spit are probably due to marine erosion of exposed outcrops such as those found in the Pukehina central to Redoubt region in 10-20 m water depth (see Chapter 7), where the sediments are often pumiceous and poorly consolidated. This material is brought onshore, especially under accretionary wave conditions as observed from field evidence, and deposited on the beach. The lack of onshore input of other minerals such as plagioclase could therefore be partly explained by the nature of the nearshore submarine outcrops, with little plagioclase and quartz crystals contained in these pumiceous sediments. Murray (1978) concluded that the glass and pumice-rich sediment of Maketu estuary is most probably derived by erosion from the Little Waihi Formation on the Town Point peninsular, and brought into the estuary by wave and current action.

6.4.2 Heavy Minerals

The heavy mineral suite that occurs in the sediments of the Pukehina-Matata region are typical of the Taupo Volcanic Zone eruptives, particularly those from the Okataina volcanic centre (Lowe, pers. comm., 1993). For the beach system, heavy mineral abundances should decrease in a downdrift direction from source, given that no additional sources add those minerals to the beach. Where this occurs the heavy mineral examined should show a peak in concentration. However the addition of other heavy minerals may act to 'dilute' the tracer mineral being examined such that the suggested alongshore transport patterns are no longer indicative of source.

Heavy mineral abundances are highest in beach sands in the centre of the study area, particularly from the region of the Pikowai Stream to the Tarawera River mouth, and may reflect the high heavy mineral concentrations in the Pikowai Stream, and localised erosion of the dune-beach system. In the Pukehina Spit area heavy mineral percentages are low, with a contrasting dominance of pumice and volcanic glass, which is suggested in part as due to the absence of significant fluvial input. Offshore and nearshore samples show reasonably uniform heavy mineral percentages along the entire coast (Figure 6.10).

The trends observed in each heavy mineral species is discussed below in relation to their alongshore concentrations and stream abundances (Figure 6.11).

6.4.2.1 Pyroxenes

6.4.2.1.1 Hypersthene

Overall hypersthene is the most abundant heavy mineral in the sediments of the Pukehina-Matata coastal sector. It tends to exist as large, partly rounded, elongated crystals in the river sands, dominating the mineralogy of all streams and rivers with the exception of the Herepuru Stream, which has a very low heavy mineral content (0.02 %). The shoreline distribution pattern (Figure 6.11I) shows high concentrations near the Waitahanui Stream, and offset peaks to the south-east

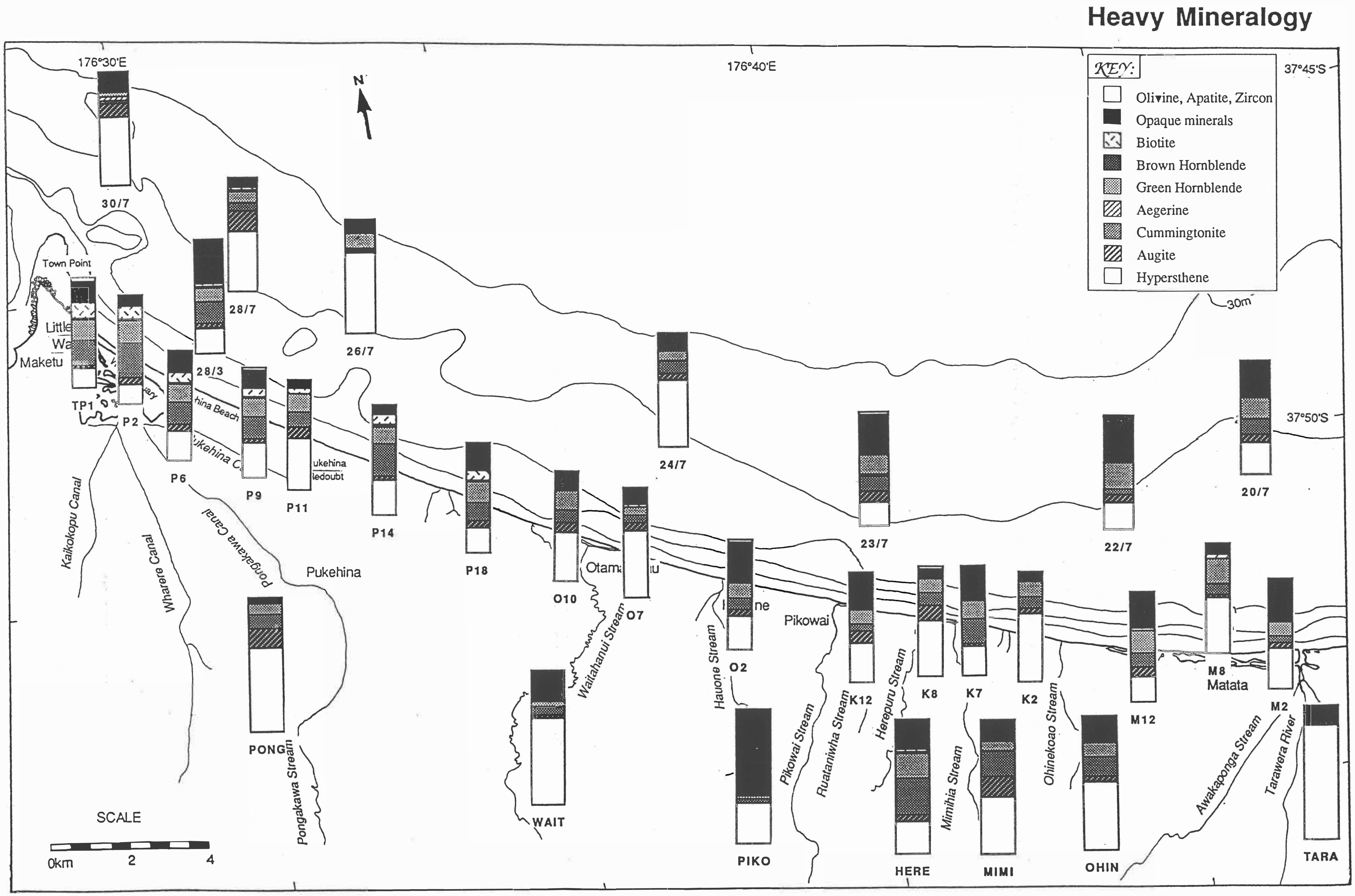


Figure 6.10 Detailed heavy mineralogy of selected samples for the beach-nearshore system of the Pukehina-Matata coastal sector, samples as for Figure 6.2.

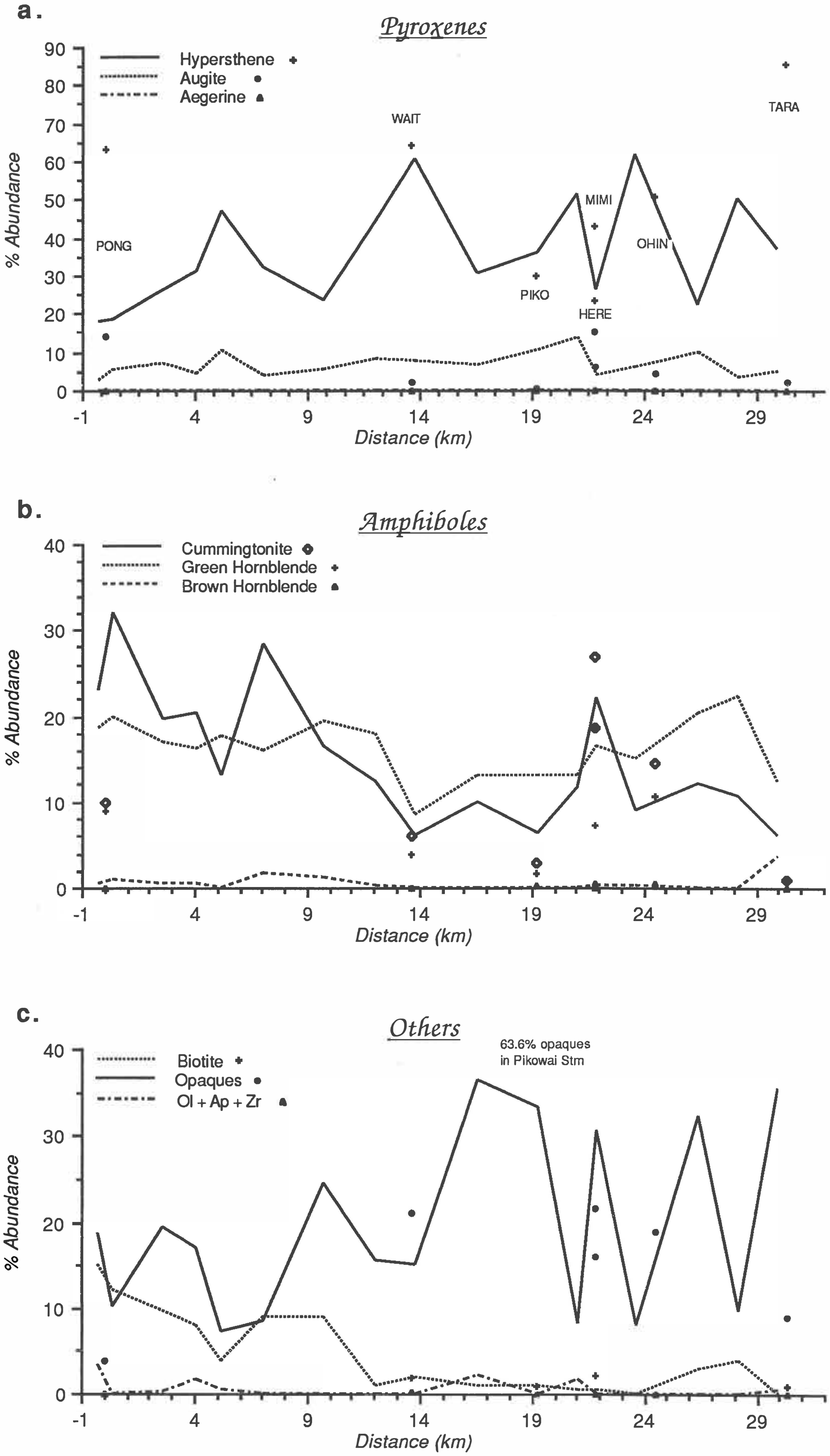


Figure 6.11 Heavy mineral alongshore surficial sediment contents for each of the three heavy mineral groups, along with stream and river values, denoted at their coastal outflow point with the appropriate key symbol.

of the Pikowai and Herepuru/Mimihia streams. These directions are assumed based on the relative sediment loads of these larger streams which have at least three to four times the sediment loads of the Ohinekoao and Hauone streams (Chapter 9).

Even though hypersthene does not travel as well in the littoral system as amphiboles, due to the nature of its crystal habit, the hypersthene pattern infers sediment movement towards the south-east. The lack of offsetting at the Waitahanui Stream may be due to insufficient sampling detail, i.e. the main peak may occur between the Waitahanui and Hauone streams, or perhaps more likely at this point along the coast sediment transport is towards both the north and south in approximately equal amounts. Alternatively the amount of sediment moving along the beach within the littoral drift system may be small at this point.

Along Pukehina Spit the hypersthene values are approximately half that of the Kaikokopu and Pongakawa streams, whereas the stream values for other sectors of the coast show close agreement, this seems to suggest that there may by additional sources supplying sediment to the beach along Pukehina Spit such that the mineralogical proportions of the heavy minerals are altered.

6.4.2.1.2 Augite

Augite concentrations are fairly uniform along the beach, probably as a result of its granular, stubby nature and lack of any significant sediment source containing high augite abundances. Contributions to the littoral environment from fluvial sediment input is again evident with a similar offset pattern along the shoreline as that observed for hypersthene. The peak between the Pikowai and Herepuru/Mimihia streams is more probably due to the Pikowai Stream which although its augite concentration is small, the volume of sediment delivered to the beach and overall heavy mineral content is high relative to other streams. The peak in both augite and hypersthene at the boundary of the Pukehina Spit and Pukehina Redoubt (P11) is interesting since there is no fluvial influence. The augite peak may therefore be the result of onshore sediment movement from site 28/7 for example, which has a high augite percentage, or from cliff erosion of tephras in the vicinity of the Pukehina Redoubt.

6.4.2.1.3 Aegerine

Aegerine is limited exclusively to material erupted from Mayor Island, of which only one named tephra exists (Tuhua Tephra) (Froggatt and Lowe, 1990). Hence, aegerine is a scarce component and is found only at trace amounts in five offshore samples.

6.4.2.2 Amphiboles

6.4.2.2.1 Cummingtonite

Cummingtonite has a bladed elongated crystal structure which makes this mineral a particularly good traveller, reflecting the sediment dynamics of the area perhaps better than other heavy minerals. Cummingtonite accounts for between 6 to 32 % of the beach sand heavy minerals, with greatest concentrations in the Pukehina-Otamarakau region. The alongshore trend infers input from the Pongakawa and Kaikokopu streams, and input from the Herepuru Stream towards the southeast. The peak in concentration between the Pukehina Redoubt and Rodgers Road may be due to addition from the tephra outcrop in the Redoubt area and erosion and onshore transport of sediments from submarine reefs in the area, or less likely it may infer input from the Waitahanui Stream with a concentration to the north of its source due to alongshore transport.

6.4.2.2.2 Hornblende

Green hornblende is a common component of the beach sands with traces of brown hornblende (oxyhornblende) occurring in some samples. The pattern of shoreline distribution for green hornblende is more uniform in the Pukehina-Otamarakau area compared with cummingtonite, with a similar trend from Otamarakau to the Tarawera River mouth. Most of the hornblende is suggested as supplied by the Pongakawa, Waitahanui, Herepuru, Mimihia, and Ohinekoao streams.

6.4.2.3 Other Heavy Minerals

In addition to pyroxenes and amphiboles, the other heavy mineral species found were principally biotite and the opaque minerals, with traces of olivine, zircon, and apatite in some sediments.

6.4.2.3.1 Biotite

Biotite is somewhat limited to the beach and nearshore system along Pukehina Spit and southern Town Point suggesting that the source of this mineral is not from the beach system to the south, as it occurs here only in trace amounts or commonly not at all in the beach and nearshore sediments. This reflects the spatial occurrence of biotite-containing tephras exposed in the hinterland (Table 6.4). The tephras (airfall deposits) within most of the Pukehina-Matata area are almost exclusively derived from the Okataina volcanic centre, with biotite containing tephras occurring mostly between Town Point and Otamarakau.

Hence the most likely source is from the streams feeding the Waihi estuary. The Kaikokopu Stream contains about 8 % biotite, however the Pongakawa Stream has only a trace amount of biotite in the stream sediments. Hence additional sources of biotite may be present which indicate sediment input to the Pukehina region:

(i) Offshore, unlikely since the concentrations offshore are small by comparison, and biotite has a flaky structure so would disintegrate easily.

(ii) Cliffs at Town Point, composed of the Little Waihi formation (Chappell, 1975) and overlying tephras, both of which are similar to that found on the southern tip of nearby Motiti Island (Table 6.4). The cliffs at Town Point are fairly extensive and composed of easily eroded pumiceous material which may supply some sediment to the beach system. Additionally some of the tephras deposited at Town Point such as the Rotoma and Whakatane do contain biotite (Henry, 1991, Chappell, 1975).

(iii) An updrift source, contributing to the littoral system. A possible source would be the Kaituna River, near Maketu. Further heavy mineral analysis was undertaken to provide evidence either for

or against this idea. The Kaituna River does flow through the weakly to non-welded Mamaku Ignimbrite which contains 1 % biotite by bulk (Fransen, 1982) and in terms of heavy minerals would possibly be a large contributor to the littoral system. Analysis by the same methods outlined previously revealed 3.0 % biotite in the Kaituna River which has its coastal outlet at the Kaituna cut (sited approximately 10.2 km, in terms of shoreline perimeter, to the north-east of the Waihi estuary inlet). The river also contained lesser amounts of hornblende, cummingtonite and hypersthene, with 67 % opaque minerals.

(iv) Cliffs at Pukehina Redoubt. At this locality the beach is periodically actively interacting with the cliff material, c.f. between Otamarakau and Matata. The cliff section is composed of late Quaternary tephras, Rotoiti Breccia, brown deeply weathered ashes (Hamilton Formation) and Mamaku Ignimbrite. These all contain some biotite which may be delivered to the Pukehina Redoubt and Spit area. The volumes of sediment available from these cliffs is estimated as extremely small, and is therefore not considered a major possible source.

Table 6.4 Significant (>10cm thickness) known and/or observed Late Quaternary tephras, and their ferromagnesium mineral assemblages for parts of the Pukehina-Matata coast.

Named tephras (oldest to youngest)	*Motiti Island (Town Point)*[1]	*Pukehina Spit and Redoubt to Otamarakau* [2]	*Otamarakau to Matata* [2]
Hamilton Tephra Formation (+bio)		✓	
Rotoiti Tephra [3] *(hyp+cgt±hbl)*		✓	✓
Rotoehu Ash (cgt+hyp±hbl)	✓	✓	✓
Matahi Tephra (hyp+hbl+bio)		✓	
Ngamotu Tephra (hyp+hbl±cgt±aug)	✓		
Maketu Tephra (hyp+aug±cgt±hbl)	✓	✓	
Omataroa Tephra (hyp+hbl+aug±cgt)	✓		
Rotorua Tephra (hyp+hbl+bio)		✓	
Rotoma Tephra (hyp+cgt±hbl)		✓	✓
Whakatane Tephra (hyp+cgt±hbl)		✓	✓
Kaharoa Tephra (hyp+hbl+bio)		✓	✓

1 From Henry (1991) for late Quaternary tephras identified on the southern tip of Motiti Island which is suggested as composed of similar if not identical material to Town Point (Henry, 1991; Healy *et al.*, 1964).
2 Based on field observations, maps and references to sites in Nairn (1972), Healy and Ewart (1965), and Pullar and Billing(1973).
3 The Rotoiti Tephra Formation comprises the Rotoiti Breccia, Rotoehu Ash and Matahi Tephra (Froggatt and Lowe, 1990).

6.4.2.3.2 Olivine

The appearance of traces of olivine in the Waitahanui and Hauone streams and in two beach samples near Otamarakau is interesting, and is inferred to have been derived from erosion, within the Waitahanui Stream catchment, of the Rotorua ash formation which contains small amounts of olivine (Lowe pers. comm., 1993). Similarly the olivine in the beach sediments at Town Point (1.3 %) suggests some sediment is derived from the Town Point cliffs.

6.4.2.3.3 Opaques

The opaque minerals, having been derived from TVZ eruptives, are probably mainly magnetite and/or titanomagnetite with small amounts of ilmenite (Bradshaw, 1992). The opaque minerals due to their high specific gravity tend to become concentrated in more erosive parts of the beach, as the lighter minerals are preferentially removed from the beachface during erosional events. Similarly they may also become concentrated on the beach at or very near to source. Opaques are present in sizeable quantity in all the streams. Substantial opaques occur in the sediment load of the Pikowai Stream (64 %), accounting for the large peak in concentration between Hauone and Pikowai. Most of the shoreline distribution of opaques shows concentrations at stream or river mouths. Exceptions to this are north-west of Rodgers Road, central Pukehina Spit, north of Matata, and possibly Hauone, all areas of the shoreline shown in Chapter 5 to be possibly erosive or sediment source regions, particularly the area immediately north-west of Rodgers Road.

The pattern of peaks in heavy mineral abundances along Pukehina Spit and Redoubt may also reflect wave refraction and wave focussing along this sector, resulting in a build-up of the lighter heavy minerals such as cummingtonite, augite, biotite, and hornblende at areas of lower wave energy. Also as shown mineralogy is dependant to an extent on sediment grain size, so for example the relatively finer sediment along Pukehina Spit indicates that greater abrasion, weathering, transportation, and sorting appear to have occurred in the Pukehina Spit sediments, or that they are derived from smaller grained terrigenous or marine sources. Some such information can be obtained by comparing not only the heavy mineral suites, but also the state of the heavy mineral crystals. Figure 6.12 shows the heavy mineralogy for two samples, P2 (northern Pukehina Beach) and K8 (Kohioawa Beach). The first grain mount consists of smaller crystals but the crystals themselves are very clean, with little of the apatite inclusions and roughness associated with the K8 sample. From the heavy mineral grain mounts the crystals in the Town Point and Pukehina Spit samples are all relatively clean, suggesting that they have not been in the beach system for very long. This provides further evidence that the sediments along Pukehina Spit are at least in part derived from cliff erosion of Town Point and offshore submarine outcrops, rather than from purely fluvial inputs.

6.5 Gravel Analysis of Swash Zone Sediments

In addition to the more detailed mineralogical examinations, the gravel fraction of the low tide swash zone samples ($> -1\phi$) were analysed under binocular microscope to determine the approximate percentages of the major constituents, particularly the greywacke content. From field observations the low tide swash zone is the zone which has the largest grain size, and dependant on beach state, can at times resemble a partly mixed sand-gravel beach in the northern parts of the study area, most notably the basal end of Pukehina Spit. Additionally the gravel size range had previously been removed for textural analysis by mechanical sieving, and this fraction is thought to contain material most recently eroded from source, particularly in cases of easily erodible and abraded

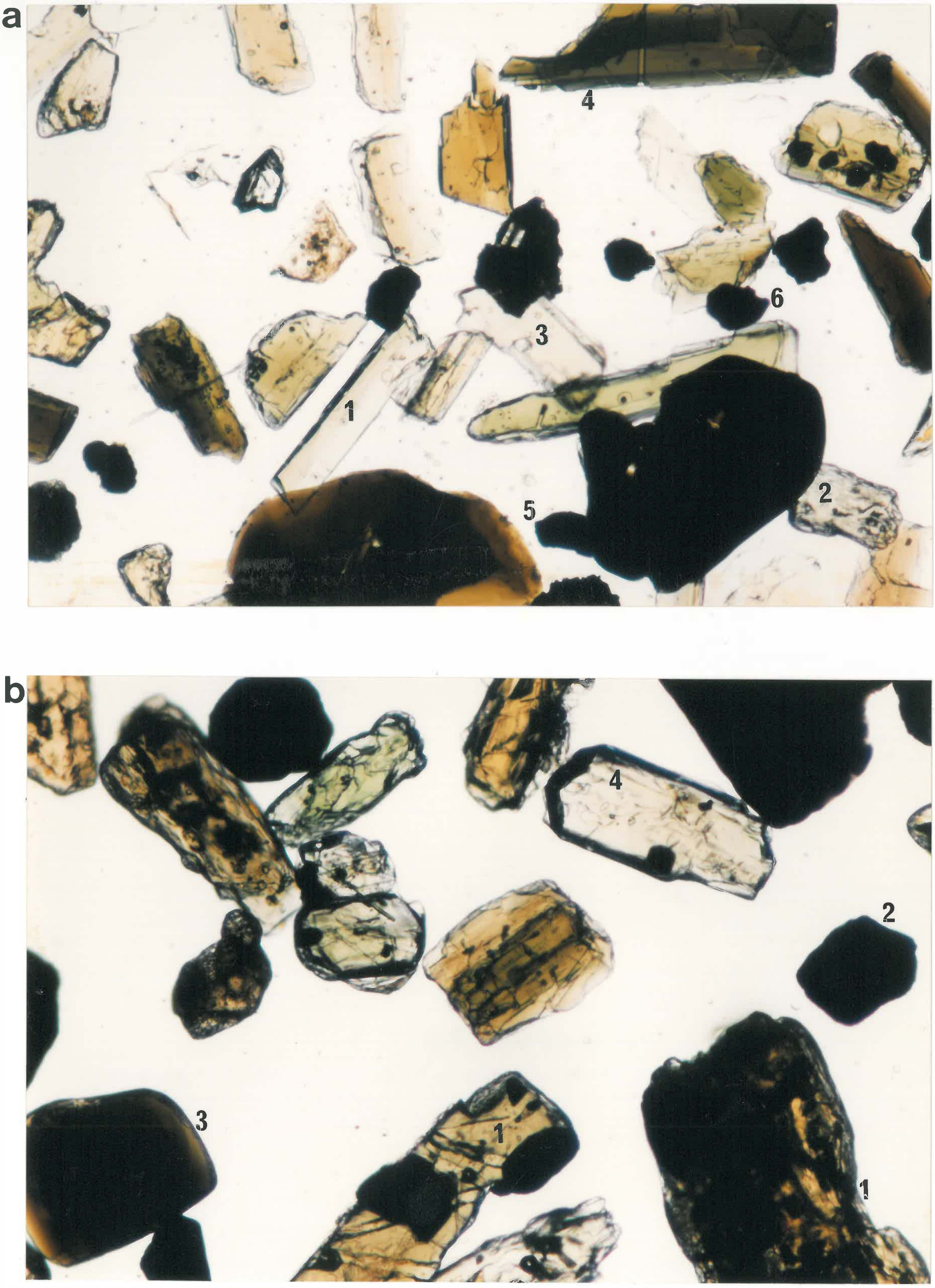


Figure 6.12 Photomicrographs of heavy mineral grain mounts under polarised light, for samples ***a)*** P2 (top), showing the presence of cummingtonite (1), augite (2), hypersthene (3), green hornblende (4), biotite (5), opaques (6). ***b)*** K8 (bottom), showing the presence of hypersthene (1), opaques (2), green hornblende (3), cummingtonite (4). Note in particular the fragmented and rough nature of the dominant hypersthene crystals in the bottom photomicrograph, which contain numerous apatite and opaque inclusions.

lithologies, such as pumice and ignimbrites. Moreover due to the relatively high proportion of gravel material in the Pukehina-Matata sediments compared with the rest of the Bay of Plenty coastline, analysis of this component of the beach sediments, which might be overlooked in mineralogical analysis of only the sand fraction, may prove helpful in determining sediment sources.

Some difficulty was encountered in differentiating between ignimbrite, conglomerate and rhyolite that occur in the sediments under the binocular microscope and hence all three are grouped together as 'ignimbrite'. The amount of each constituent in the samples was determined by both point counting and weighing, since the weight of each may be used to calculate volumes present.

Results of the shoreline distribution of gravel material are given in Figures 6.13a&b. Both counting and weight methods show similar trends although the weight method tends to show these trends more clearly.

The trend of abundance of large grains of quartz, feldspar, and glass is consistent with the detailed mineralogy showing these minerals increase in frequency towards the Tarawera River.

Scoria percentages exhibit a simple trend inferring a single point source rather than multiple sources as for the other mineral species. The source of scoria is predominantly derived from the Tarawera River, with the odd fragment found further north.

Table 6.5 Percentage abundance by weight of the major gravel sized components (> 1ϕ) in stream and river sediments within the Pukehina-Matata coastal sector.

River/stream	*Total Ignimbrite*	*Total Greywacke*	*Scoria*	*Pumice*	*Others- glass, quartz,feldspar*
Kaikokopu	91.8	0	0	4.2	4.0
Waitahanui 1	37.5	0	3.2	59.3	0
Waitahanui 2	89.5	0	2.8	5.1	2.4
Hauone	12.6	0.4	0.3	84.5	2.2
Pikowai	93.7	2.3	0.6	3.0	0.4
Herepuru	0.4	0	3.1	94.5	2.0
Mimihia	16.9	0	2.0	77.1	4.0
Ohinekoao	56.6	14.9	0	24.5	4.0
Awakaponga	52.0	37.6	0.2	9.8	0.4
Tarawera	12.3	0	26.0	56.0	5.7

From scoria and pumice abundances the apparent effect of the Tarawera River as a sediment source appears to be at least as far as six kilometres to the north-west (Awaateatua Beach). Healy *et al.* (1977) stated that the Matata sandmining site (BOPCES site 21), at M12 in this study, was replenished by both south-easterly littoral drift and the Tarawera River. However this depends

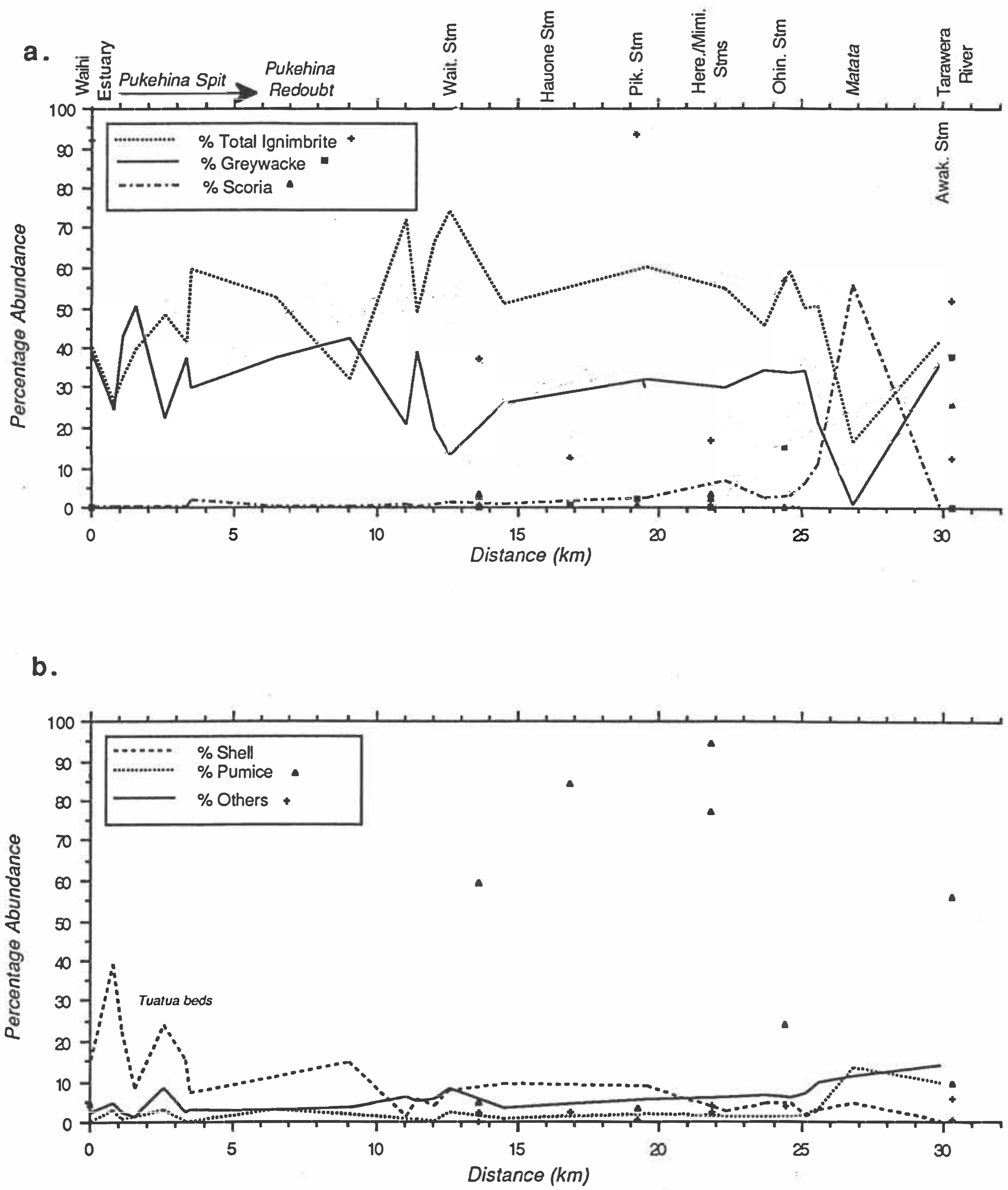


Figure 6.13 Shoreline compositional abundances in gravel-sized sediments of the low-tide swash zone, along the Pukehina-Matata coastal sector, determined by the weight of each mineral component. Stream and river values are denoted at their coastal outflow point with the appropriate key symbol.

greatly on antecedent beach state, wind and wave conditions, and the sediment capable of being transported. Being relatively light scoria (S.G.= 1.8) would travel further than denser lithologies under wave and current motion. A large concentration of both scoria and pumice in the gravel fraction occurs at site M11. Healy (1989) found that Matata experiences wave refraction and it is possible that this accounts for the concentration of 'lighter' fragments in a zone of wave divergence. Alternatively this site could be the leading edge of the Tarawera sediments dispersed from source under the wave regime at the time of sampling, with the lighter fragments grouped along these edges.

Ignimbrite, conglomerate, and rhyolite gravels are concentrated at southern Pukehina Spit and along the shoreline from Otamarakau to the Ohinekoao Stream, 3.5 km northeast of Matata. The concentrations in the latter section are most probably due to fluvial input, principally from the Waitahanui, Pikowai, Herepuru, and Ohinekoao streams. The low amounts of ignimbrite (and greywacke) near Matata is perhaps due to the large amount of scoria in the beachface sediments, rather than a sudden decrease in supply of these materials. Similarly the pattern along Pukehina Spit is affected to some degree by the greater amounts of shell material in the sediments. A significant number of cobble sized volcanic rocks occur along the foreshore at the basal end of Pukehina Spit, which correspond with the peak shown in Figure 6.13a. The source is suggested as the submarine rock outcrops offshore in 12-20m water depth which under a storm similar to the July 1978 storm (Hs= 9.9m) (Frisby and Goldberg,1983) could erode these outcrops and bring cobble sized material onshore, particularly since based on SCUBA observations these outcrops and reefs are predominantly conglomerates and poorly consolidated pumiceous sediments. Alternatively the local current patterns may transport material eroded from Town Point to this area, although the gravel material occurs much less frequently and in small amounts along the rest of Pukehina Spit, suggesting that little transport of the magnitude required to entrain gravel sized sediment occurs within the littoral zone between Town Point and the basal end of Pukehina Spit.

The greywacke distribution pattern is fairly uniform, with decreases in abundance where streams are adding volcanic derived materials to the beach system. Some greywacke is present in the Hauone, Pikowai, Ohinekoao, and Awakaponga streams. The quantity from the Awakaponga Stream to the beach system is extremely small, due to the small size of the stream and lack of any greywacke in samples from the Tarawera River into which the Awakaponga Stream flows. The source of greywacke at this stream is probably from marine sandstones exposed along the Whakatane fault through which the stream flows. The Hauone Stream greywacke is of granular size similar to the beach sediments, and as the stream originates within the isolated greywacke outcrops inland from Otamarakau this stream may be a source. Extensive searches by the author of the stream beds and river bar deposits of the Waitahanui and Hauone streams, which are suggested to perhaps receive greywacke material from outcrops in the hills inland from Otamarakau (refer geological map, Figure 2.1), failed to find any significant quantities of greywacke gravels. A few pebbles were found, suggesting that some greywacke can on extreme flood occasions potentially come from both these streams.

It is apparent that any greywacke contributions to the littoral system are minimal in comparison with other components, although as indicated from the nearshore zone light mineralogy in Figure 6.6, the less erodible lithologies tend to remain in the beach sediments whereas pumice and ignimbrite derived material is rapidly degraded and moved offshore. Thus the greywacke contribution may be greater than reflected in the stream sediments. From the data collected there appears overall to be no modern fluvial source large enough to account for the numerous greywacke pebbles found in the beach sediments (Figure 6.14).

The higher ratios of greywacke to ignimbrite (> 1.0) at Pukehina north, Pukehina south and Rodgers Road (from left to right) coincide with areas in which gravel patches periodically appear. Although at Pikowai and Kohioawa Beach where the ratio is also above 1:1, no true gravel patches were noted at any stage.

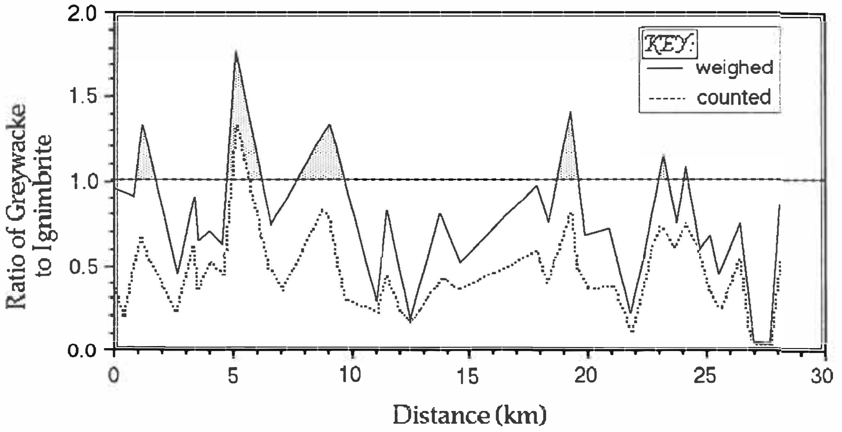


Figure 6.14 Ratio of greywacke to ignimbrite in the swash zone. Shaded areas are sections of the beach where the ratio is greater than 1, notably ***1.*** Pukehina north, ***2.*** Pukehina south-Redoubt, ***3.*** Rodgers Road, ***4.*** Kohioawa Beach-Pikowai, and ***5.*** Awaateatua Beach. The two alongshore distributions relate to the two methods applied, with the counted method the number of granules or pebbles of each constituent regardless of size, and the weighed method the weight of each constituent thereby taking into account the size and density of the gravels.

Based on Figure 6.14 it appears that the greywacke is fairly well distributed along the entire beach, making it difficult to infer a single source. Town Point, offshore from the Pukehina Redoubt and Kohioawa Beach are all possible inferred sources, and indicate that multiple sources. However field observations by the author of the cliffs at Town Point, revealed that the conglomerate layers within the cliffs have no significant quantities of redeposited greywacke pebbles, and the boulders at its base consist only of conglomerates, ignimbrites, and dark grey rhyolites. Due to the wide-spread distribution of the greywacke pebbles within the beach sediments of the Pukehina-Matata region, their roundness and reasonably uniform grain size, it is probable that the pebbles have been in the littoral system for some considerable time and that there is longer a significant modern source for them. These occurrence of greywacke gravel beds within the Pukehina-Matata coastal sector are suggested as lag deposits which are exposed when the overlying sand veneer is removed, and originate from marine cliffing of the Matata-Otamarakau-Pukehina Redoubt cliffs, which contain inter-bedded greywacke gravels.

6.6 Statistical Classification of Mineralogical Data

As a final part of the sediment compositional analysis, statistical grouping of the mineralogy data was undertaken, using the *Entropy* program (Chapter 5). Such statistical grouping of the sediments may allow for a simplified pattern of provenance.

Compositional data from both the bulk (light) and heavy mineralogical analysis were entered into the *Entropy* program. Results are shown in Figure 6.15, from which a classification of 7 groups explaining 68.2 % of the matrix variability was obtained. There are strong similarities in mineralogy between some of the entropy classes since the study area is constrained by similar geology, fluvial inputs, and sedimentation patterns, nevertheless there are slight significant differences which allow for the distinct groupings used.

Plots of the average values for minerals within each class are illustrated in Figure 6.16.

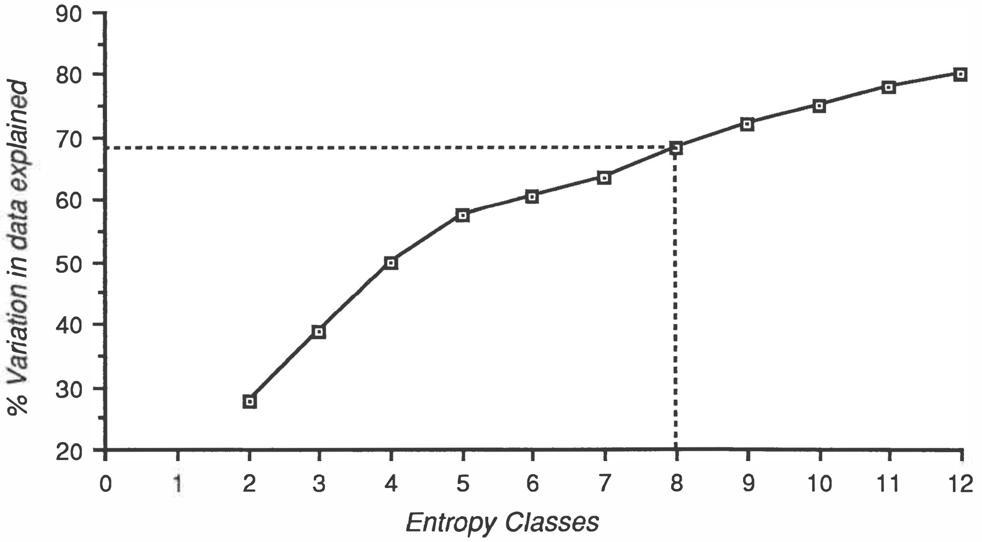


Figure 6.15 Plot showing the number of entropy classes into which the mineralogical data can be classified, and the amount of variation in the data matrix that each classification will explain. From this analysis an 8 entropy class classification was used as this is the point on the graph where additional entropy classes do not result in any significant increases in the amount of data variation explained. Also since the number of samples is relatively small there is a limit to the number of data classes that can be employed.

6.6.1 Entropy Class Descriptions

Class 1 (Glass and biotite enriched sands): Entropy class 1 is distinguished by large amounts of volcanic glass (mean 45%), with common plagioclase (mean 25%) and pumice (mean 18%), with scarce quartz (mean 6%), lithics (mean 3%), and heavy minerals (mean 2%). The heavy mineral fraction is characterised by the inclusion of significant amounts of biotite (mean 12%), with common amounts of cummingtonite (mean 25%), hypersthene (mean 21%), and green hornblende (mean 19%).

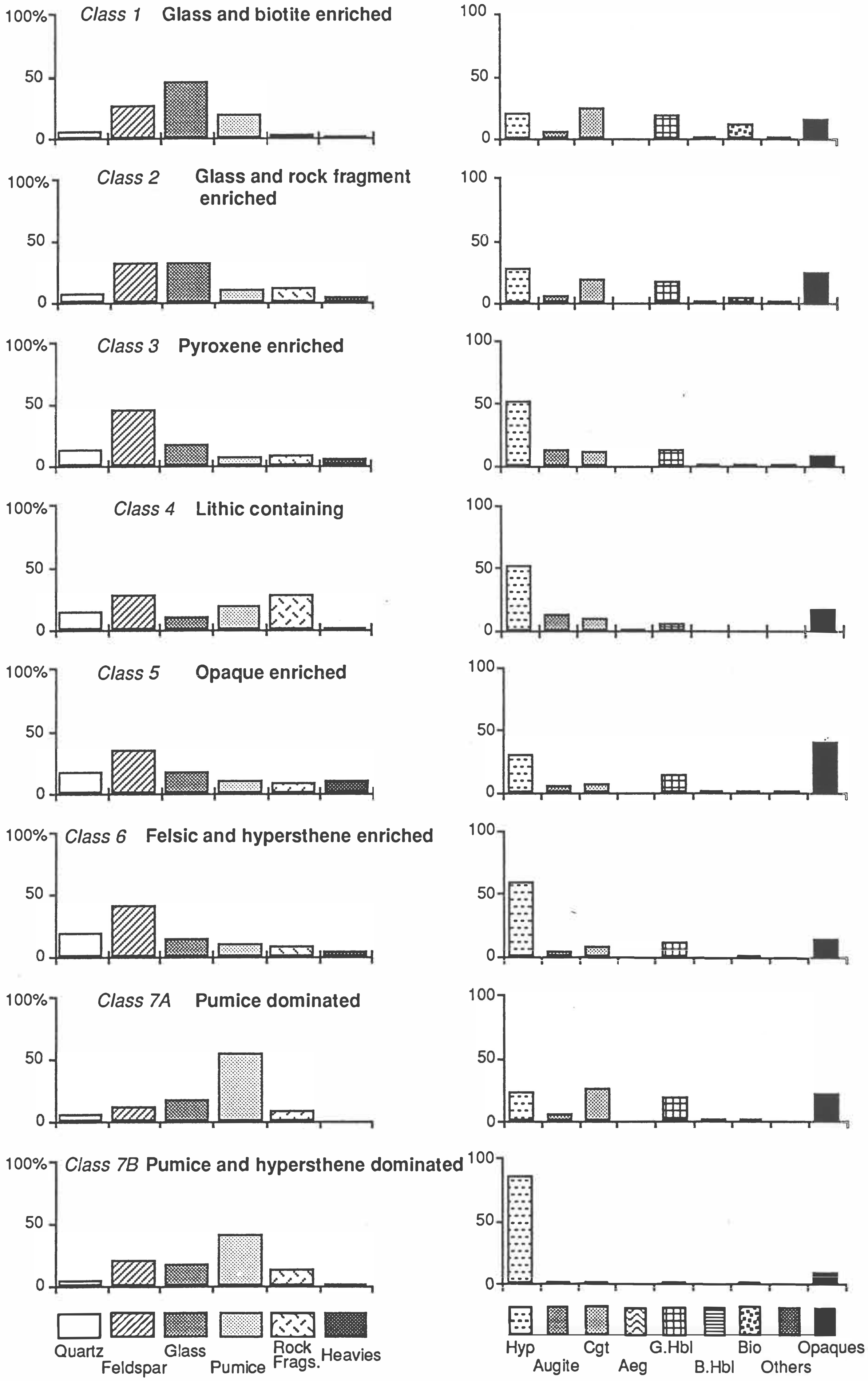


Figure 6.16 The average class mineralogical composition of light and heavy minerals for each of the seven entropy classes.

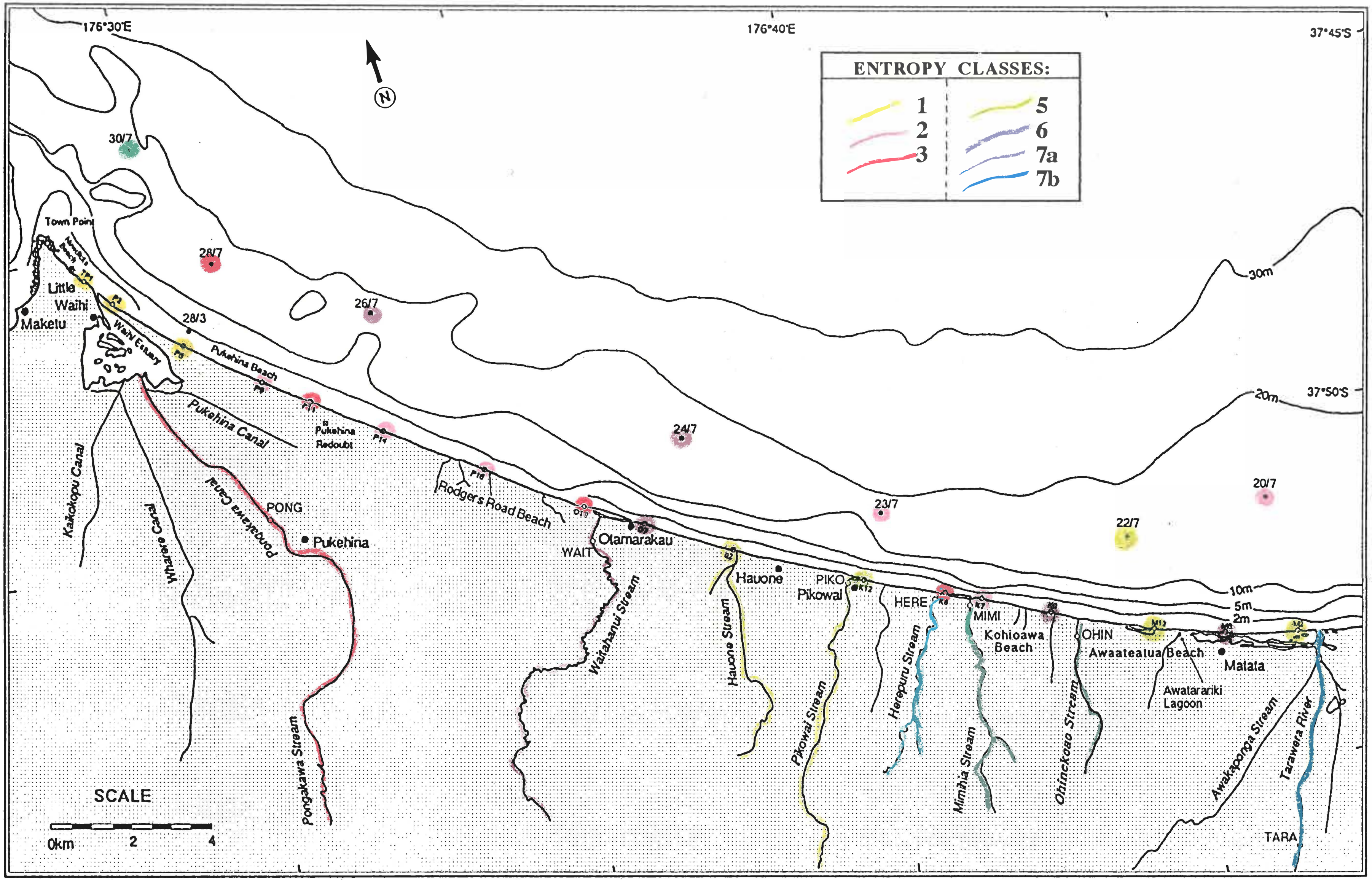


Figure 6.17 The distribution of the eight mineral entropy classes within the Pukehina-Matata coastal sector, for beachface, nearshore, and stream samples (as for Figure 6.1). Entropy classes are based on both the bulk mineralogy and the heavy mineralogy.

It also contains some opaques (mean 16%).

These glass and biotite enriched sands are found in beach deposits from Town Point to central Pukehina Spit (Figure 6.17).

Class 2 (Glass and rock fragment enriched sands): Entropy class 2 is similar to class 1 sands but is characterised by significant amounts of rock fragments (mean 12%), with large quantities of volcanic glass (mean 33%) and plagioclase (mean 32%). Quartz (mean 8%) and heavy minerals (mean 5%) are present in scarce amounts. In the heavy mineral fraction scarce biotite is present (mean 4 %), with common hypersthene (mean 27%), opaques (mean 24%), cummingtonite (mean 19%), and green hornblende (mean 17%).

This class is found in beach deposits from southern Pukehina Spit and to the north of Rodgers Road beach, as well as near the Mimihia Stream mouth. It occurs in sediments offshore from Pikowai and the Tarawera River.

Class 3 (Pyroxene enriched sands): Entropy class 3 is distinguished by pyroxene abundances. Large amounts of hypersthene (mean 52%), and common augite (13%). The light fraction is dominated by plagioclase (45%).

The pyroxene enriched sands are found scattered in various deposits, in beach sediments near the Pukehina Redoubt, north of Otamarakau, and north of the Herepuru Stream mouth, in sediments offshore from central Pukehina Spit and in the Pongakawa stream feeding the Waihi estuary.

Class 4 (Lithic containing sands): Entropy class 4 is characterised by common amounts of rock fragments (mean 28%) with common plagioclase (mean 27%), pumice (mean 18%), and quartz (mean 14%). The heavy mineral fraction is dominated by large quantities of hypersthene (mean 51%), with common opaques (mean 16%), and augite (mean 14%). Trace amounts of aegerine (mean 2%) are also a distinguishing feature of this group.

These lithic enriched sands are found in the Mimihia Stream and in the sediments around Town Point.

Class 5 (Opaque enriched sands): Entropy class 5 is characterised by an opaques dominant heavy mineral fraction (mean 40%), with common hypersthene (30%). The light minerals contain abundant plagioclase (34%), with common quartz (mean 18%), and glass (mean 18%).

Opaque enriched sands are found in beach deposits between Hauone and Pikowai and along most of Awaateatua Beach, in the Pikowai Stream, and in sediments offshore from Matata.

Class 6 (Felsic and hypersthene enriched sands): Entropy class 6 is composed of felsic sands of abundant plagioclase (mean 40%) and common quartz (20%), with lesser amounts of glass (15%), pumice (mean 10%), and rock fragments (mean 9%) in similar amounts as classes 3 and 5. The heavy mineral fraction is again dominated by large quantities of hypersthene (mean 60%).

This class is found in beach deposits at Otamarakau, Kohioawa Beach, and Matata, in Waitahanui and Ohinekoao stream deposits, and in offshore deposits off Otamarakau and Pukehina Redoubt.

Class 7 (Pumice dominated sands): Entropy class 7 is a distinctive by the dominance of pumice (mean 41 to 55%). Originally this group was two classes, but are grouped in the same class due to the dominance of pumice in both groups, and each class containing only the one sample.. Sub-class 7a has a heavy mineral suite of common cummingtonite (27%), hypersthene (24%), opaques (2%), and green hornblende (9%), while sub-class 7b is dominated nearly exclusively by hypersthene (86%). Pumice dominated sands are exclusive in river deposits of the Herepuru Stream and Tarawera River.

6.7 Provenance and Sediment Dynamics for Pukehina-Matata Sediments

In general nearshore sediments (15 m water depth) are composed of less pumice and volcanic glass than beach deposits, due to their breakdown during transport from an onshore source, but contain a higher proportion of heavy minerals by depletion of some of the lighter fraction components.

As lithic fragments are mainly pumice and weathered Quaternary volcanic deposits, they are likely to breakdown fairly rapidly when extensively reworked or sub-aerially exposed. Thus the presence of abundant lithic fragments in coastal sands is a useful indicator of recently derived terrigenous sediments.

The large amounts of pumice and volcanic glass which are difficult to differentiate under the microscope and may therefore be mostly pumice, on Pukehina Spit is derived from the onshore input of pumiceous sediments from marine erosion of offshore outcrops in 10-15 m water depth. These outcrops occur as collections of boulders and possible remnant wave-cut shore platforms restricted to the Pukehina south and Redoubt areas, yet a peak occurs at Pukehina north, suggesting sediment transport to the north-west along Pukehina Spit.

6.7.1 Feldspar, Quartz and Glass Ratios

The ratios of certain light minerals, especially feldspar and quartz, can be diagnostic in determining sediment sources and transport pathways, as shown by Schofield (1970), Healy (1978), Healy and Dell (1982) and Bradshaw (1991).

The ratio of plagioclase feldspar to quartz in coastal sediments can be useful in determining sediment provenance, particularly the degree to which streams and rivers influence coastal sand mineralogy. The feldspar to quartz ratio for data obtained in this study have been plotted in Figure 6.18a, along with ratios obtained from other studies within the broad bounds of the study area. Comparison between studies shows little similarity. This arises mainly due to the differences in methods used for obtaining the mineralogy data. Healy *et al.* (1977) carried out XRD analysis on

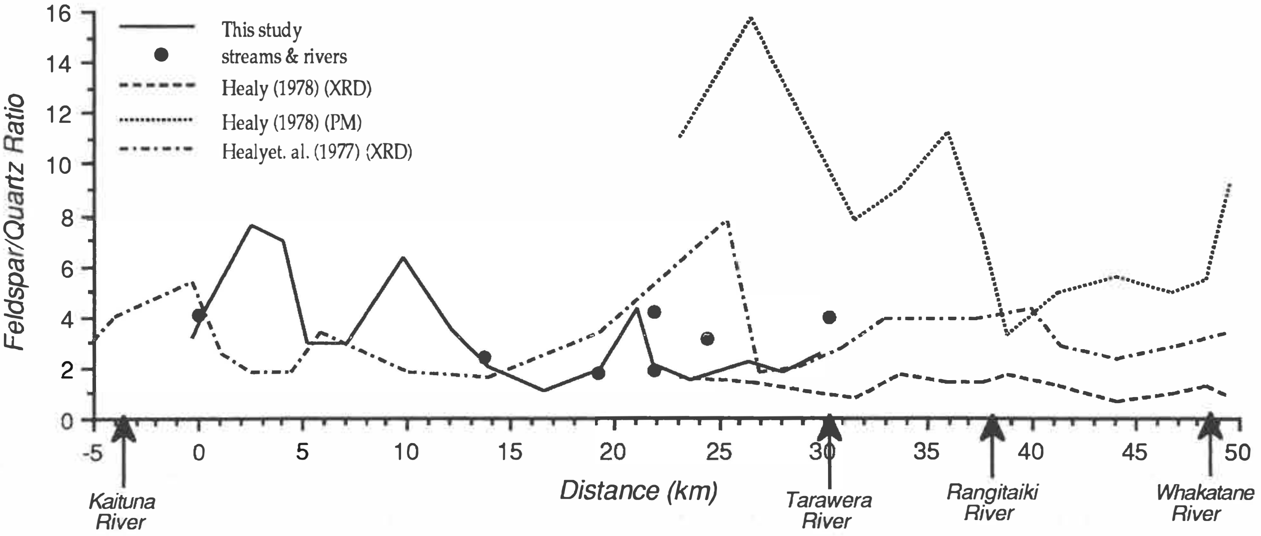


Figure 6.18a The alongshore ratio of feldspar to quartz (F/Q) for beachface sediments from this study, and F/Q ratios derived from other studies that include the Pukehina-Matata study area.

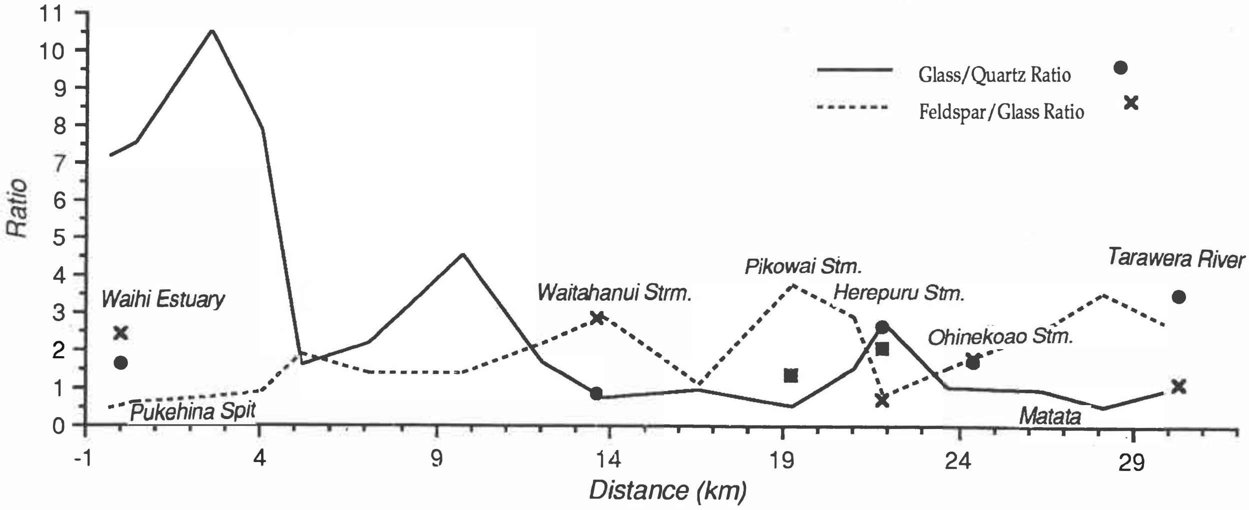


Figure 6.18b The alongshore ratio of feldspar to glass (F/G)and glass to quartz (G/Q).

the bulk sediment sample, with the results considered accurate to within ± 10% (Nelson and Cochrane, 1970). In general quartz being more resistant to abrasion and weathering, is a more dominant component of the coarser grain sizes than feldspar which is a softer mineral and therefore more likely to breakdown and dominate the mineralogy of the finer sediments. Hence, the proportion of quartz identified in this study of coastal sediments is higher than reported by Healy (1978) using standard petrography of the fine sand range (2-4phi). Healy (1978) also undertook XRD analysis using the modal grain size for each sample, since this should give a more accurate indication of the sediment mineralogy. This study yielded the lowest F/Q ratios found, but does show similarity with the earlier XRD analysis of Healy *et al.* (1977), for the beach sands from the Tarawera River to the Whakatane River.

Other light mineral ratios, such as glass to quartz and feldspar to glass (Figure 6.18b), can also be of use in determining sediment provenance. The predominance of volcanic glass in the Pukehina Spit area has a strong effect on the trends observed in both ratios. The ratio of glass to quartz exhibits a very similar pattern to the F/Q ratio, with the same three main peaks at Pukehina central, Rodgers Road Beach, and Kohioawa Beach.

The quartz, feldspar, and rock fragment data were recalculated to 100% and plotted against each other as a triangular plot (Figure 6.19), after Folk *et al.* (1970). The coastal sediments from Pukehina to Matata can be classified as feldsarenite and lithic feldsarenite, with the nearshore sediments having a greater overall lithic content, and the beach sands a higher proportion of feldspars.

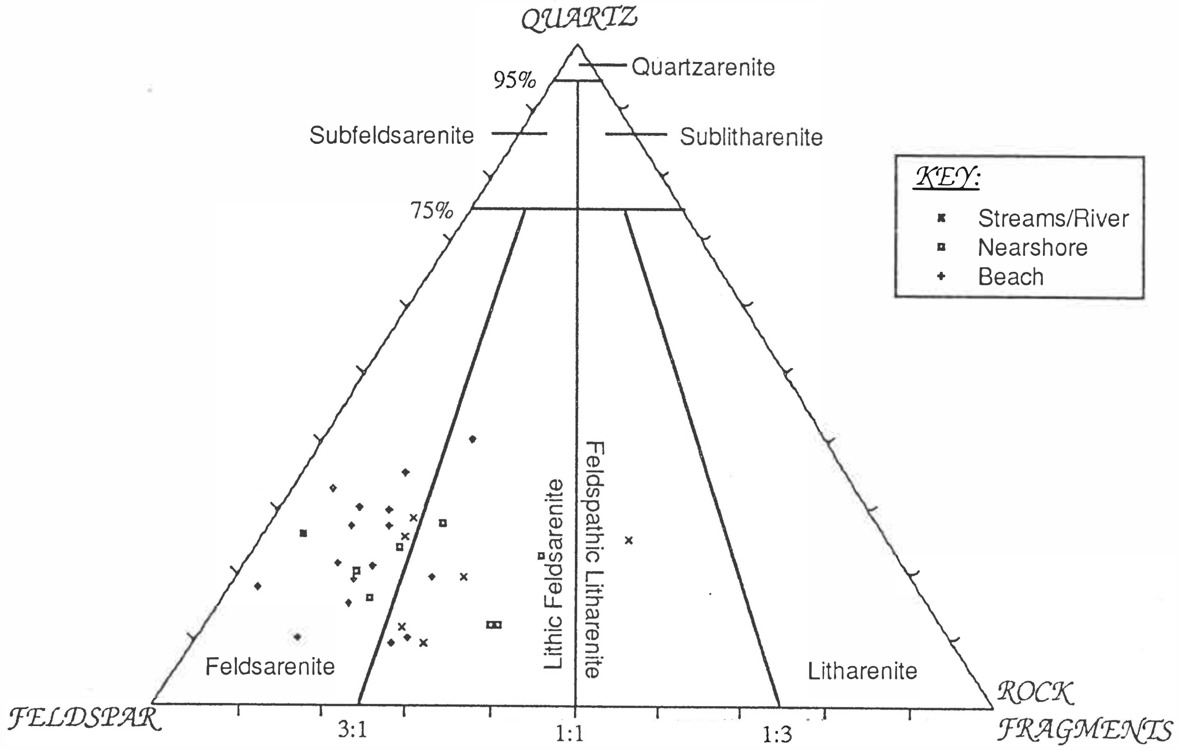


Figure 6.19 Triangular plot of the relative abundances of quartz, feldspar, and rock fragments for Pukehina-Matata surficial sediments, showing the feldspar dominant mineralogy of the beach, fluvial, and nearshore environments.

6. 8 Summary

- Light minerals constitute between 92.1 to 98.5 % of the beach sediments, heavy minerals 0.2 to 5.6 %, with the remainder due to biogenic production of carbonate material. The mineralogy reflects the high input of quartzo-felspathic sediments from the Okataina volcanic centre.

- The alongshore trends presented for each mineral show varying degrees of certainty for indicating sediment transport, summarised in Table 6.6.

Table 6.6 Summary table of the sources and possible sediment transport directions inferred from each sediment mineral species, and the degree of confidence that can be assigned to each.

Mineral	*Inferred Transport*	*Confidence*	*Source*
Quartz	NW from Otam.	Poor	Waitahanui Str., Tarawera R.
Plagioclase Feldspar	NW from Otam.	Poor	streams, Tarawera R.
K-Feldspar	NW from Tarawera River mouth	Good	Tarawera River
Volcanic Glass	NW along Pukehina	Good	Pukehina-Rodgers Road offshore,
Pumice	NW along Pukehina	Good	Herepuru Stream
Rock fragments	NW and SE from Rodgers Road	Fair	Pikowai Stm., Puk Red.-Otam.
Heavy Minerals	NW and SE from Hauone	Fair	Pikowai, Wait. Stms.
Hypersthene	NW (?) and SE from Otam. to Mat.	Fair	All streams (esp. Wait), Puk. Red.
Augite	SE from Otam.	Fair	Pikowai, ± other streams, Puk. Red
Cummingtonite	SE from Waihi est., or NW from Puk.	Fair	Puk. Red., Waihi est., Mimihia stm.
	Red, and Wait. Stm.	Fair	
Green Hornblende	NW & SE from Otam.	Good	Pik., Wait. stms
Brown Hornblende	-	-	Waihi est., Rodgers Road (?)
Biotite	SE from Waihi est.	Fair	Waihi est., Puk. Red., Town Pt.
Opaques	-	-	Streams, esp. Pik.

NW= north-west, SE= southeast, -= unknown; Waihi est.=Waihi Estuary; Otam.= Otamarakau, Mat.= Matata., Puk.= Pukehina, Puk. Red.= Pukehina Redoubt, Pik.= Pikowai, stm.= stream., esp.= especially, R.= river.

- The heavy mineral trends suggest that the streams in the Otamarakau-Matata sector appear to provide much of the sediment to this area of the beach, however along Pukehina Spit and in the vicinity of the Pukehina Redoubt the mineralogy of the streams implies additional sediment sources are present adding material to the beach system and altering the mineralogical proportions of the surficial beach sediments. The suggested source are nearshore reefs which are geologically similar to the coastal hinterland, with no unusual minerals present to suggest a difference.

Within the beach sediments the overall trend observed in the heavy minerals is for an increasing abundance from the Waihi estuary towards Otamarakau, culminating in a peak at Hauone. Towards Matata abundances decrease with small peaks where streams add new sediment.

- Carbonate percentages in the beach surficial sediments indicate two distinct areas of marine species diversity, linked to differences in sediment texture and substrate, and possibly wave energy. Between Newdicks Beach and Rodgers Road the carbonate content is between 3-5 %, with a decrease to 1-2 % from Otamarakau to the Tarawera River mouth. In the nearshore zone a similar pattern is apparent, with higher carbonate sediments in the shell and lithic hash containing sediments area between Pukehina and Otamarakau identified from the textural distributions of surficial sediments in Chapter 5. The largest carbonate contents also are associated with the presence of rocky substrates in this area identified in Chapter 8.

- Both the ratio of feldspar to quartz, and glass to quartz decreases from Pukehina to Matata, with peaks at central Pukehina Beach, Rodgers Road, and Kohioawa Beach. The feldspar:glass ratio shows the opposite general trend increasing from Pukehina to Matata.

- Although there are greywacke gravels present within the beach system the mineralogy of the beach, nearshore and stream sediments is consistent with their derivation from Okataina Volcanic Centre eruptives which constitute the majority of the Pukehina-Matata hinterland, with no minerals found that are indicative of beach sediments, in addition to the gravels already present, being derived from greywacke materials. The greywacke pebbles while numerous on the beach are not an active source of sediment *input* to the littoral system and contribute little to the sand fraction in terms of abrasion. No greywacke unique minerals were found that could not also have been derived from acid volcanics, as expected since the rate of weathering of the often poorly consolidated volcanogenic material is far greater than that for rounded greywacke pebbles.

- While some of the alongshore mineral trends support the bi-directional sediment transport system concluded in Chapter 5, varying sediment source volumes, and stream-beach-nearshore interaction complicates this, with minerals such as cummingtonite, indicating a source rather than a transport direction. Furthermore, the suggested low rates of littoral drift along the Pukehina-Matata coastal sector, may indicate mineralogical trends which are in part at least due to diabathic sediment transfers and storm wave versus fairweather effects on the littoral sediments.

CHAPTER SEVEN:

Nearshore Oceanography

CHAPTER SEVEN
NEARSHORE OCEANOGRAPHY

7.0 Introduction

Open beaches, such as those along the Pukehina-Matata coastal sector, accrete and erode primarily in response to differing combinations of winds and waves. They accrete during periods of offshore winds when surface water movement offshore is balanced by a near bed flow onshore, carrying sand mobilised by low swells. With strong onshore conditions of wind and surface waves, possibly enhanced by larger swells, sand mobilised off the beach is carried seaward to form offshore bars which trip larger waves and eventually trend towards equilibrium.

In order to determine sediment transport patterns, some information is required on the regional and local current patterns that operate within and affect the nearshore zone, and the nearshore wave regime. This necessitated deployment of two *InterOcean* S4 current meters for a two month period at the approximate limit of significant onshore-offshore sediment movement, to obtain information on parabathic and diabathic currents and possible sediment transport during this period.

7.0.1 Bay of Plenty Wave and Currents Review

Existing wave and current data for the Bay of Plenty are mainly confined to measurements taken at Tauranga. The wave climate of the Tauranga inner shelf region was reviewed by de Lange (1991), based on instrumental data from A Beacon, located at the entrance to Tauranga Harbour. He concluded that the Bay of Plenty can be defined as a low energy lee-shore environment, with a wave climate consisting of a persistent long period swell with a superimposed local sea. The mean conditions during a two year period from June 1989 to August 1991 were H_s= 0.81 m, T_p = 10.6 s, and T_s= 9.06 s (de Lange, 1991).

Oceanographic data for 153 historic storms in the western Bay of Plenty presented by Hay (1991), predicted from wave hindcasting significant deep water wave heights of 1.01 m to 5.00 m, and periods ranging from 4.3 s to 10.4 s.

From wave and current information for the period 13 August to 16 October 1991 at the dredge spoil dumping site offshore from Tauranga Harbour, Foster (1992) concluded that a wind-driven current system is present on the Tauranga shelf.

Harms (1989) examined currents on the Tauranga inner shelf in July 1988 using an Aanderaa current meter sited 1 m above the seafloor. He found that weak currents moving in a southerly direction with a velocity less than 10 cm/s were associated with either light winds of variable direction or strong onshore directed winds. Harms noted that the reaction of the current speed to high wind speed during storms indicated that the currents were probably wind driven, but did not exceed the threshold velocities necessary to entrain sediment even during storm conditions.

Foster (1992) deployed two *InterOcean* S4 current meters in 23 m water depth in the water right area associated with the dredge spoil dump site at Tauranga (2.7 km off Mt. Maunganui Beach). Currents were measured for a two month period from August to October 1991, at 1 m and 15 m from the seafloor. He found that when winds are offshore, waves are generally less than 1 m high and a bottom current up to 33 cm/s and directed between 90° and 180° (relative to magnetic north) is present. When winds are directed onshore, the wave heights increase and a current directed between 270° and 360° is present. Foster (1992) considered that the Bradshaw (1991) model (Figure 3.4b) for the generation of wind driven currents on the East Coromandel shelf can also explain the current generation on the Tauranga shelf.

Bradshaw (1991) concludes that the interaction of waves with wind-driven currents is an important mechanism for sediment transport over the east Coromandel inner shelf, with wave orbital motions agitating or entraining bottom sediments, and superimposed steady currents transporting the sediments. Thus, waves determine when, and currents determine where, sediment is transported (Bradshaw, 1991).

7.1 Current and Wave Measurements

7.1.1 Methodology

An *InterOcean* S4DW current meter was initially deployed for two months from April 21st to June 23rd 1993, in 14.6 m water depth offshore from Pukehina Beach, but due to a failure in the battery pack no data was recorded. Two *InterOcean* S4DW meters were then deployed in 16.1 m water depth approximately 1400 m offshore from the south-eastern end of Pukehina Spit (37° 46'.32S, 176° 31'.64E), from July 15th to August 25th. The mooring system of the current and wave recorders is shown in Figure 7.1. A current recorder was sited 1 m from the seafloor 40 m to the south-west of the marker buoys in an onshore direction, with a wave and current recorder sited below the marker buoys 10 m from the water surface.

The wave and current meter site at deployment consisted of well-defined coarse sand megaripples (λ= 0.7 m, η= 0.4 m), with gravelly sand troughs consisting of granules of greywacke, ignimbrite and rhyolite, and small 2-5 mm broken shell material (M_Z= 0.68 mm).

Wave and current data from the top S4 (S4/10) were recorded in 3 minute bursts every 6 hours, with values averaged over a one second interval. The lower S4 (S4/1) recorded current data as one minute averages every ten minutes.

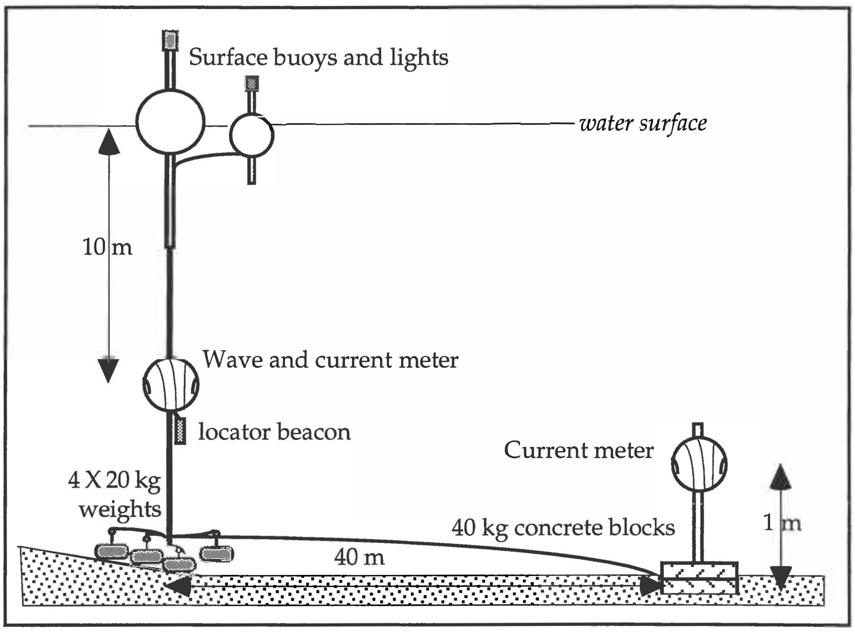


Figure 7.1 Schematic set-up of the wave and current recorders in 16.1 m water depth offshore from south-eastern Pukehina Beach, utilising a modified U-mooring system.

7.1.2 Results Analysis

Several wave and current analysis programs were applied to the current and wave data collected from the S4 (S4/1) and S4DW (S4/10). The computer program *S4Reform* (de Lange *et al.*, 1993) was used to extract the individual data bursts, and format a summary file of the average wave parameters for each burst over the entire record length.

For the current data obtained from S4/1 the programs *Thanal, Thpred, and Thresi* were used (de Lange *et al.*, 1993) which utilise the calibrated data file from *S4Reform* to remove the tidal effects from the depth, x-direction current, and y-direction current data, producing various data files, most important of which are the residual depths, current directions and velocities after removing tidal current effects. These data can then be further analysed using the University of Waikato's progressive vector analysis program *Residual*. In addition the program *TCA* (de Lange *et al.*, 1993) was used to determine the effects of the tidal constituents on the measured currents.

7.1.2.1 Wind Information

A complete set of three-hourly wind data, including velocity and direction was obtained from the nearest recording station sited at Whakatane airport on the Rangitaiki Plains for the period 15th July to 26th August. These exhibit a reasonable comparison with observed wind data collected from Pukehina Beach during the same period, in terms of the relative velocities and wind direction. Although the observed wind measurements appear to overestimate the actual wind speeds (section 7.1.4). The average daily wind speeds (Figure 7.2) are only slight to moderate during the period of S4 deployment, and only on occasion were velocities in excess of 10 m/s, as discussed later.

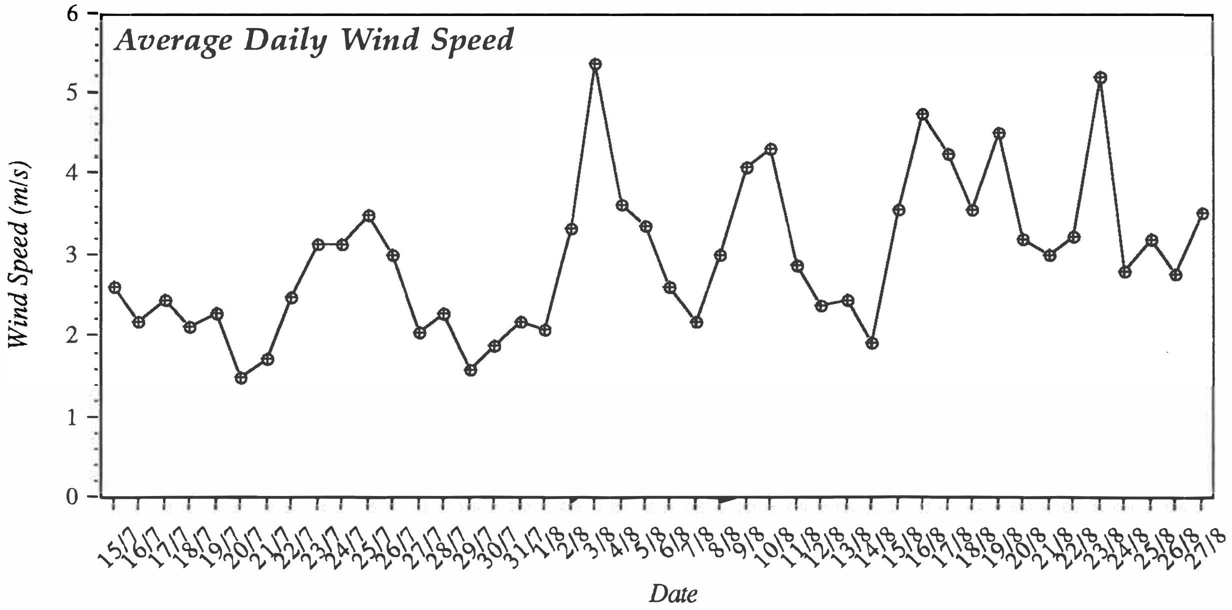


Figure 7.2 Average daily wind speed from Whakatane airport for the period 15th July to 26th August, wind speeds are slight to moderate during this period, although wind gust periods produce larger wind speeds.

7.1.3 Beach Wind and Wave Observations

In addition to the S4 deployments, a local resident (Mrs Clarkson, 131 Pukehina Parade) monitored the beach wind and wave characteristics during both the initial failed deployment and the later deployment. Observations were made daily an hour either side of 12 pm, to correlate with the data obtained from the wave and current meters. This gave a three and a half month record of wave heights, wave periods, wind direction, angle of wave approach, beach slope, wind force on the Beaufont scale (Appendix VIIa), and general observations concerning the nature of the beach morphology (Figure 7.3).

As discussed in Chapter 4, Figure 7.3 shows more stormy weather periods in autumn compared with the later winter months, coinciding with the typical seasonal occurrence of storms. Hay (1991) found that from 153 historic storms in the Bay of Plenty on a monthly basis the largest percentage of storms occurred in May (15.0%), with autumn (March, April, May) the most stormy season. During the first beach observation period (20/4- 23/6) the wind and wave conditions have a higher incidence of storm-type conditions with the cumulative effect of 3 stormy periods in one month removing most of the sub-aerial beach sand reservoir. Wave conditions were similar during both periods of $H_{b\ av.}$= 0.6 m and 0.5 m, and $T_{b\ av.}$= 9.2 s and 9.3 s respectively.

The two observed wave height peaks labelled A and B in Figure 7.3c, correspond with the two major peaks in wave height recorded by S4/10. However there is some difference in the wave heights observed at the beach compared with those offshore. This is partly due to wave shoaling transformations which cause a deep water wave to produce a breaking wave height which is less than the deepwater wave height and with a longer period. The difference in observed wave

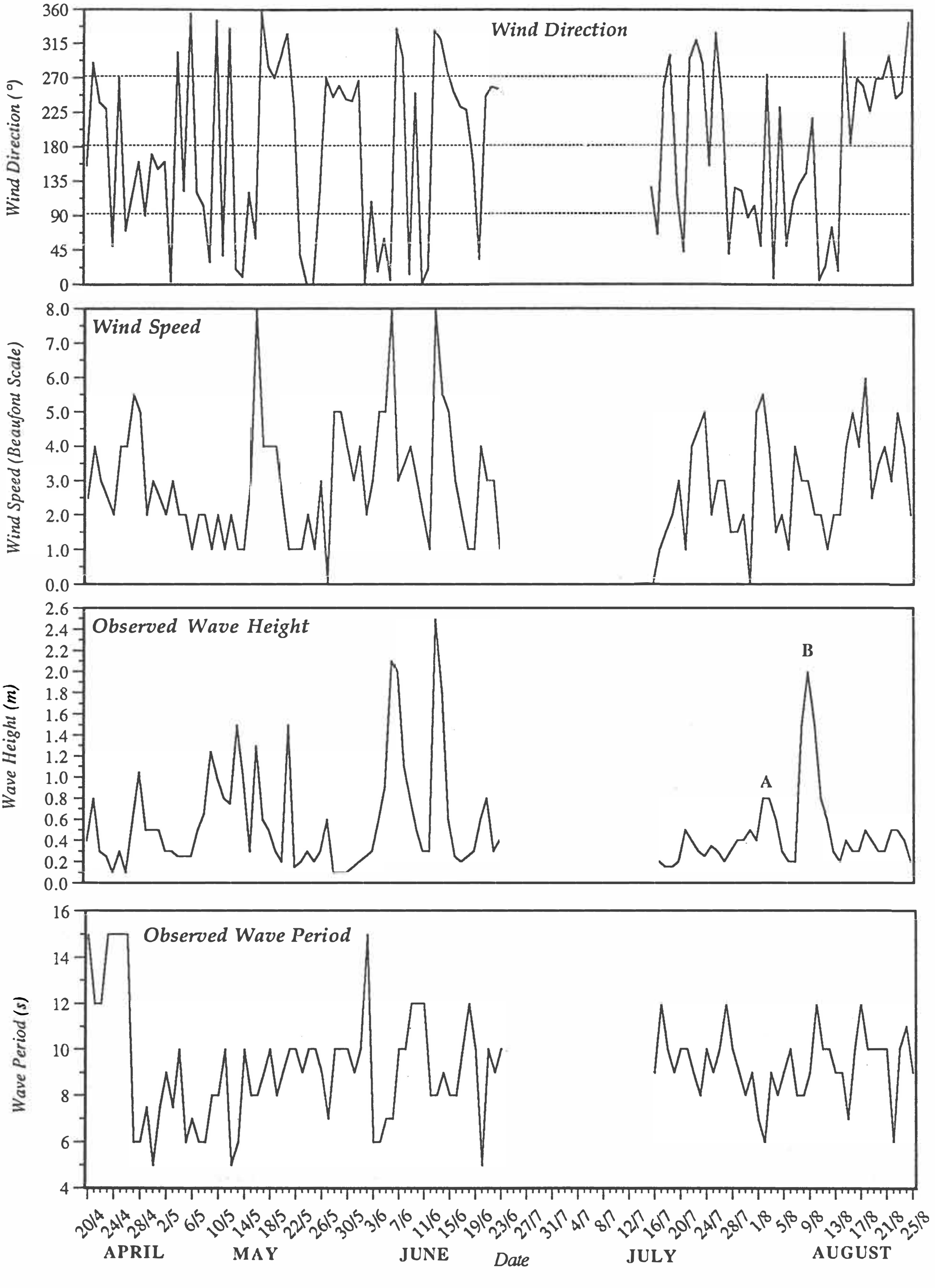


Figure 7.3 Time series plots of observational beach, wave and wind data gathered at Pukehina Beach for the period 20/4/93 to 23/6/93 and 16/7/93 to 25/8/93. The two peaks labelled A & B in Figure c correspond with two storms recorded by the S4 wave recorder.

heights may also be attributed to differences in the direction of wave approach on the two dates causing a zone of wave divergence at the beach during storm A, resulting in a lower wave height than that expected, and contrasting wave focussing during storm B resulting in a higher wave height than expected. Also wave heights observed at the beach were taken as the average wave height observed during a minute period (H_S), whereas those from S4/10 are the significant wave height (H_σ), which in shallow water is greater.

A wind rose for Pukehina Beach has been produced for the period 20th April to 25 August 1993 (Figure 7.4). This wind rose only represents part of the year, and may therefore differ from a mean annual wind rose, however it does indicate to a limited extent the wind frequencies in terms of wind speed and direction.

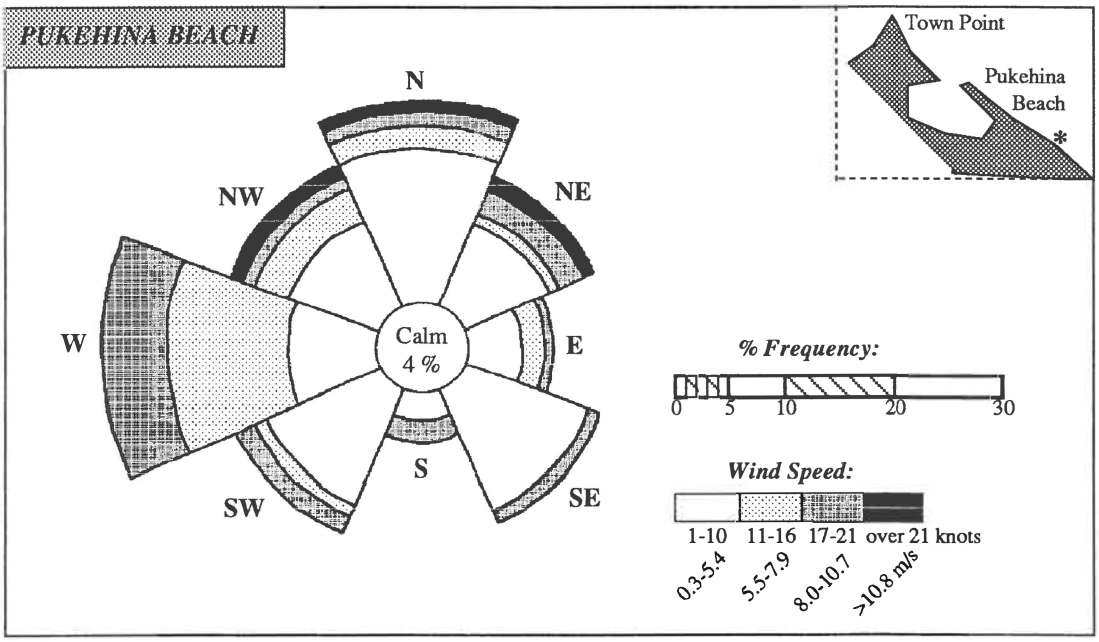


Figure 7.4 Wind rose for Pukehina Beach, for the period covering 20/4-23/6/93 and 15/7 to 26/8/93 (108 days data).

The wind direction has a strong westerly component typical of the Bay of Plenty (Quayle, 1984), with winds blowing from this quadrant over 21 % of the time, followed by northerly winds (17%). Winds from the north-west, north-east, south-east, and south-west have a similar frequency of occurrence, with a smaller easterly component, and occasional southerly winds. The highest wind speeds tend to occur when the wind direction is from the northerly quadrants, as would be expected since the regional topography (i.e. Papamoa Hills, Kaharoa Plateau) and local topography (i.e. Town Point, Pukehina Spit dunes) combine to shelter Pukehina Beach from southerly and westerly winds. The wind conditions are expected to be similar over the rest of the study area. Onshore winds occurred approximately 47 % of the time.

7.1.4 Wave Results

For the six week period in which the S4DW was deployed, the average and extreme wave parameters are given in Table 7.1. Weather conditions varied, but overall were moderately fair

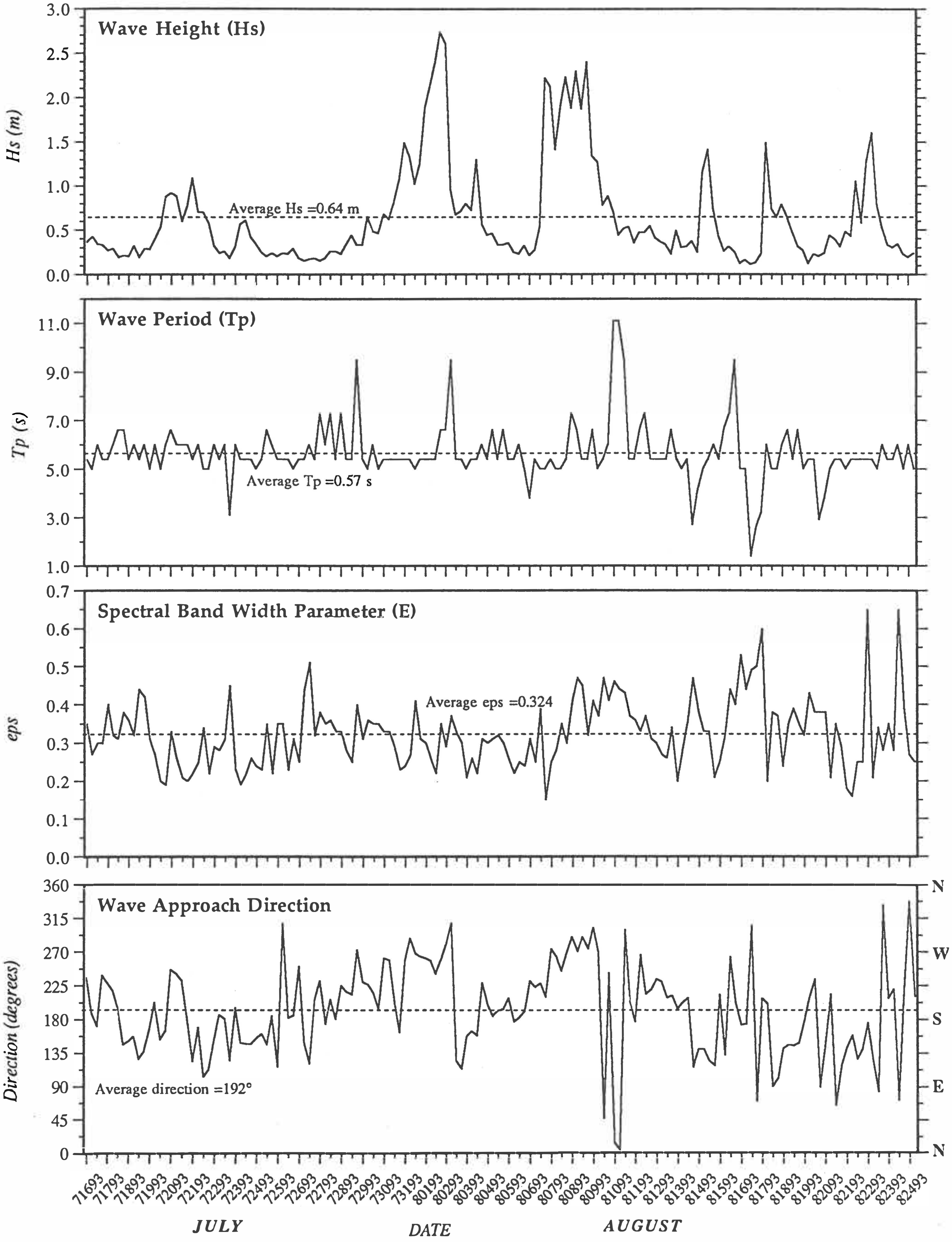


Figure 7.5 Time series plots of the average wave parameters for each 6 hourly data burst, from Pukehina Beach in 16.1 m water depth for the period covering 16/7/93 to 25/8/93.

weathered.

Table 7.1 Minimum, maximum, and average 6-hourly selected wave parameters for Pukehina Beach during the period from 16 July to 25 August 1993.

Wave Parameter	*Minimum Value*	*Maximum Value*	*Average Value*
Significant wave height (H_σ)	0.11 m	2.74 m	0.64 m
Peak wave period (T_p)	1.37 s	11.13 s	5.75 s
Significant wave period (T_s)	5.45 s	9.26 s	6.36 s
Spectral band width parameter (ε)	0.17	0.72	0.324
Direction of wave approach	-	-	192°

The wave regime during the deployment period contained two storms of small size (on 30/7 to 2/8 and 6/8 to 10/8), which produced significant wave heights of approximately 2.7 and 2.4 m respectively (Figure 7.5). The spectral band width indicates that there is no observable trend in the association of larger wave heights with a stronger swell component (as value approaches 0), or of more wind generated waves which display a wider wave frequency spectrum (value closer to 1). Although winds may help to increase wave heights as shown for storm B where the effects of stronger offshore winds on the wave spectra are more pronounced.

Use of the *InterOcean S4Wave* program to isolate individual burst data from the S4/10 was applied for representative storm (burst 92, 8/8/93) and fair weather (burst 110, 13/8/93) bursts (Figure 7.6). Each burst consisted of three minutes of one second averages.

The fair weather burst (110) had a reasonably consistent current directed to the south-east at an average speed of about 15 cm/s. The storm burst (92) by contrast had a widely fluctuating current with speeds of up to 116 cm/s, and as low as 0.4 cm/s. The differences in the generated bottom currents are attributed to the dissimilarity in wave action during each burst period, with large wave orbital velocities during the storm burst giving rise to currents predominantly in an easterly or westerly direction as either the crest or trough of a wave passes over the current meter site (wave orbital motions). Wave heights are further enhanced by moderate speed winds from the south-east of up to 10 cm.s^{-1}. For the fair weather burst the wave action was minimal (only a small persistent swell present) from a southerly direction with light offshore westerly winds developing the observed south-easterly directed steady current.

7.1.5 Currents

The velocity of tidal currents vary over the tidal cycle and also tend to increase over wide continental shelves (Niedoroda *et al.*, 1985) or in regions where tidal flows are constricted (Hume *et al.*, 1992). In shallow waters (less than 20 m) frictional effects reduce tidal and shelf currents (Niedoroda *et al.*, 1985). In deeper waters tidal current speeds, near the bottom, can be reduced by up to two thirds of the surface velocities (Carter and Heath, 1975). While tidal currents may be

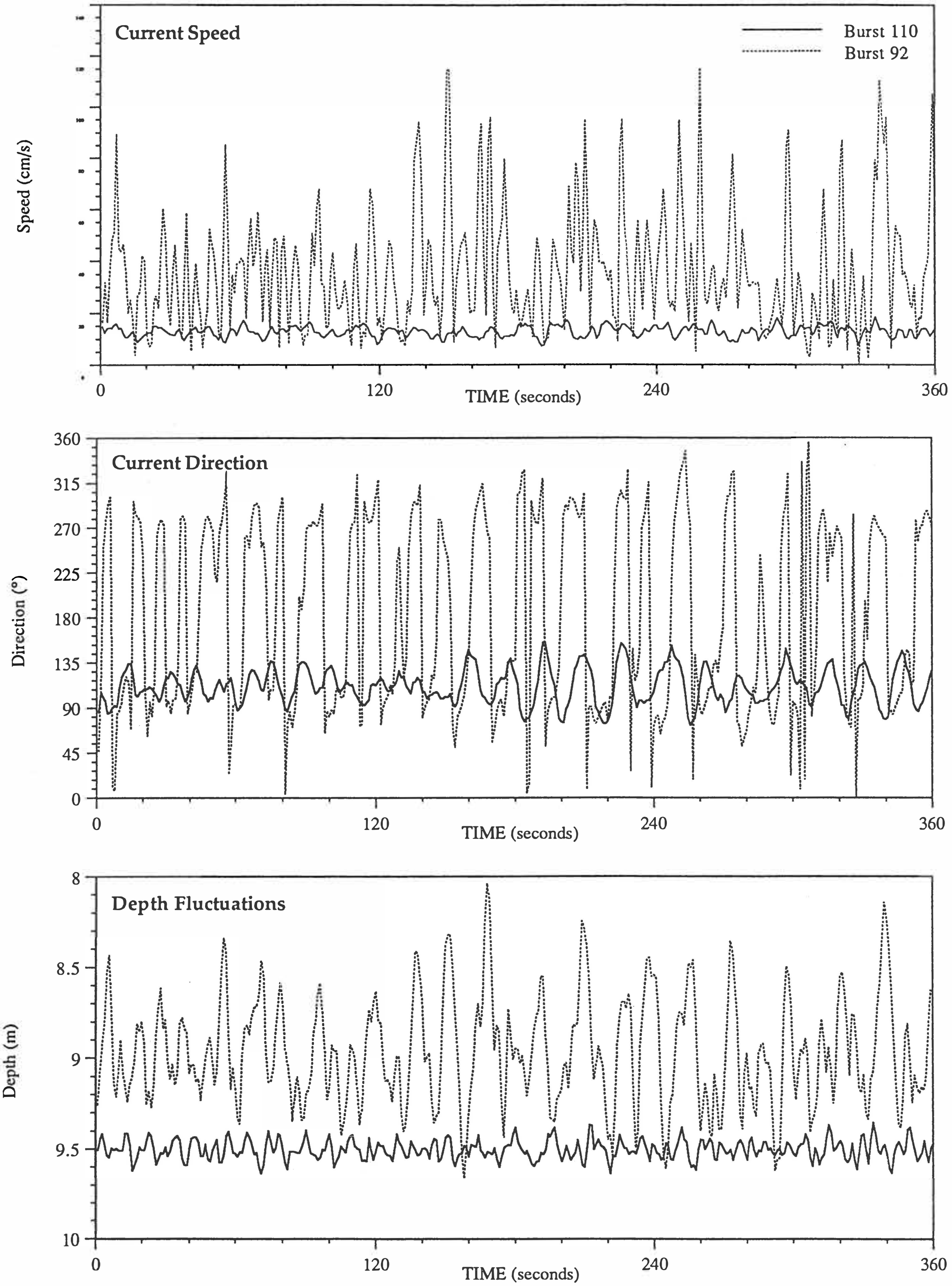


Figure 7.6 Time series plots of current speed, direction, and depth variation over 3 minute representative fair weather (burst 110) and storm (burst 92) periods, from data recorded by the S4/10.

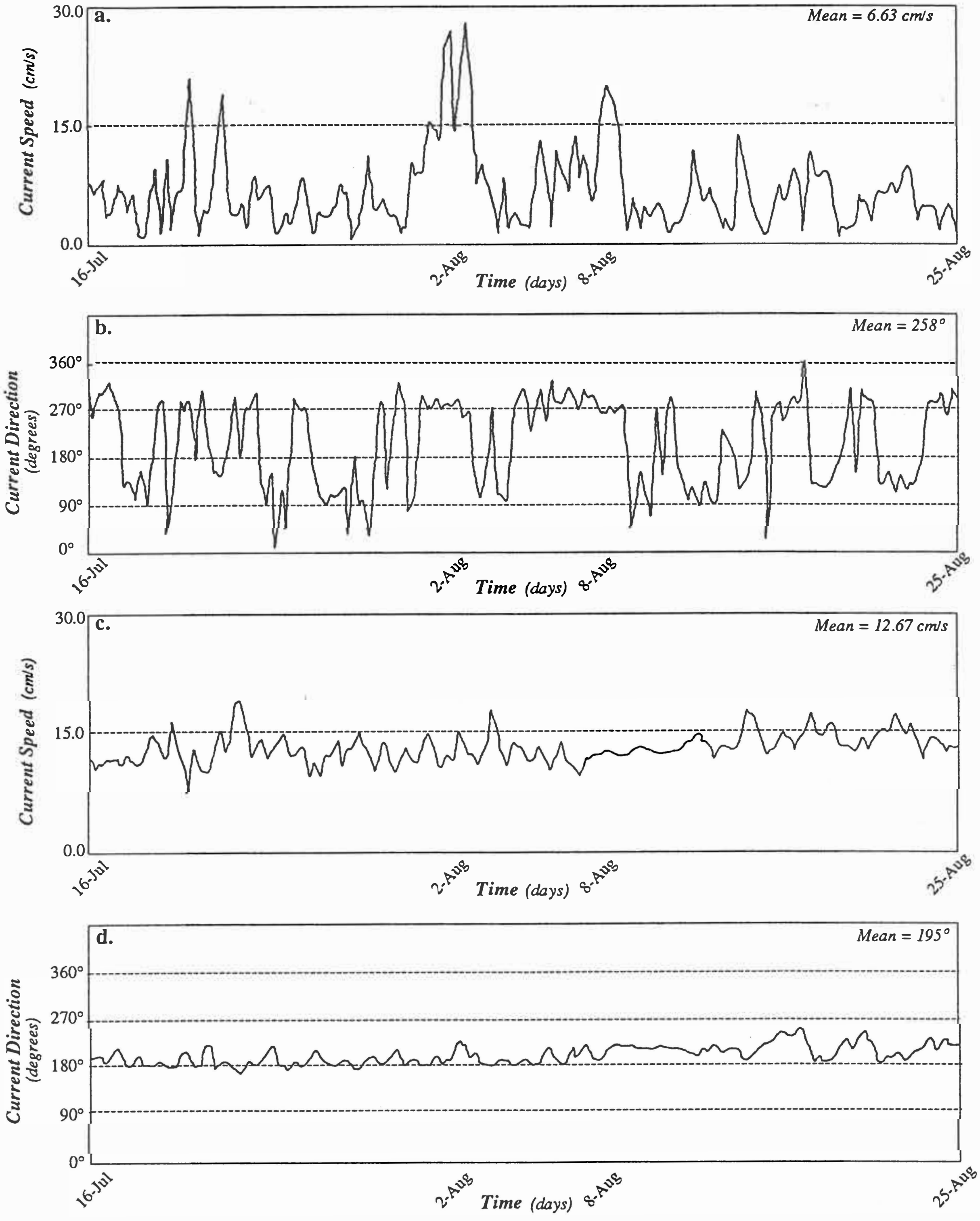


Figure 7.7 Time series plots of 6-hourly average current speed and direction from the S4/10 (top recording meter, Figures a & b); and S4/1 (bottom recording meter, Figures c & d), for the period 16/7/93 to 25/8/93.

important for keeping sediment in suspension, they contribute little to net sediment transport (Niedoroda *et al.*, 1985), with other flows, such as wind forced currents, acting to transport sediment. Thus in determining sediment transport it is important to remove the tidal current effects from the bottom currents.

The S4/1 and S4/10 current meter data were averaged to give the mean current speeds and directions at 6 hourly intervals over the deployment period (Figure 7.7). For S4/1 the current speed varied between 8 and 20 $cm.s^{-1}$, with an approach direction predominantly from the north. It was noted however that from the 6th August onwards (storm B) the current direction tended to become more westerly, relating to a wave approach direction which is more easterly during this period creating a bottom current in a south-westerly direction. For S4/10 the influence of wave orbital motions on the currents was more apparent. Current speeds are more variable, ranging from 2 to 28 $cm.s^{-1}$, with larger currents generated when wave heights are higher. Current direction is also variable, and again is consistent with the wave approach direction.

Analysis of the entire data record from S4/1 shows that the average current velocity was 13 $cm.s^{-1}$ directed in a southerly direction (192°) (Figure 7.8). During the second storm period 6/8-10/8 the bottom currents were not appreciably higher in terms of a steady current, although the current is directed more in a south-westerly direction into the beach. The lack of increased current velocities expected during storm conditions may be due to the short periods of the waves during this event (T_p= 5.4 s) creating minimal bottom currents. The lack of change in direction also suggests that no significant downwelling bottom flow current was generated, although at one interval there is a 90° oscillation which does suggest a bottom return flow, coinciding with larger current speeds.

Directional changes in the bottom currents capable of entraining and transporting sediments are more noticeable in the alongshore and onshore-offshore current velocity plots (Figure 7.9), with the U currents for the two storm events showing that during peak storm conditions current speeds may have been capable of transporting fine sand material in an onshore direction, exceeding the 0.18 m/s threshold value suggested by Bradshaw (1991) for the East Coromandel inner shelf. Harris *et al.* (1983) for the north-east coast of New Zealand suggest that the threshold velocity for fine sand (0.2 mm) is 18 to 22 cm/s, .

7.1.6 Tidal Reduction

Tides on New Zealand's east coast are characterised as semi-diurnal, with a small diurnal inequality (Pickrill and Mitchell, 1979). The tidal range for the Pukehina-Matata coastal sector is based on the secondary port tidal station at Whale Island (Whakatane), which has a tidal range of 2.0 m, with mean sea level at 1.20 m above chart datum (N.Z. Nautical Almanac, 1992).

Tidal reduction was undertaken by deriving tidal constituents (Table 7.2) by least squares best fit harmonic analysis using the computer program *Thanal* (de Lange *et al.*, 1993). Tidal constituents

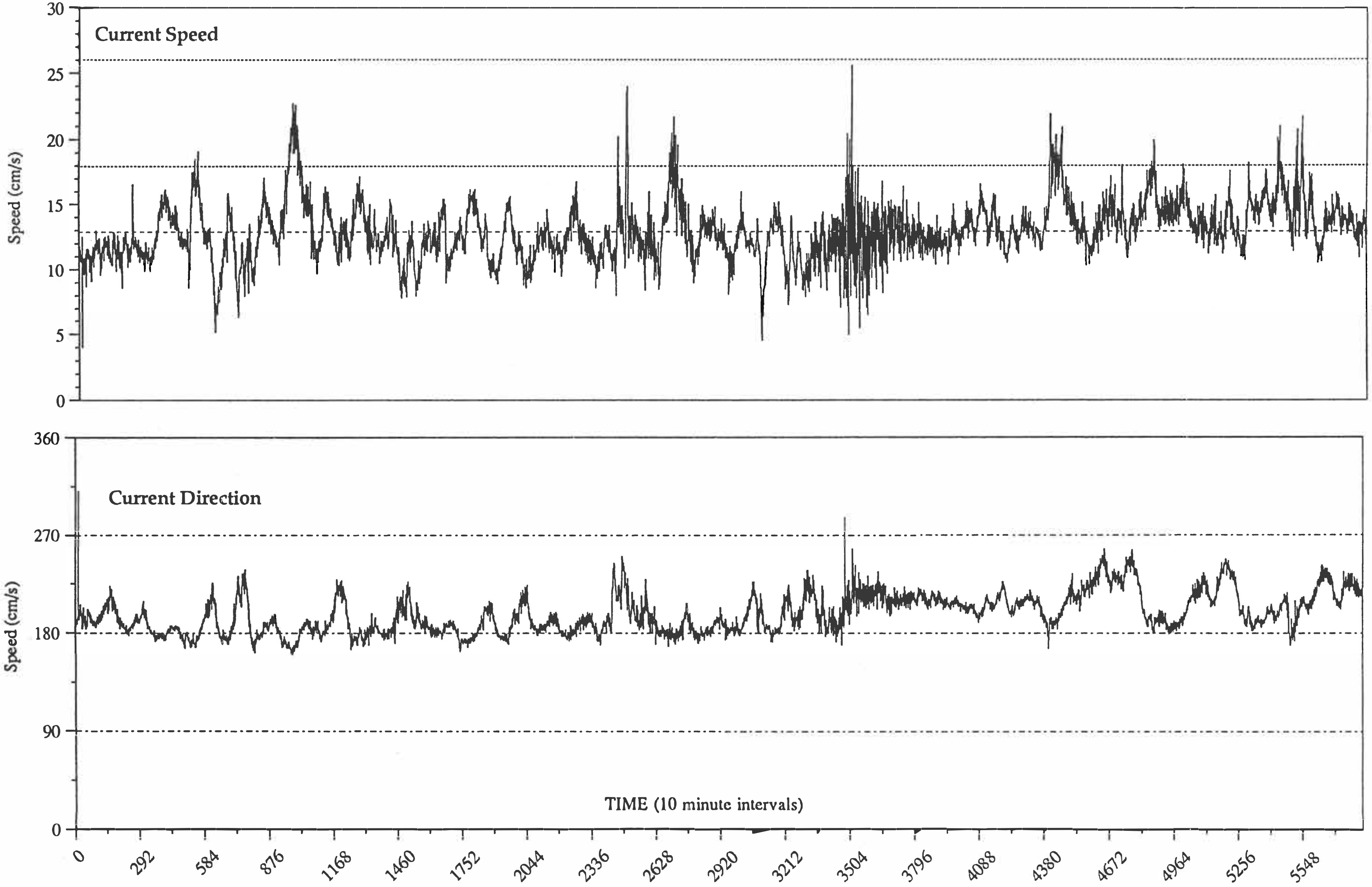


Figure 7.8 Time series plots from the S4/1 of *a)* current speed, and *b)* current direction, for the period 16/7/93 to 25/8/93. Time intervals on the x-axis are graduated in days.

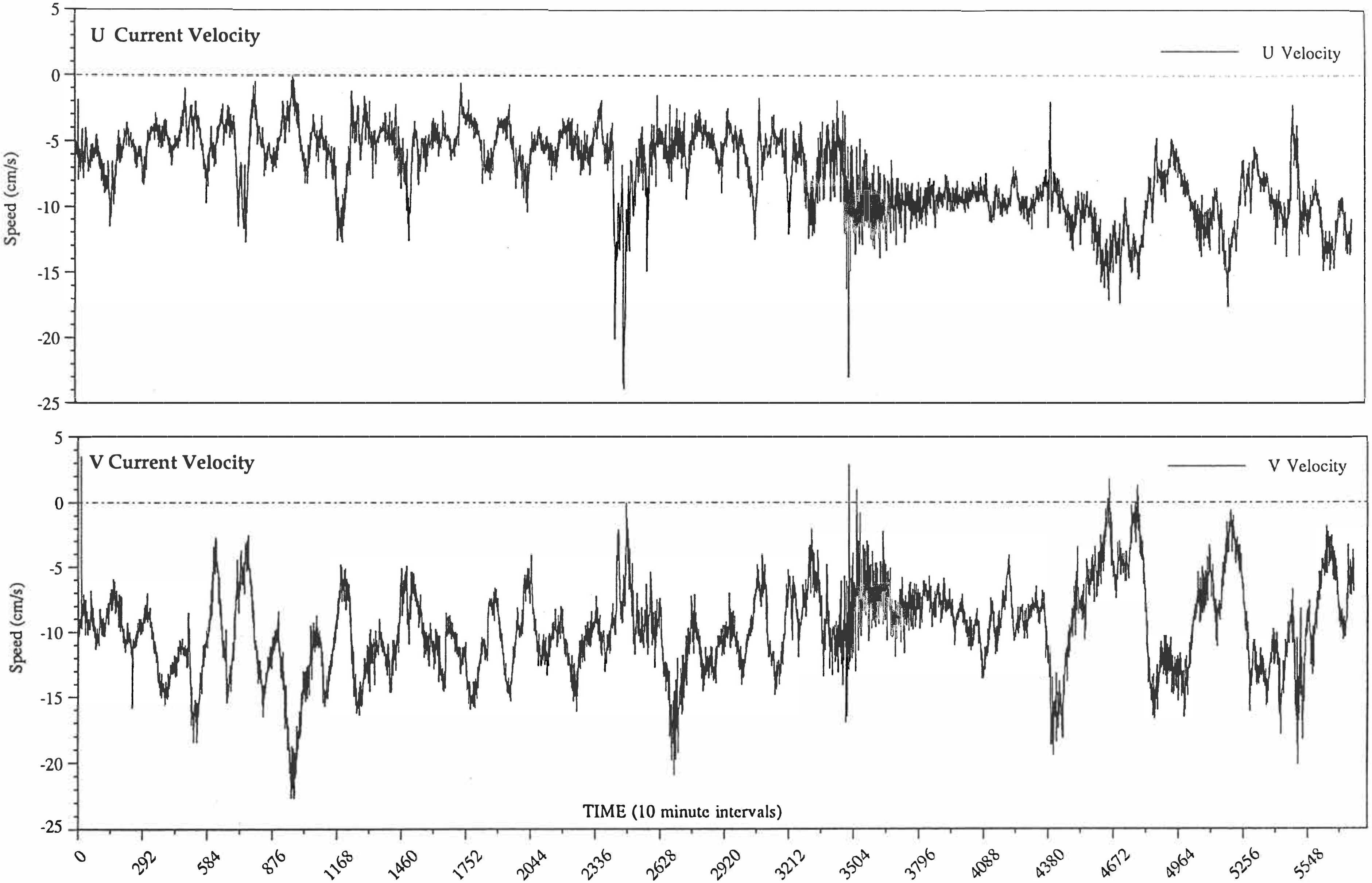


Figure 7.9 Time series plots from the S4/1 of *a)* U-velocity currents (alongshore), and *b)* V-velocity currents (onshore-offshore), for the period 16/7/93 to 25/8/93. Time intervals on the x-axis are graduated in days.

were fitted to pressure (depth) and velocity data, in the alongshore (U; east-west) and onshore-offshore (V; north-south) direction, giving the main tidal constituents and the amount of depth variation, current speed or direction accounted for by each constituent (Appendix VIII).

Table 7.2 Selected principal tidal constituents. *(source: Macmillan, 1966; McLellan, 1965)*

Constituent	*Symbol*	*Period (hours)*	*Relative size (M_2=100%)*
Principal lunar	M_2	12.42	100
Principal solar	S_2	12.00	46.6
Larger lunar elliptic	N_2	12.66	19.2
Lunisolar semidiurnal	K_2	11.97	12.7
Lunisolar diurnal	K_1	23.98	58.4
Principal lunar diurnal	O_1	25.82	41.5
Principal solar diurnal	P_1	24.07	19.4
Lunar fortnightly	M_f	327.86	17.2
Lunar monthly	M_m	661.30	9.1

* Tidal constituents are denoted by letter symbols which are abbreviations of their main characteristics, the subscript numbers indicate whether they are diurnal, semi-diurnal, quarter diurnal, sixth diurnal etc., or longer period (Macmillan, 1966; p.52)

For the depth data the M_2, N_2, and S_2 constituents are the most important, followed by the diurnal constituents, showing that the tidal effects on the still water level are predominantly due to semi-diurnal variations. For the U velocity data the M_m, O_1 and K_1 constituents derive most of the tidal effects, with the K_1, O_1 and M_m for the V velocity data. Therefore the tidal velocities recorded are due mostly to diurnal variations, with the longer period constituents (e.g. M_m) being particularly important for the alongshore current velocities. An example of the predicted tidal effects for the depth data is presented in Figure 7.10, where larger neap-spring tidal cycles are superimposed on the smaller scale semi-diurnal tide.

The depth variations recorded by the S4/1 current meter (Figure 7.11a), show distinctive semi-diurnal tidal effects, with other effects also apparent associated with wave motions. From tidal reduction the residual depth fluctuations show only minor variation of less than ± 0.3 m, except for the two storm periods, particularly in the second instance (storm B) where large variations of up to ± 1.3 m occur, corresponding with storm surge (Figure 7.11b). The residual variations are the result of winds producing mini-storm surges and of atmospheric pressure fluctuations that raise or push down the local water level (Komar, 1976).

7.1.7 Residual Current Results

Removal of the predicted tidal oscillations from the current data using the computer programs *Thpred* and *Thresi* (de Lange *et al.*, 1993), yields the residual currents which are responsible for directional sediment transport. Residual current speeds (Figures 7.12& 7.13) are high in comparison

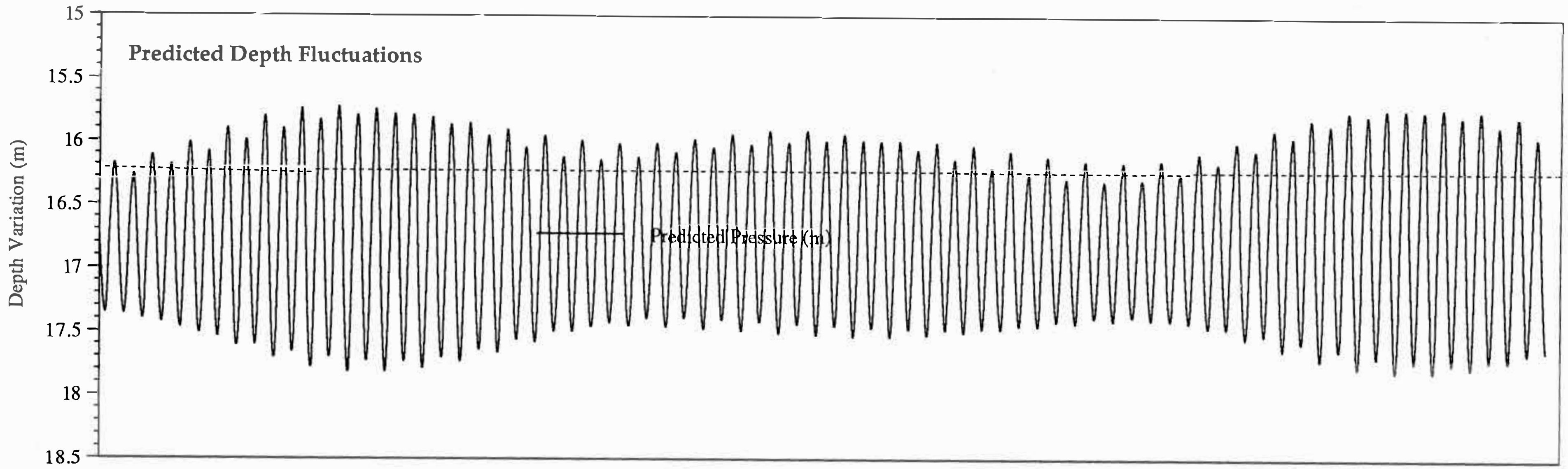


Figure 7.10 Time series plot of the predicted depth fluctuation from tidal effects, based on the pressure data recorded at the S4/1 site for the period 16/7/93 to 25/8/93. The plot displays a typical semi-diurnal tide. Time intervals on the x-axis are graduated in days.

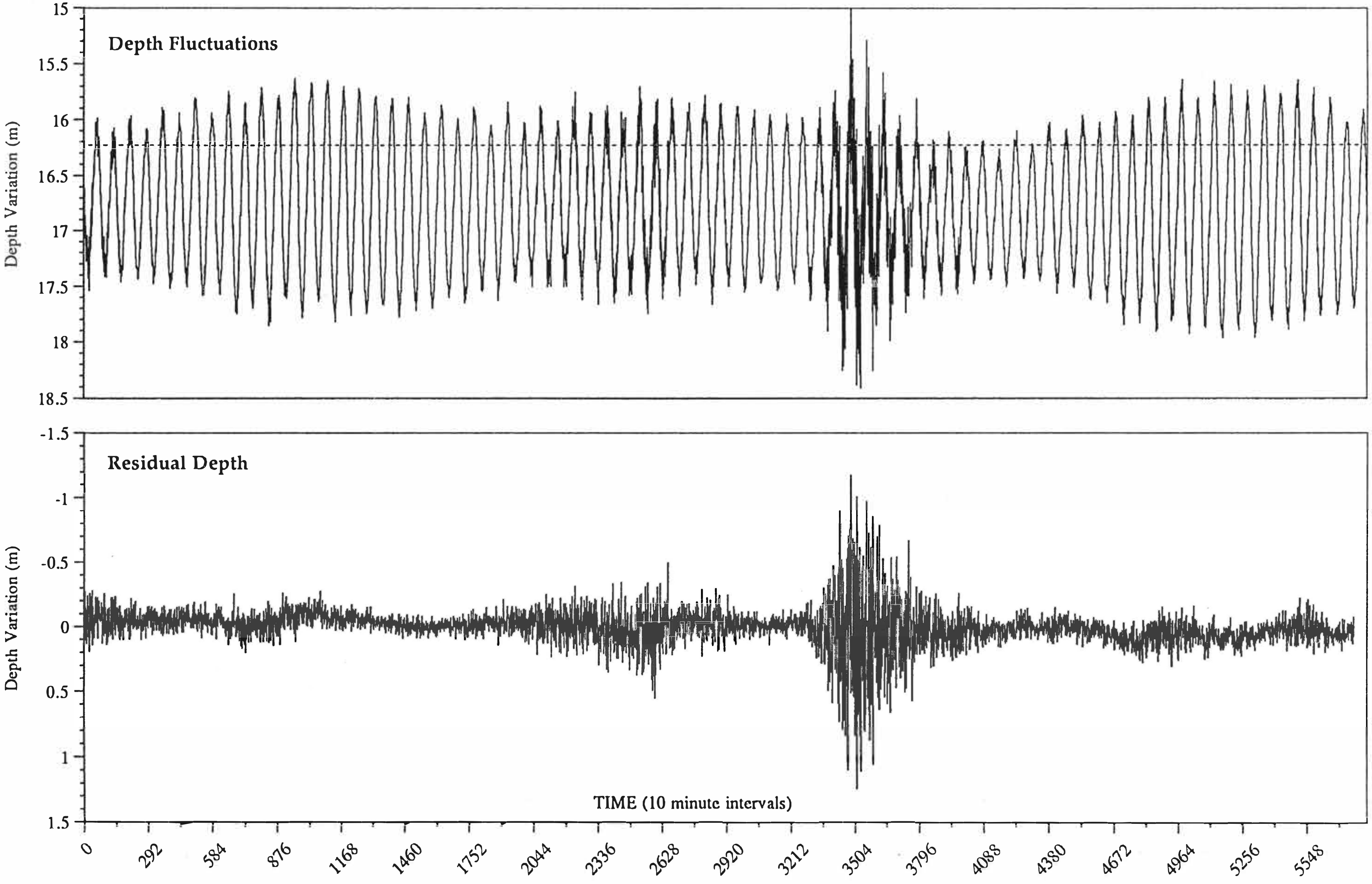


Figure 7.11 Time series plot of *a)* the recorded depth fluctuations, and *b)* the residual depth fluctuations after the removal of the predicted tidal effects. Based on the pressure data recorded at the S4/1 site for the period 16/7/93 to 25/8/93, displaying the effects of storm B on the data record. Time intervals on the x-axis are graduated in days.

with the total current velocities, and show a bottom current directed to the north-east.

The large residuals are due to the low velocities associated with tidal waves at Pukehina, as evidenced by the tidal current ellipse parameters (Table 7.3). The measured long-period currents at Pukehina are therefore not dominated by tidal waves, and instead may be:

(i) Rip currents;

(ii) Coastal currents;

and/or (iii) Wind driven currents.

Table 7.3 Tide ellipse parameter output from the *TCA* computer program, for S4/1 current data.

Constituent name	Period (hours)	Major axis (cm/s)	Minor axis (cm/s)	Inclination (degrees)	Phase (degrees)	Dir
O1	25.82	1.657	0.336	123.1	178.6	c
K1	23.93	1.651	0.154	116.1	-62.4	a
MM	661.31	1.204	0.539	148.3	-86.4	c
MSF	354.37	0.624	0.107	127.3	-145.4	a
J1	23.10	0.605	0.020	102.7	-73.6	a
M2	12.42	0.430	0.213	75.6	-124.6	c
Q1	26.87	0.415	0.052	130.0	157.1	c
ALP1	29.07	0.410	0.025	114.8	-23.9	a
OO1	22.31	0.289	0.004	112.8	-7.6	c
UPS1	21.58	0.274	0.169	117.1	-146.4	a
2Q1	28.01	0.242	0.073	8.2	-145.5	c
M4	6.21	0.186	0.055	171.0	-20.1	c
N2	12.66	0.184	0.009	76.9	-131.9	a
MK3	8.18	0.183	0.087	166.0	-162.5	c
NO1	24.83	0.179	0.102	21.4	-80.7	c
L2	12.19	0.175	0.086	97.8	78.8	a
ETA2	11.75	0.160	0.025	128.5	-47.6	a
SK3	7.99	0.157	0.004	97.6	114.8	c
M3	8.28	0.145	0.037	171.2	-75.6	c
MO3	8.39	0.145	0.016	128.8	52.3	c
S4	6.00	0.140	0.026	138.7	-51.7	c
MS4	6.10	0.138	0.055	99.8	-57.2	c
MU2	12.87	0.122	0.014	40.3	-148.2	c
MN4	6.27	0.108	0.012	160.7	-160.2	c
SN4	6.16	0.106	0.016	164.5	-160.1	a
M6	4.14	0.088	0.005	66.1	-30.4	c
S2	12.00	0.087	0.022	173.3	-150.4	c
EPS2	13.13	0.086	0.017	11.8	79.0	c
2MK5	4.93	0.074	0.011	149.1	52.1	c
2MN6	4.17	0.071	0.011	150.8	112.8	a
3MK7	3.53	0.053	0.023	176.9	157.1	a
2SK5	4.80	0.051	0.014	55.9	14.1	a
M8	3.11	0.042	0.017	51.2	153.7	c
2SM6	4.05	0.036	0.016	35.0	-29.2	c
2MS6	4.09	0.033	0.015	104.6	-106.4	a

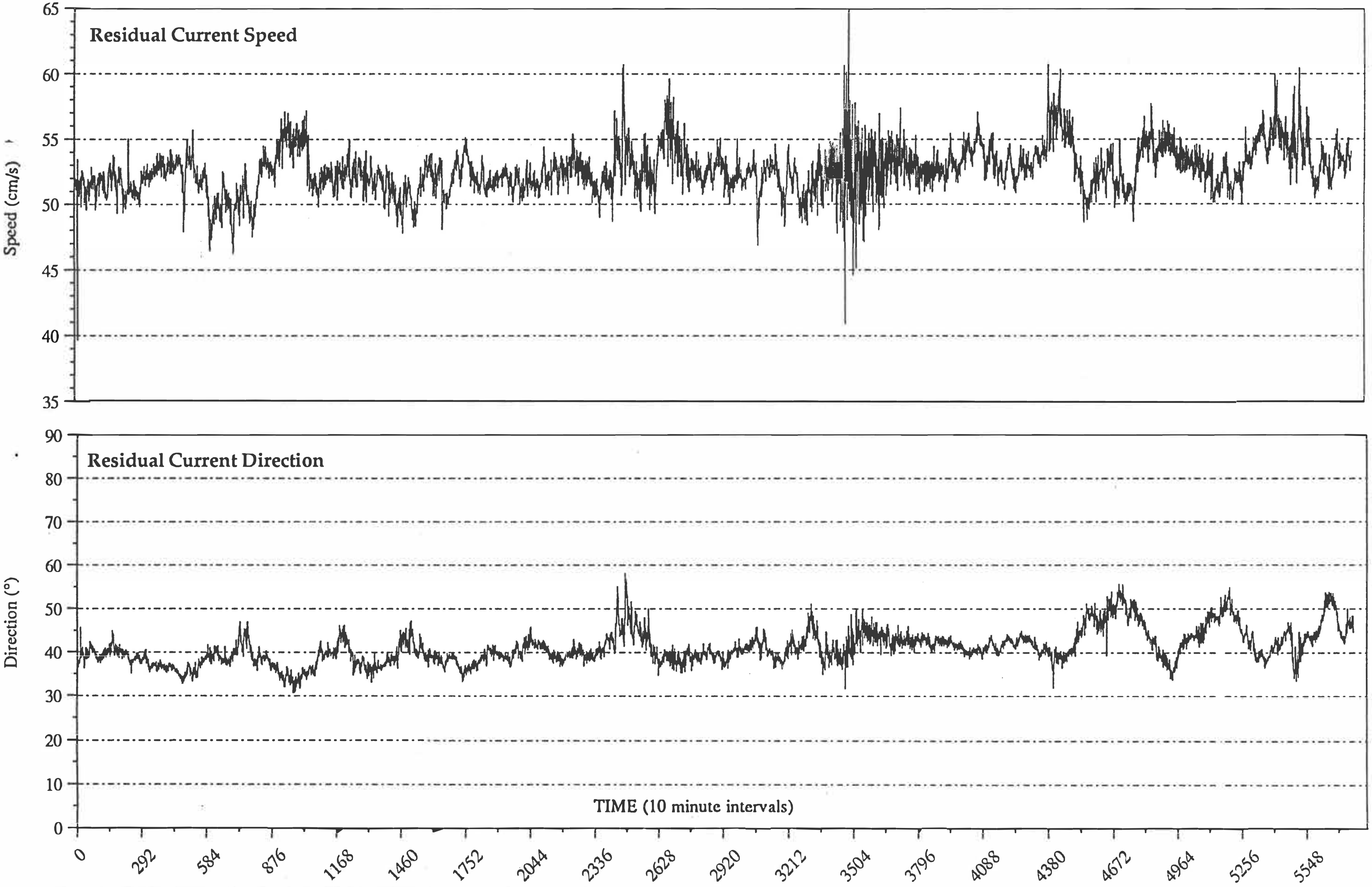


Figure 7.12 Time series plot of *a)* residual current speed, and *b)* residual current direction, derived from removal of the predicted tidal effects on the recorded current data at the S4/1 site for the period 16/7/93 to 25/8/93. Residual currents shown are overly large due to inaccurate prediction of the tidal currents. Time intervals on the x-axis are graduated in days.

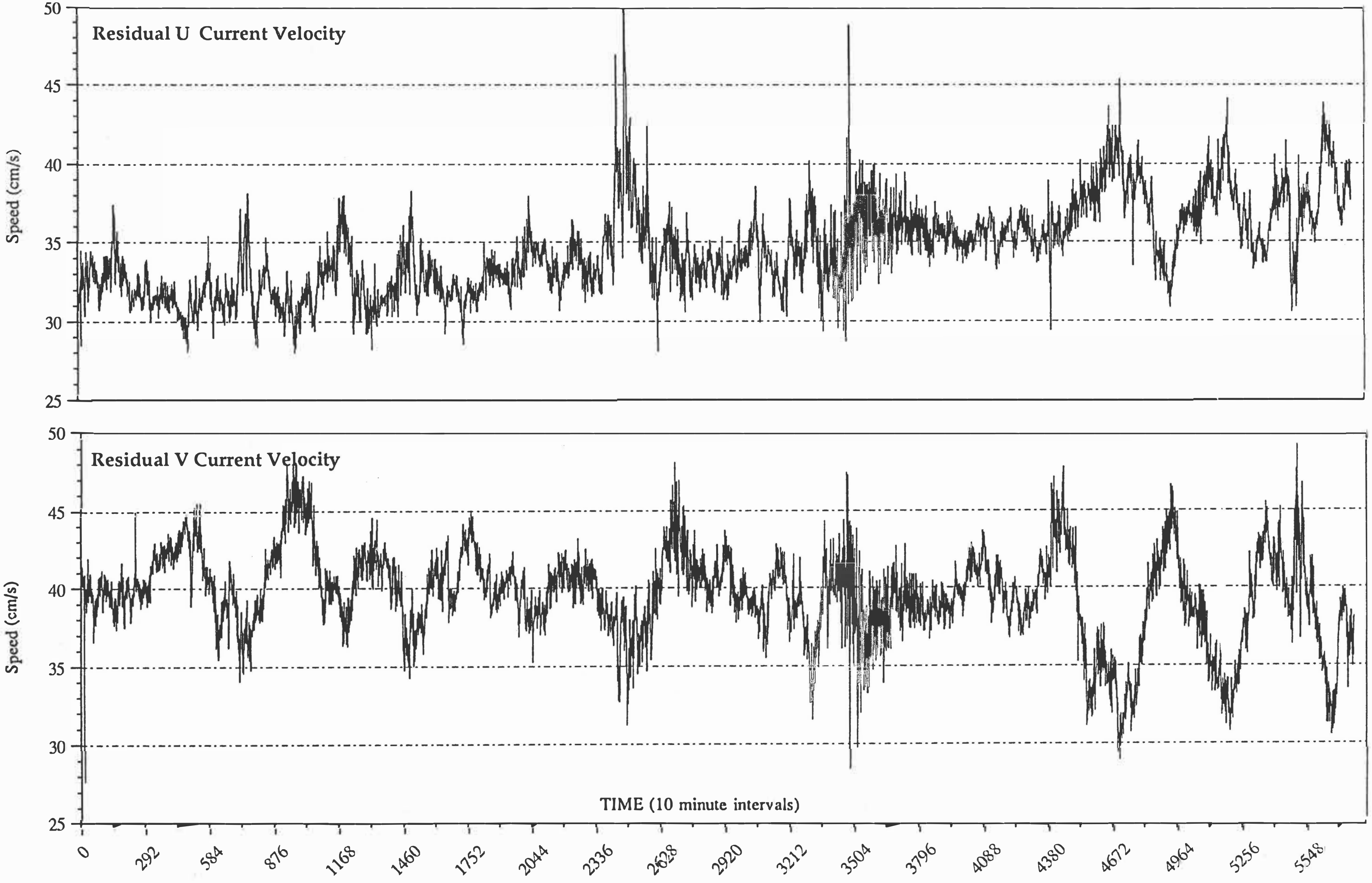


Figure 7.13 Time series plot of *a)* U-velocity currents (alongshore), and *b)* V-velocity currents (onshore-offshore), derived from removal of the predicted tidal effects on the recorded current data at the S4/1 site for the period 16/7/93 to 25/8/93. Residual currents shown are overly large due to inaccurate prediction of the tidal currents. Time intervals on the x-axis are graduated in days.

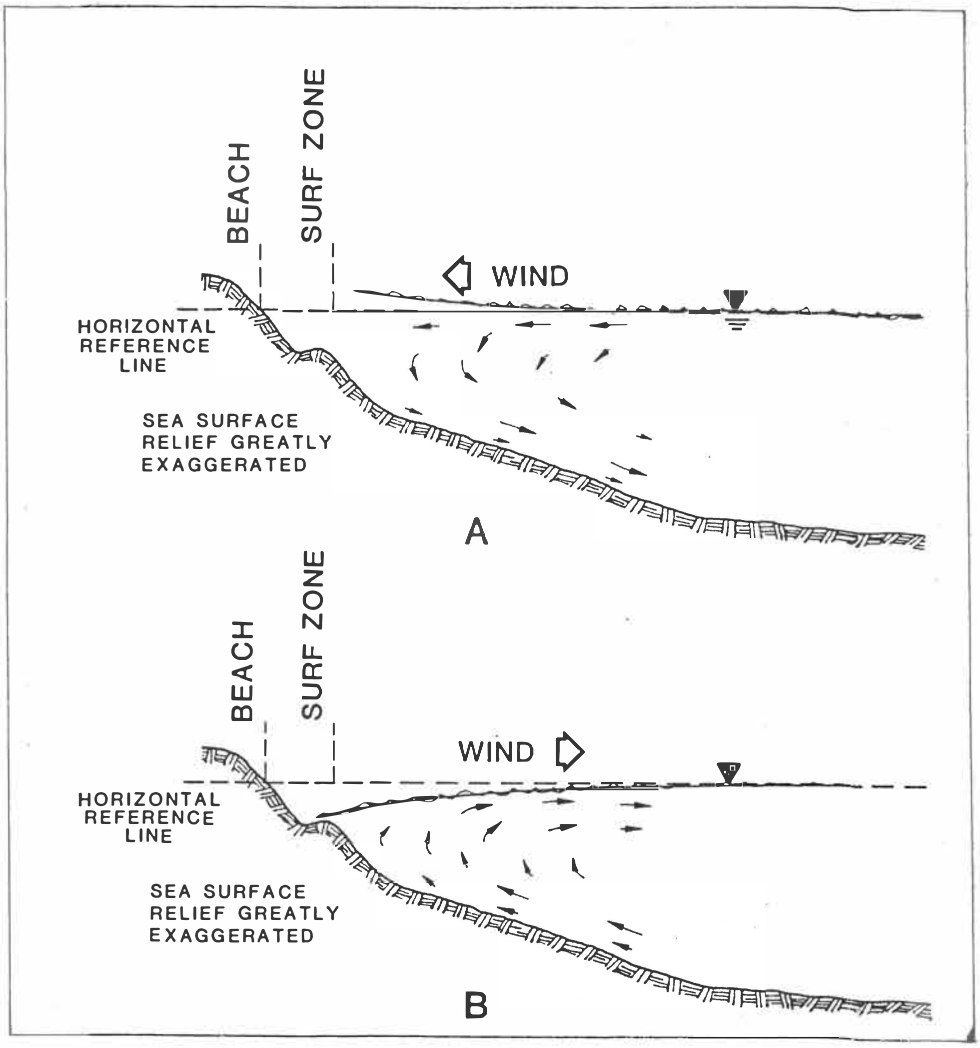


Figure 7.14 Characteristic simplified current flow patterns within the shoreface under: a) onshore winds and downwelling circulation pattern; and b) offshore winds and upwelling circulation. Note that onshore or offshore winds from oblique angles complicate these basic current flows setting up alongshore counter flows and shore-normal divergences and convergences. *(source: Niedoroda et al., 1985)*

Rip currents are unlikely due to the distance offshore of the S4 site of 1.5 km, and the short nature of the surfzone which acts to shorten the offshore influence of rip currents. In terms of transporting sediments seaward of the surfzone rip currents are an important process, but are unlikely to affect nearshore and inner shelf sedimentation more than a few hundred metres beyond the outer breaker zone (Wright, 1987). Similarly coastal currents may not have a large effect on the nearshore zone due to the relatively shallow water depth. However at deeper depths on the east Coromandel inner shelf the East Auckland current has been shown to produce local bottom currents capable of sediment transport (Bradshaw, 1991). Wind-driven currents are hence the most likely, as implied by the residual depth plot (Figure 7.11b) which shows large scale fluctuation events coinciding with the two storms. Outside of the surfzone, oceanic water circulations on storm-dominated shelves are largely controlled by the action of wind-driven currents (Wright, 1987), which are regarded as most significant in the nearshore and inner shelf environment (Wright, 1987; Harms, 1989;

Bradshaw, 1991). Bradshaw (1991) found that while the currents themselves do not appear to be responsible for sediment transport, upwelling (due to offshore winds) and downwelling (due to onshore winds) in the nearshore zone and inner shelf are of some importance in sediment transport (Figure 7.14). However the strength of wind-driven currents, and therefore their role in sediment transport, is dependant on the strength, duration and direction of the wind (Bradshaw, 1991).

Comparison of the actual and residual depth and velocity values with wind data from Whakatane airport for the same period (Figures 7.15a and 7.15b), shows that storm A corresponds with an easterly wind of up to 9.8 m/s, blowing over a local fetch. During storm B by contrast, the wind direction was from the south-west at speeds of up to 9.1 m/s. During both stormy periods the wind conditions were of short duration, with the residual currents and depth fluctuations greatest during the second storm, due to the greater swell component in comparison with storm A.

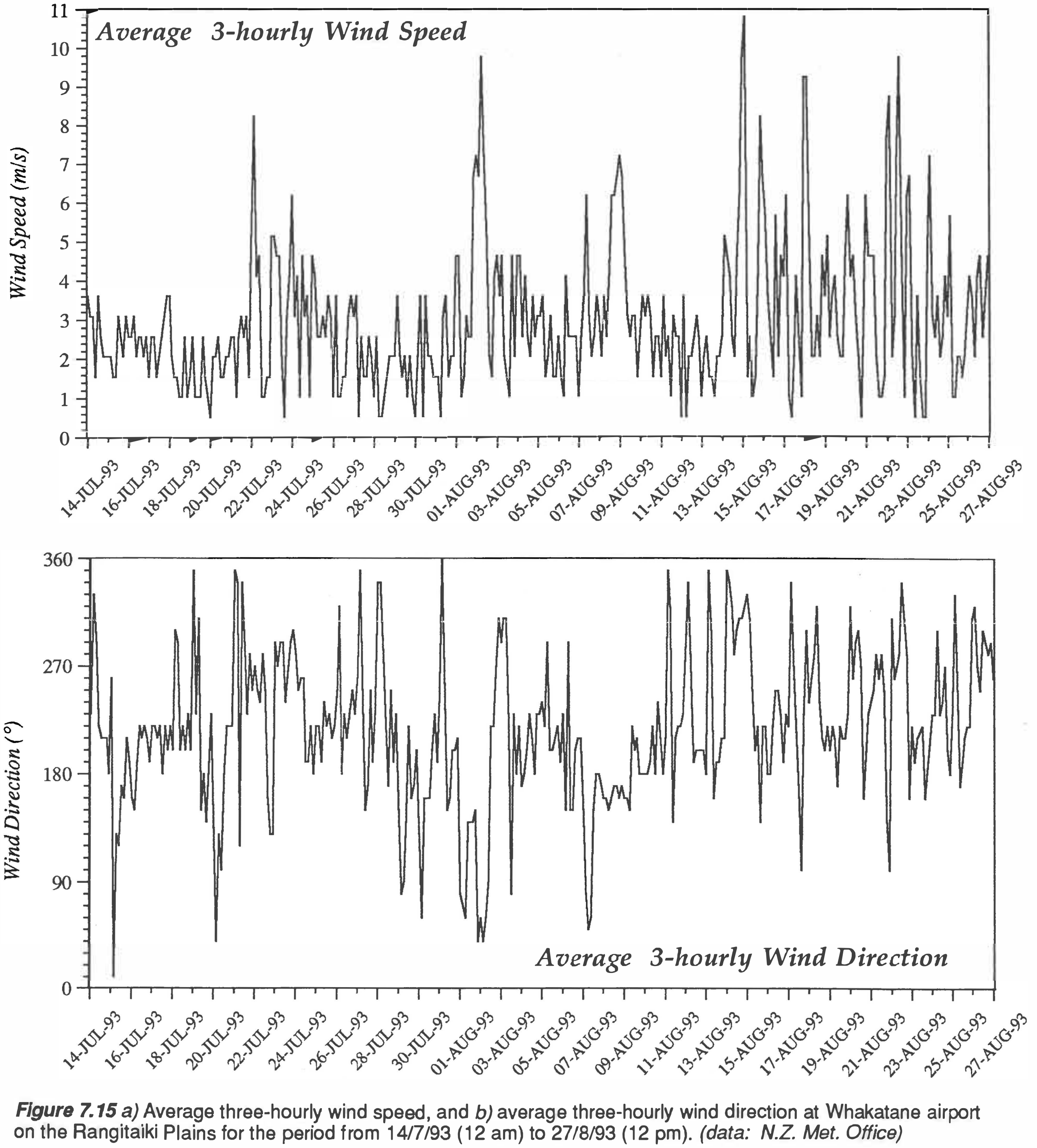


***Figure 7.15** a)* Average three-hourly wind speed, and *b)* average three-hourly wind direction at Whakatane airport on the Rangitaiki Plains for the period from 14/7/93 (12 am) to 27/8/93 (12 pm). *(data: N.Z. Met. Office)*

7.1.8 Discussion of Local Oceanography in Relation to Littoral Drift

The alongshore drift is driven solely by the wave energy and the wave-generated longshore current, and not by oceanic currents. The maximum depth to which sediment is mobile within the littoral drift zone is dependant upon the wave energy (height) and period, which at Mt. Maunganui Beach for example is suggested as about 12 m (Foster, 1991).

Smith (1986) suggests along the Otamarakau-Matata coast during the spring, summer and autumn months the swell waves may have a locally derived choppy sea superimposed on them by sea breezes, causing minor erosion of the beachface.

While the wave data collected here is the first instrumental data for the central Bay of Plenty coast, both Healy *et al.* (1977) and Smith (1986) have estimated the net littoral drift direction from determination of the average wave approach angle.

Smith (1986; pers. comm., 1992) suggests that an indication of the net wave approach between Matata and Otamarakau can be obtained from the local beach shape. The minor irregularities in the coastline in the lee of nearby offshore islands (i.e. Motuhora, Rurima, Motiti, and Motunau) are explained as indicating that the dominant wave approach is from the northeast.

Smith (1986) also indicates that published wave data do not support the view of Healy *et al.* (1977), who concluded from sediment data an overall eastward drift of sediments. Smith (1986) reasons that wave roses for wind and swell waves in Quayle (1984) from ship reports on wave conditions in the Bay of Plenty, indicates a dominance of north and easterly wave conditions, inferring a westward net littoral drift. Some 22% of all swell waves are from the east and a further 22% are from the north and northeast (Quayle, 1984). Locally derived wind waves are suggested as having a higher westerly component (Smith, 1986), as found during the period of beach observations. However, the deep water wave conditions in Quayle (1984) are not particularly relevant to the wave conditions within the surfzone which develop longshore currents and determine the net littoral drift direction. These local wind generated waves over short fetches are however apparently a significant component of the wave regime, although their influence on sediment erosion and transport of nearshore and littoral sediments is small by comparison with swell generated waves.

Recently numerical modelling of wave height data by Laing (1993) indicate wind-sea directions with a dominant westerly component, although the largest waves are generated from the north-east.

Wind conditions have been compiled for the Bay of Plenty previously (Quayle, 1984) from data collected at both Tauranga and Whakatane airports, which both lie about 30 km from the extremes of the study area boundaries, and due to local topographic effects may not be entirely representative of the Pukehina-Matata wind conditions, as indicated in the wind rose for Pukehina Beach (Figure 7.4). Whakatane, for example, is exposed more to southerly winds coming down the Rangitaiki Plains which are sheltered from further north by the coastal cliffs and Pleistocene topography.

From the six week wave and current meter deployment period, the waves had an averaged approach direction at 192° in an offshore direction. The corresponding bottom currents were to the south-south-west (average 197°). Hence, during the period 15th July to 26th August the expected net littoral drift would be in a south-easterly direction along the beach. However, this provides no indication of long-term net littoral drift, especially in light of the lack of storms and characteristic easterly swell conditions (Pickrill and Mitchell, 1979). Also the wave measurement site is outside of the littoral zone in which longshore drift takes place (deep water wave data) and wave conditions may differ from those experienced at the beach due to the increased effects of wave refraction for example, although beach observations at the time confirm a dominance of north-westerly wave approach.

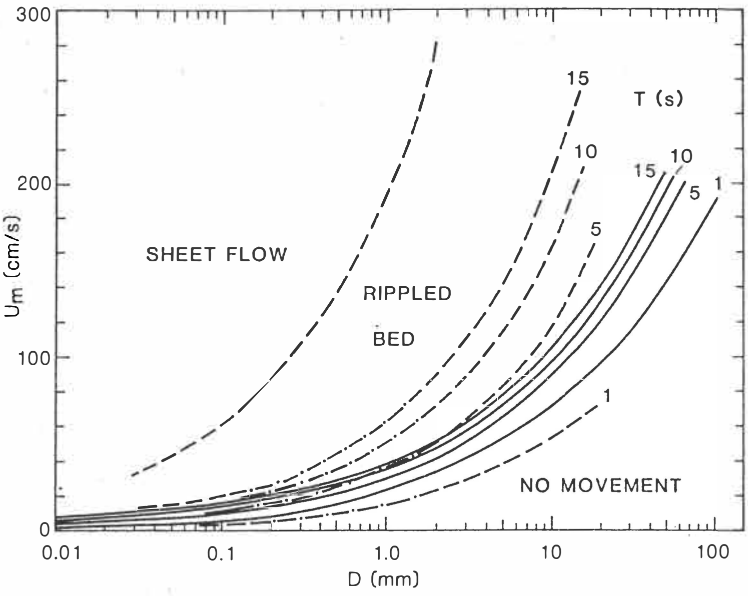


Figure 7.16 Derived velocity threshold curves for grain movement and sheet flow of quartz sand in water. Solid lines are threshold curves of Komar and Miller (1975). Dashed and dotted lines are experimental threshold curves of Dingler (1979), with dots absent where curves are extrapolated from the range of experimental evidence. Threshold curve for sheet flow, from Dingler and Inman (1977), is solid in the range of experimental evidence, and dashed where extrapolated. *(source: Clifton and Dingler, 1984).* The maximum bed conditions recorded at the S4/1 are denoted by a cross.

7.2 Sediment Transport by Waves and Currents

Once sediment movement has been initiated by waves, the sediment may be transported by a combination of wave and current induced flows. Most sediment transport occurs close to the sea-bed in the region of interaction between the wave boundary layer and the steady current (Sleath, 1984; Vincent *et al.*, 1982), and predominantly does so under storm conditions which induce larger waves and stronger bottom currents (Vincent *et al.*, 1982). Coarser sediment is moved as bedload, and this occurs within a few millimetres of the sea-bed (Komar, 1976; Sleath, 1984; Vincent *et al.*, 1982). Finer sediment is transported as suspended load above the sea-bed. As sediment motion is initiated, the sediment is thrown off the bottom and entrained by mean flows (Komar, 1976; Grant and Madsen, 1979). A rippled bed is known to enhance sediment suspension by increasing the intensity of vortices downcurrent from the crests and increasing the skin friction (Komar, 1976; Grant and Madsen, 1979; Vincent *et al.*, 1982; Bradshaw, 1991) (Figure 7.16).

7.2.1 Threshold Conditions for Sediment Transport

7.2.1.1 Unidirectional Currents

Accounting for the surface roughness of the seabed, the sediment threshold values for the action of currents only without any wave orbital motion effects can be calculated following a method outlined in Black (1983) for Whangarei Harbour sediment transport, and used by Bradshaw (1991) for east Coromandel sediment transport at Onemana.

An initial requirement is the critical skin friction velocity ($\bar{u}_{*\,cr}$), which can be calculated from Yalin's (1977) threshold curve, or alternatively and more simply it can be read off a graph such as that given in Miller *et al.* (1977), derived for quartz grains (ρ_s= 2650 kg/m^3 and ρ= 1000 kg/m^3). Sediment threshold velocities are also effected by the presence of bedforms which create eddies and aid sediment entrainment, which is incorporated from equation 7.1.

Surface roughness (z_o) over 2-dimensional bedforms:

$$z_o = \frac{\eta^2}{2\,\lambda} \qquad \text{...equation 7.1}$$

where: η= bedform height (m), and λ= wavelength (m). For the Pukehina S4 site this gives a z_o value of 0.0875.

The critical friction velocity is given by:

$$u_{*\,cr} = \frac{\bar{u}_{*\,cr}}{\left\{\left[1 - \frac{5.75}{c''}\log_{10}\left(\frac{0.37\,h}{z_o}\right)\right]^2\right\}^{0.5}} \qquad \text{...equation 7.2}$$

where the critical form drag factor c" is determined from:

$$\frac{c''}{8} = 3.3\log_{10}\left(\frac{h}{2\,z_o}\right) - 2.3 \qquad \text{...equation 7.3}$$

Relating the critical threshold velocity at 1 m above the seafloor to correspond with current measurements, is given as:

$$u_{1\,cr} = 5.75\,u_{*\,cr}\log_{10}\left(\frac{1}{z_o}\right) \qquad \text{...equation 7.4}$$

Using this method the critical threshold value for fine sand/medium sand boundary (0.25 mm) is 0.23 m/s which was only occasionally exceeded during the deployment period. For sediment of 0.11 mm, equivalent to the very fine sand/fine sand boundary, the critical threshold velocity is 0.15 m/s, which was exceeded approximately 35 % of the time. For the mean grain size of the site sediments (0.68 mm), there were no currents which exceeded the threshold value of 0.41 cm/s, necessary for sediment transport.

This method however does not include the influence of wave-induced currents on the threshold speed of sediment transport. It can be therefore be concluded that the currents themselves at Pukehina Beach in 16.1 m water depth are insufficient to entrain all but the very fine sands, and requires wave motion to initiate entrainment.

7.2.1.2 Combined Wave and Current Transport

Wave driven sediment transport under the influence of a steady bottom current was determined from the computer program *Mobile* developed for the University of Waikato Vax by Dr. Willem de Lange. The program was used to calculate the wave conditions required to initiate and entrain sediment under a range of conditions using a range of grain sizes. The threshold limits of wave height and period for fine sand, medium sand, coarse sand, and gravel for the Pukehina S4 site (h = 16.1 m), using an approximate corrected sediment density of the site sediments of 2540 kg.m^{-3} (Dommerholt, pers. comm., 1993), is depicted in Figure 7.17. For this analysis a steady bottom current of 12.0 cm/s was used, based on the current speed data obtained from the S4/1.

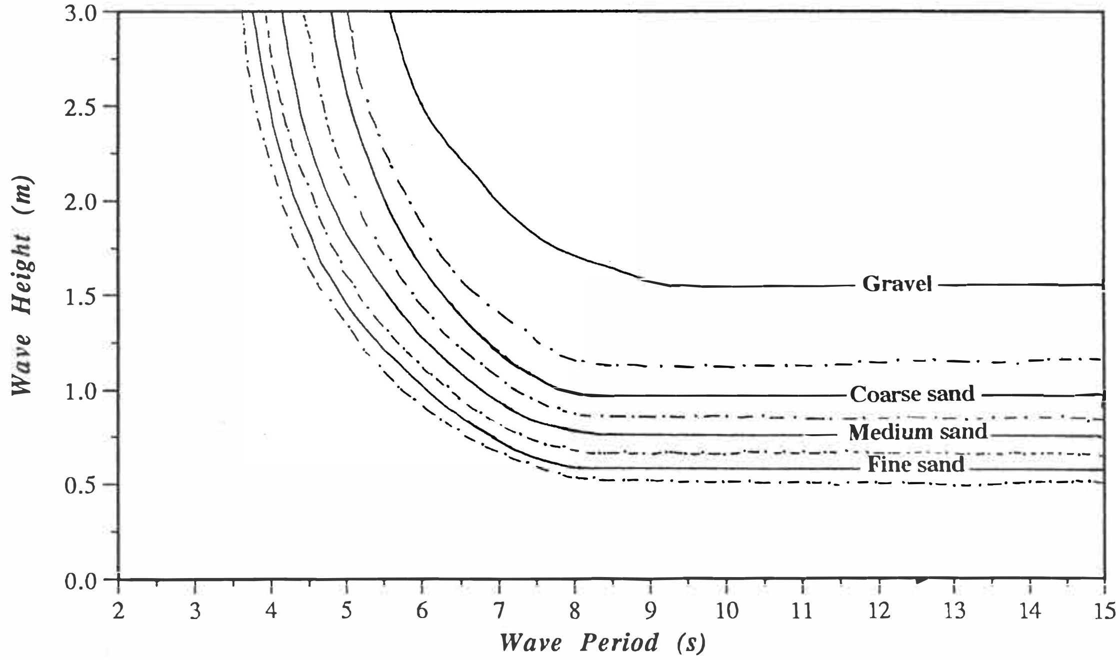


Figure 7.17 The critical combinations of wave height and period required for exceeding the threshold conditions for initiation of sediment transport at the S4 site, Pukehina south, for various grain sizes: fine sand (0.21 mm), medium sand (0.35 mm), coarse sand (0.71 mm), gravel (2.83 mm). The grain size values used were taken at the mid-point of each grain size interval, except for the gravel class, represented by solid lines. The inner and outer limits of each grain size class are denoted by the dashed and dotted lines. In all cases the sediment density used was 2540 kg.m^{-3}. Note that the mean grain size of the S4 site is 0.68 mm, which is about the median threshold limit of the coarse grain size curve shown.

Based on these threshold curves, the mean grain size of the sediments at the S4/1 site (0.68 mm) is expected to be transported if wave heights exceed 1.2 m and have periods of at least 8 seconds. However most of the wave periods recorded during deployment had periods of 5-7 seconds, i.e. short, steep waves generated over short fetches and mainly wind-driven, requiring 3.0 m waves to initiate sediment transport of 50% of the site sediments if the corresponding wave period is 5 s.

7.2.1 Frequency of Initiation of Sediment Transport

Using the wave data collected by the S4/10 during the deployment period the frequency of exceedence of the threshold conditions required to initiate sediment transport at the S4 site was determined (Figure 7.18). Based on this, movement of fine sand occurred 24.8 % of the time, medium sand 15.9 %, coarse sand 10.2 %, and gravel 3.1 % of the time. These figures are only applicable for the time period of S4 deployment, since the mean wave heights and wave periods appear to be underestimates of the annual wave regime at Pukehina. This underestimation is apparent from results obtained for the Tauranga inner shelf. Warren (1991) found that the frequency of initiation of fine sand was 35 % in 15 m water depth, with Harms (1989) reporting a figure of at least 40 % and probably up to 50-60% of the time for sediment in 13 m water depth. It is suggested that the figure of 24.8 % obtained for fine sands in this study is probably 5 % less than the true value.

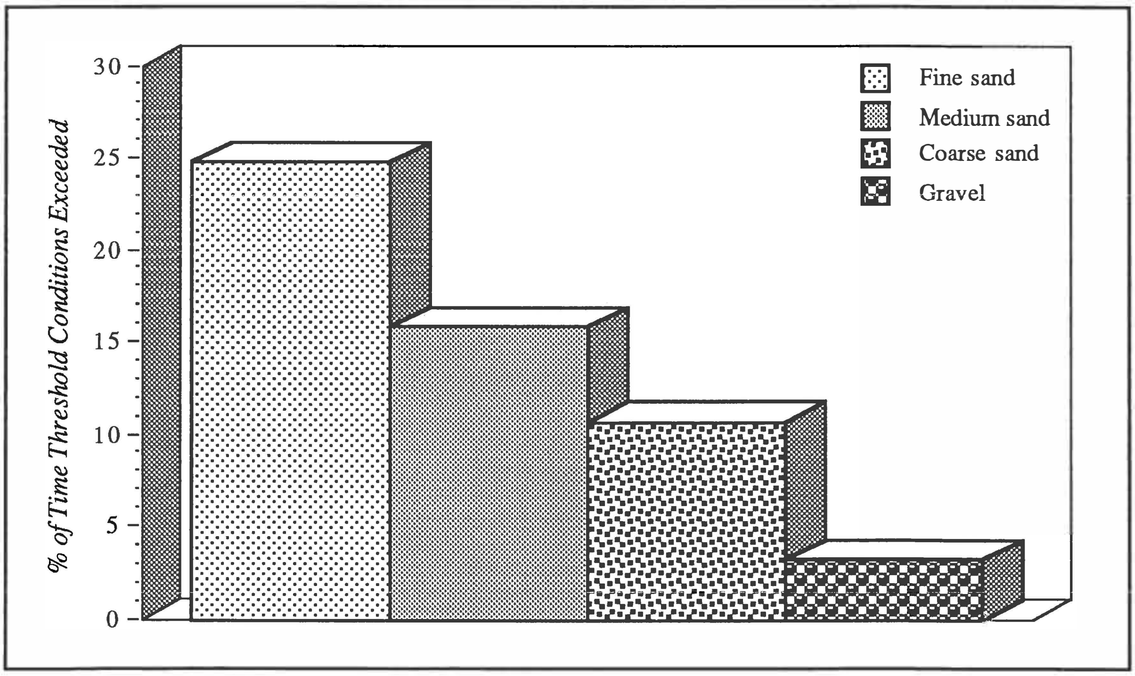


Figure 7.18 The percentage frequency of time that sediment motion, for four median grain sizes, is initiated on the lower shoreface, southern Pukehina Beach at the S4 site (16.1 m water depth), for the wave conditions recorded by the S4 wave meter for the period spanning 15th July to 26th August, 1993.

An interesting aspect to note is the much coarser grain size of the S4 site compared to further shoreward in 11 m water depth (Figure 7.19), giving rise to a textural change at the 12-14 m water depth. At the S4 site and at 15 m water depth (Chapter 5) there is very little fine sand material (~ 1.1%) by comparison with the 11 m water depth sediments, with only about 18 % medium grained sand. This would imply that sediment erosion occurs in the lower nearshore zone in this area (probably due to the reefs and submarine rock outcrops in the area), with removal of the finer fractions of the grain size curve, and sediment transport either onshore or offshore dependant on wave and current interactions. It may also represent the limit of significant onshore-offshore sediment transport (D_d) discussed in following sections.

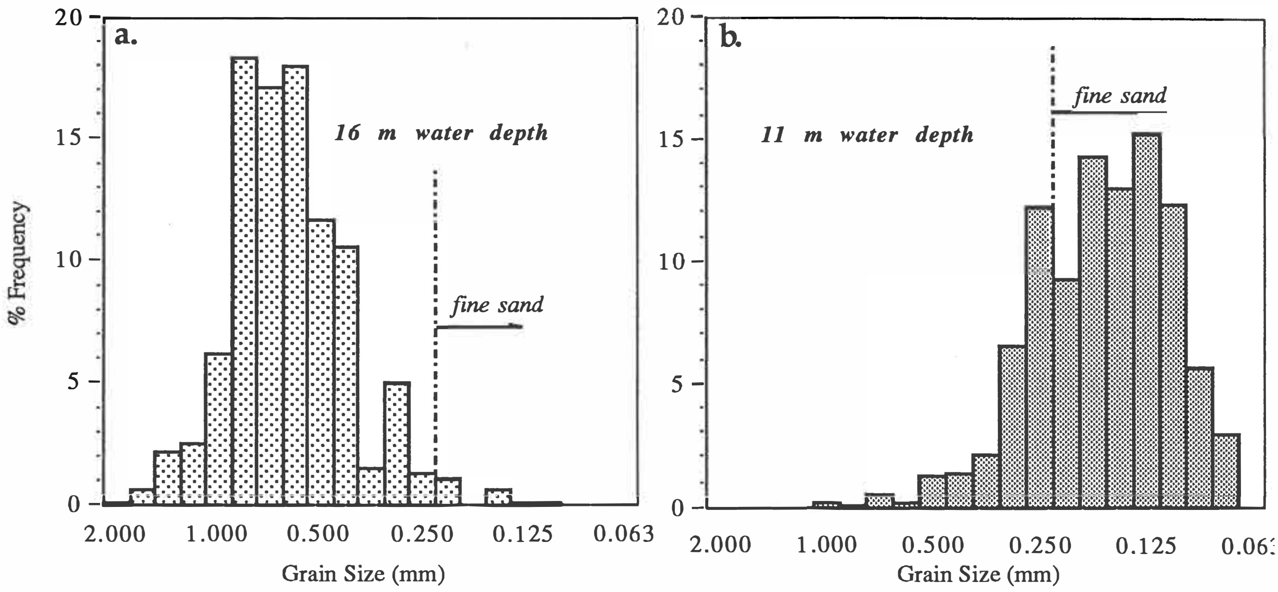


Figure 7.19 Grain size distribution histograms for the *a).* S4 site (16.1 m water depth), and *b).* further inshore at 11 m water depth.

From the current data collected in this study only a southerly directed current was observed, rather than both fair weather southerly directed current and storm induced northerly current found to occur on the east Coromandel shelf and Tauranga inner shelf (Bradshaw, 1991; Foster, 1992).

Bedforms remained similar over the duration of current meter deployment providing further evidence that current velocities were insufficient to entrain all but a small proportion of the sediments at the S4 site (i.e. fine sands), or less likely that wave conditions at the start and end of deployment were similar and in combination with the grain size characteristics of the sediments produced similar bedform characteristics.

7.3 Wave Refraction

Hay (1991) undertook broad scale wave refraction analysis of the western Bay of Plenty, which indicate the occurrence of wave refraction for the Town Point and Pukehina Beach region (Figure 7.20). The only specific wave refraction information contained within the study area, is an unpublished report produced as part of the internal graduate assessment at the University of Waikato.

Wave refraction patterns off Matata were originally analysed by Heather Dunbar (1989), as part of an unpublished beach erosion study within the Department of Earth Sciences, University of

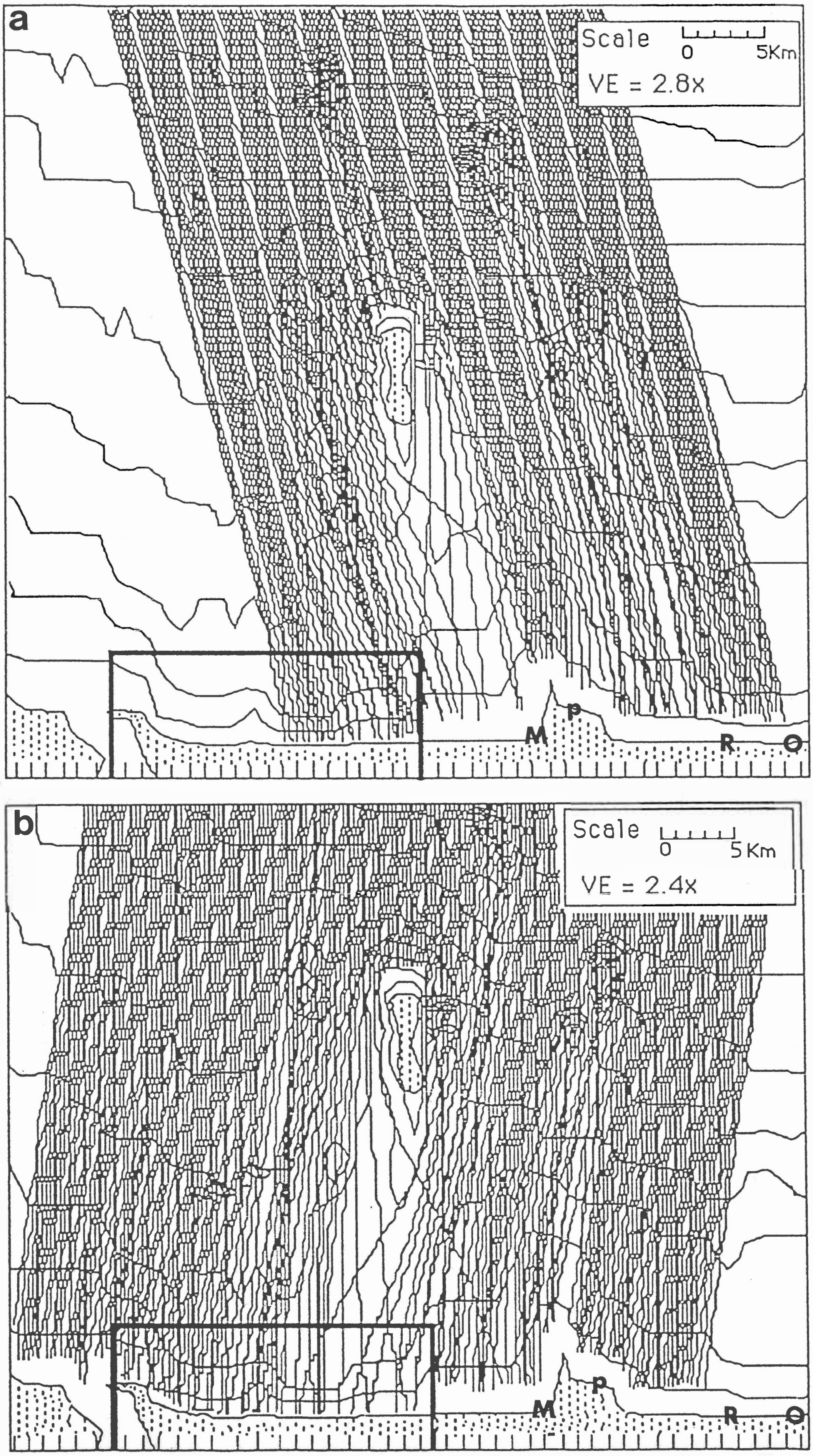


Figure 7.20 Wave refraction patterns for the Bay of Plenty incorporating the north-western segment of the Pukehina-Matata coastal sector, showing areas of wave focussing along Pukehina Beach (P). Wave rays are at 250 m inetrvals approaching from a) the north, and b) north-east. M= Maketu, P=Pukehina Beach, R= Rodgers Road, O= Otamarakau. *(source: Hay, 1991)*

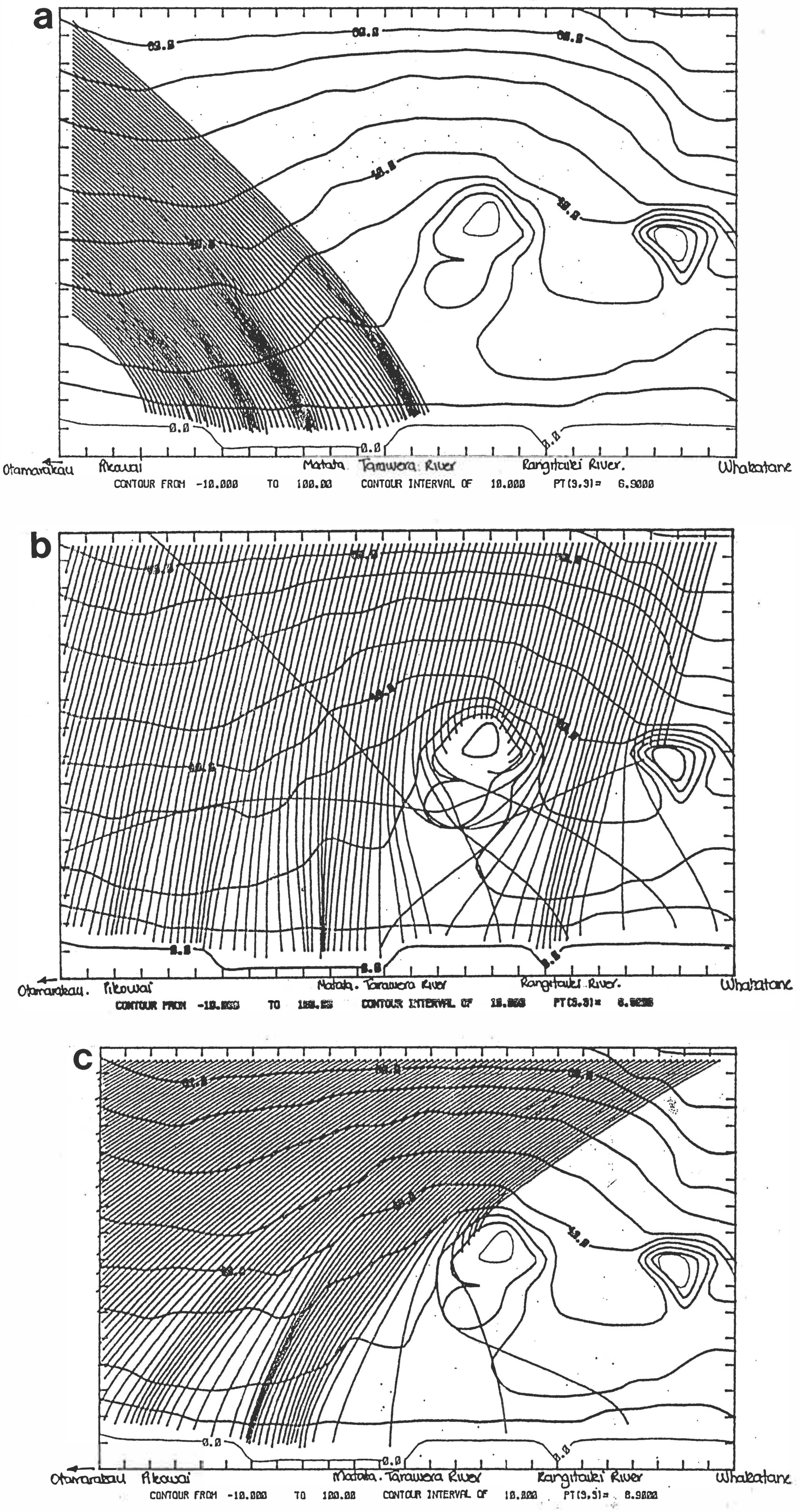


Figure 7. 21 Wave refraction patterns and zones of wave focussing in the nearshore for Matata, from north of Whakatane to Hauone for wave approach angles of *a)* 115° (WNW), *b)* 180° (N), and *c)* 225 (NE), using a design storm wave of H= 7.66 m and T = 11.9 s *(source: Dunbar, 1989)*

Waikato in 1989. Waves were run on an 30 km by 18 km grid, with a 1200 m grid spacing, covering an area from Hauone to west of Whakatane. Design waves in the analysis were hindcast from Cyclone Bola, 1988, which caused significant beach erosion to much of the area, as H_S= 7.7 m and T = 11.9 s, with media sources reporting observations of 8 m waves at sea.

Reverse wave tracking show that waves arriving at Matata mainly come from the north-west to north, with those from the north-east affected by wave refraction of the offshore islands of Motuhora (Whale Island) and Rurima Rocks. Results from the wave refraction analysis are shown in Figures 7.21a,b,c for orthogonal approach angles of 115° (WNW), 180° (N), and 225° (NE). Waves from a westerly direction (WNW), show areas of intense wave focussing at Matata, and about three kilometres north-west of Matata, with some wave focussing also at Herepuru. At more northerly angles the zones of wave focussing at the beach are less pronounced and shift progressively in a north-westerly direction, with the offshore islands and submarine ridge offshore from the Tarawera River mouth having an increased effect. Hence with storm waves from a north to north-easterly approach direction wave focussing and possible erosion is expected between Pikowai and Matata. Dunbar (1989) also provides some suggestion that larger breaking waves occur at greater depths if the angle of wave approach is more from the easterly tending quadrants, with lower values for more westerly wave approach.

Healy (1989) included a numerical wave refraction plot for Matata carried out as part of a hazard analysis for Whakatane Spit (Healy 1984), concluding that *"clearly design storm waves indeed focus on Matata Beach"*.

For the Pukehina end of the study area, wave refraction has also been shown to occur by Andy Duncan as part of an unpublished beach erosion study, within the Department of Earth Sciences, University of Waikato in 1991. These results unfortunately were not available, but there is a suspected strong influence on wave refraction patterns from the irregular nearshore submarine topography, illustrated in Figure 7.22.

7.4 Summary

- Wave approach directions from the north-east at Matata may be effected by wave refraction processes from Rurima rocks and Whale Island, lessening the effects of north-westerly littoral drift, causing an alongshore variation in breaking wave heights and hence greater or lesser alongshore sediment transport.

- An S4 current meter and S4DW wave and current meter were deployed in 16.1 m water depth offshore from the south-eastern (basal) end of Pukehina Spit near BOPCES site 27 (Healy *et al.*, 1977), for a six week period from 16th July to 26th August. During this period mean wave conditions were H_S= 0.64 m, T_S= 6.36 m, with an averaged wave approach direction of 192°. Maximum conditions were H_s= 2.79 m and T_p= 11.13 s. Two small duration storm events (30/7-2/8 and 6/8-10/8) were recorded during deployment.

- Wave and wind information together with Whakatane wind records and beach observations of local wind and wave conditions, suggest that a wind-driven current circulation predominates on the Pukehina nearshore and inner shelf regions.

- Daily beach observational data at Pukehina Beach over a three and a half month period from 20-April to 23-June 1993 and 15-July to 25-August 1993, gave an average breaking wave height of 0.58 m and period of 9.26 s. Winds were predominantly westerly (21 %), with the greatest wind speeds estimated for winds from the north-west, north, and north-east.

- Analysis of the nearshore seabed bottom currents offshore from Pukehina Beach, showed that the average current speed during S4 deployment was 12.95 cm/s directed overall at 192° in a southerly direction. Current speeds during the two recorded storm events, particularly the second storm (6/8-10/8) produced bottom currents of up to 25.4 cm/s, with a brief bottom return flow developed to the north-west, however this was of a minimal duration due to the short wave periods having a lessened effect of the bottom currents than for longer period waves of similar wave height (2.4 m).

- The effect of tides on the water level fluctuations at the S4 site is due principally to the semi-diurnal tidal constituents. However for the bottom currents, tides have minimal effect and are due to diurnal tidal constituents and longer period neap-spring tidal cycles, with the nature of the tidal ellipse for most constituents indicating significant wave shoaling effects in the nearshore zone at Pukehina Beach.

- Bottom currents in the Pukehina-Matata coastal sector nearshore and inner shelf are due primarily to wind-driven currents, with rip currents and coastal currents having some possible effect at shallower (littoral zone to middle shoreface) and deeper (lower inner shelf to middle shelf) depths respectively.

- Wave heights of > 3.0 m with a 5 s period, are required to initiate sediment motion for fine sand Initiation of fine sand movement is calculated to have occurred 24.8 % of the time, medium sand 15.9 %, coarse sand 10.2 %, and gravel 3.1 % at the S4 site. In terms of annual figures these are underestimates, particularly for the fine sand which is estimated to undergo movement approximately 35 % of the time at 16.1 m water depth.

- Current data was analysed using several computer programs to remove tidal effects from the current record. Tidal currents at the S4 site, southern Pukehina Beach, are near insignificant.

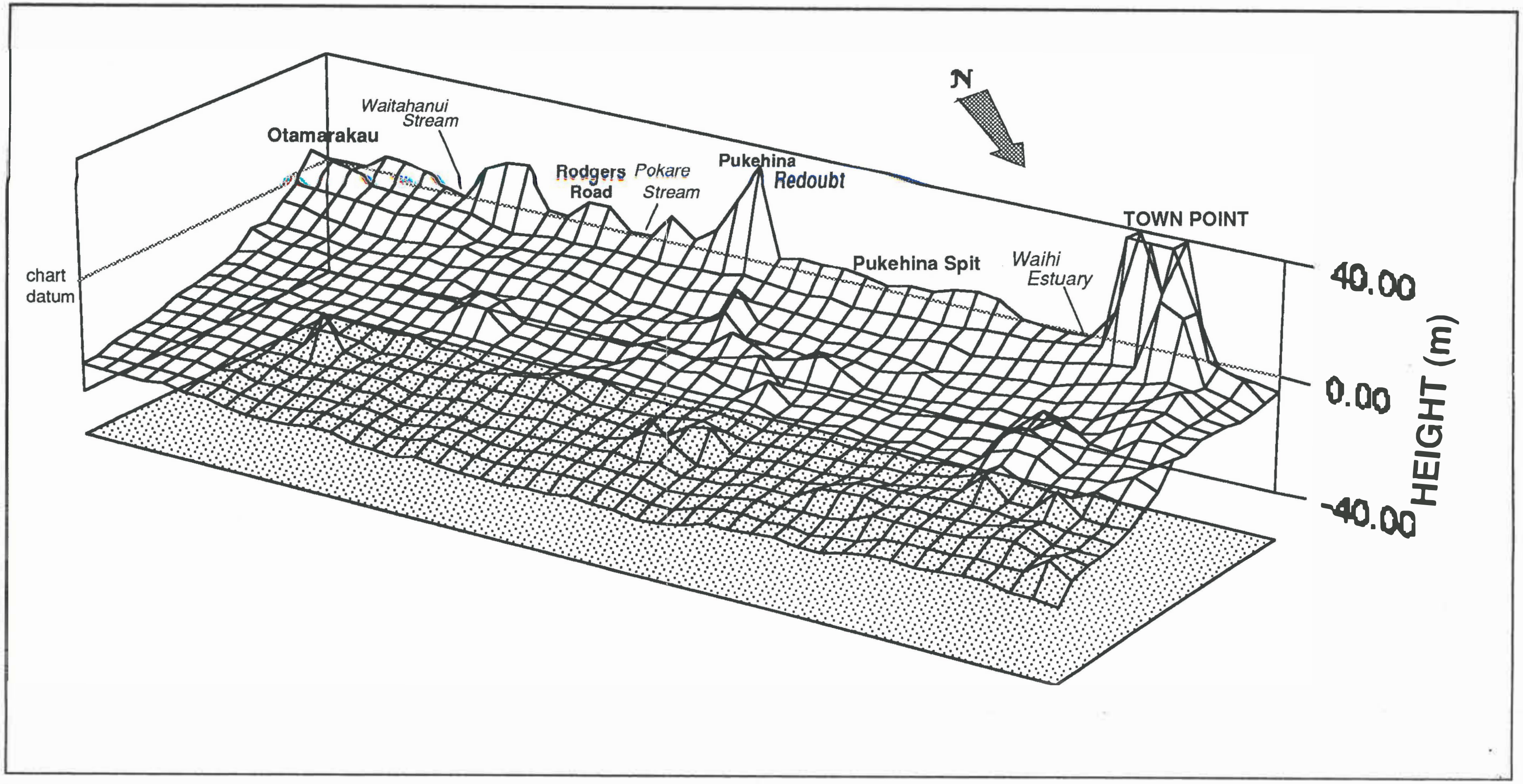


Figure 7.22 WINGZ™ plot of the nearshore bathymetry between Town Point and Otamarakau, showing the irregular topography present , which may cause significant wave refraction, as suggested from Figure 7.20.

CHAPTER EIGHT:

Nearshore Morphology and Sediment Transport

CHAPTER EIGHT
NEARSHORE MORPHOLOGY AND SEDIMENT TRANSPORT

8.0 Introduction

To help define the sediment transport and hydrodynamic processes responsible for the nearshore sediment distribution found in Chapter 5, the nearshore zone was mapped using side-scan sonar. The mapping aims to identify the extent and locations of morphological features, such as bedforms, and the extent and submarine rock outcrops and reefs which are thought to provide a source of sediments for the nearshore zone and beach (Chapter 5).

This chapter presents results from morphological surveys of the Pukehina-Matata nearshore zone, and the hydrodynamic conditions responsible for bedform generation. Sedimentation patterns and transport pathways along the coast are suggested by integrating this information with results from S4 deployment and sediment textural and mineralogical data from previous chapters. Additionally ideas and understandings of the beach-dune-nearshore system interaction within the study area are brought together and examined, with the development of conceptual models for Pukehina Beach.

8.1 Bedforms

8.1.1 Bedform Generation

Sediment bedforms within the nearshore and inner shelf zones are indicative of sediment transport, and accordingly, identification of bedforms and their implied hydraulic regimes indicates zones and relative magnitudes of sediment transport. Bedforms associated with the study area and Bay of Plenty coast are typical of wave dominated shelves (Harms, 1989; Bradshaw, 1991; Foster, 1991; Foster, 1992; Warren, 1992), and include in order of increasing size: ripples, megaripples, and low energy sand waves, and sand ridges (Table 8.1).

Table 8.1 Morphological definition of various bedforms. *(source: Boothroyd, 1985; and Bradshaw, 1991*)*

	Ripples	*Megaripples*	*Sand waves*	*Sand ridges**
Spacing	< 0.6 m	0.6 to 6.0 m	> 6 m	>100 m
Height vs spacing	variable	relatively large	relatively small	very small
Geometry	highly variable	sinuous to highly 3-dimensional, prominent scour pits in troughs	straight to sinuous, uniform scour in troughs	long crested, scour concentrated on up-current flanks
Characteristic flow velocity, u	low (>25-30, <40-50 cm/s)	high (>70-80, <100-150 cm/s)	moderate (>30-40, <70-80 cm/s)	n/a
Velocity asymmetry	negligible to substantial	negligible to substantial	usually substantial	n/a
Detection	divers	divers and sonographs	divers and sonographs	sonographs and echosounder

Bedforms change as the bottom orbital velocity changes, resulting in a progression from low order linear ripples, through megaripples, to a flat bed, with increasing flow velocity (Figure 8.1) (Clifton, 1976; Boothroyd, 1985). Linear ripples develop at a flow velocity just above that required to entrain sediment. As the velocity increases, ripple crests amalgamate and increase in size, and in coarse sediment megaripples develop (Boothroyd, 1985).

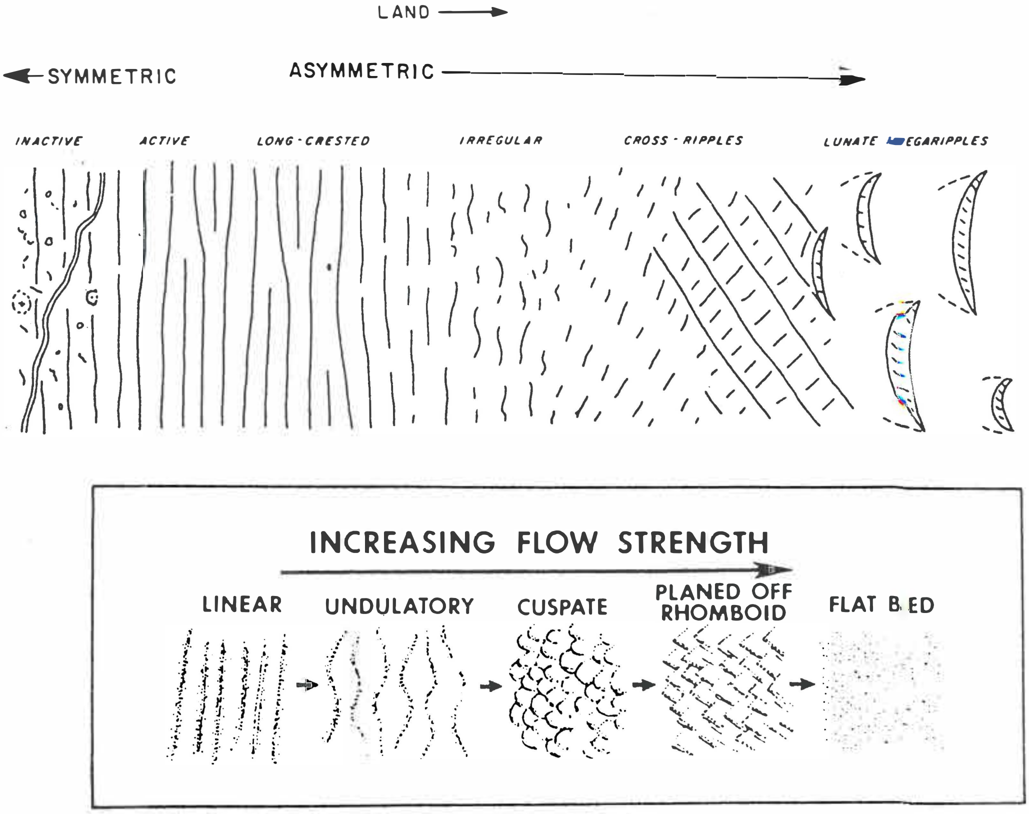


Figure 8.1 *a)* The progressive change in bedforms with increasing wave orbital asymmetry, and *b)* Change in shape from 2-dimensional to 3-dimensional bedforms with increasing current flow strength. *(source: Davis, 1985)*

Ripples and megaripples tend to form under oscillatory flow conditions. Bradshaw (1991) suggests that the presence of ripples and megaripple bedforms on the east Coromandel coast shows that flows associated with wave orbital currents are important in reworking nearshore and inner shelf sediments in that region.

8.1.2 Bedform Diver Observations

Observations of ripple and megaripple bedforms and general characteristics of the sea bed were initially undertaken by SCUBA divers from 21st to 23rd of April 1993, who measured the wavelength (λ), orientation (θ), and height (η) of bedforms where present, and took underwater photographs at each site station. Four sites (BOPCES sites 21, 24, 26, and 29) were selected covering the study area and any differences between sites based on information collected from nearshore sediment sampling. The BOPCES sites were chosen since these sites were previously profiled and their sediments sampled. Where possible diver observations were taken at approximately 2 m water depth intervals from an initial depth of 15 m, using a Ratheon DE 719B echo-sounder and Trimble Navigation *NavTrac* GPS satellite navigation system to determine exact positions and water depths. The diver ripple and megaripple observations are given in Table 8.2.

Table 8.2 SCUBA diver observations of nearshore morphology and bedforms measurements at BOPCES sites. Note site 0 is the S4 site of the original deployment.

Site No.	Location	Date	h (m)	Mz (mm)	λ (m)	η (m)	Observations*
0	Pukehina Sth	20-Apr-93	15.0	0.68	0.8	0.4	rocky reef outcrop (wave cut platform) 1m drop under cut with pumiceous seds. under harder congl., m. ripples on offshore side, c. sand
1	Puk. Redoubt	21-Apr-93	15.4	0.67	0.7	0.10	grav. sand, boulders everywhere 1-1.5m high, rounded congl./rhyol., weed
2	Puk. Redoubt	21-Apr-93	13.0	0.28	0.2-0.35	0.05	c.-med. sand change to green silty (algae?) layer (few mm) on top in onshore. direction.
3	Puk. Redoubt	21-Apr-93	10.8	0.18	0.2-0.31	0.04	green layer present on fine sand
4	Puk. Redoubt	21-Apr-93	8.8	0.16	0.15	0.01	small ripples, fine sand
5	Puk. Redoubt	21-Apr-93	6.9	0.18	0.16-0.2	0.01	sed. transport obs., surgy
6	Puk. Redoubt	21-Apr-93	4.9	0.21	0.1-0.15	0.01	strong surge
7	Otamarakau	21-Apr-93	15.4	0.59	0.7	0.13	megaripples, some coarse sand amongst 1 m across rocky outcrops
8	Otamarakau	21-Apr-93	12.7	0.20	0.25	0.07	fine sand with greenish layer on top
9	Otamarakau	21-Apr-93	10.7	0.19	0.25	0.06	fine sand with greenish layer on top
10	Pukehina Nth	21-Apr-93	15.8	0.31	0.45	0.03-0.04	irregular (discontinuous) sandy ripples
12	Pukehina Nth	21-Apr-93	11.7	0.16			no bedforms, flat featureless bed, very small holes, some surge
13	Pukehina Nth	21-Apr-93	9.0	0.18	0.15	0.01	slight surge
14	Matata	22-Apr-93	13.9	0.41	0.4	0.05-0.07	irregular ripples
15	Matata	22-Apr-93	12.2	0.48	0.7	0.10	v. sl. surge, fairly regular m. ripples, finer sand in middle, lots of scallop shells
16	Matata	22-Apr-93	9.7	0.52	0.9-1.0	0.15	very well defined megaripples, rocks (greywacke up to 40cm) & shells (*Mactra, Tawera spissa,* common Helmet shell) in troughs, some surge
17	Matata	22-Apr-93	7.0	0.23	0.05-0.1	0.01	small irregular ripples, fine sand, surge
18	Matata	22-Apr-93	5.2	0.25	0.1	0.01	irregular, sand dollars throughout

* Shell species (Penniket, 1982): *Mactra discors* (large trough shell)- sub-tidal to shallow water depths, sandy beaches; *Tawera spissa* (morning star)- shallow water to medium depths; *Xenophalium pyrum* (common helmet shell)- low tide to moderate depths, sandy beaches; *Pecten novaezelandiae* (queen scallop)- inter-tidal to moderate depths.

grav.= gravelly; congl.= conglomeritic; rhyol.= rhyolitic; c.= coarse; med.= medium; sed.= sediment; m.= mega; v. sl.= very slight; obs.= observed.

8.1.3 Ripple and Megaripple Observations

The bedforms observed appear wave generated, indicated by the orientation of bedforms in a shore parallel direction or at a slight angle to the shore. This corresponds to the predominant NW to WNW (310°) swell direction which was present at the time and preceded the field work, in which wave heights were about 1.5 m with short wave periods of approximately 7 s. Nearly all the sites where measurements were taken contained bedforms that had rounded crests, indicating that the bedforms had not been recently formed and were undergoing some degradation.

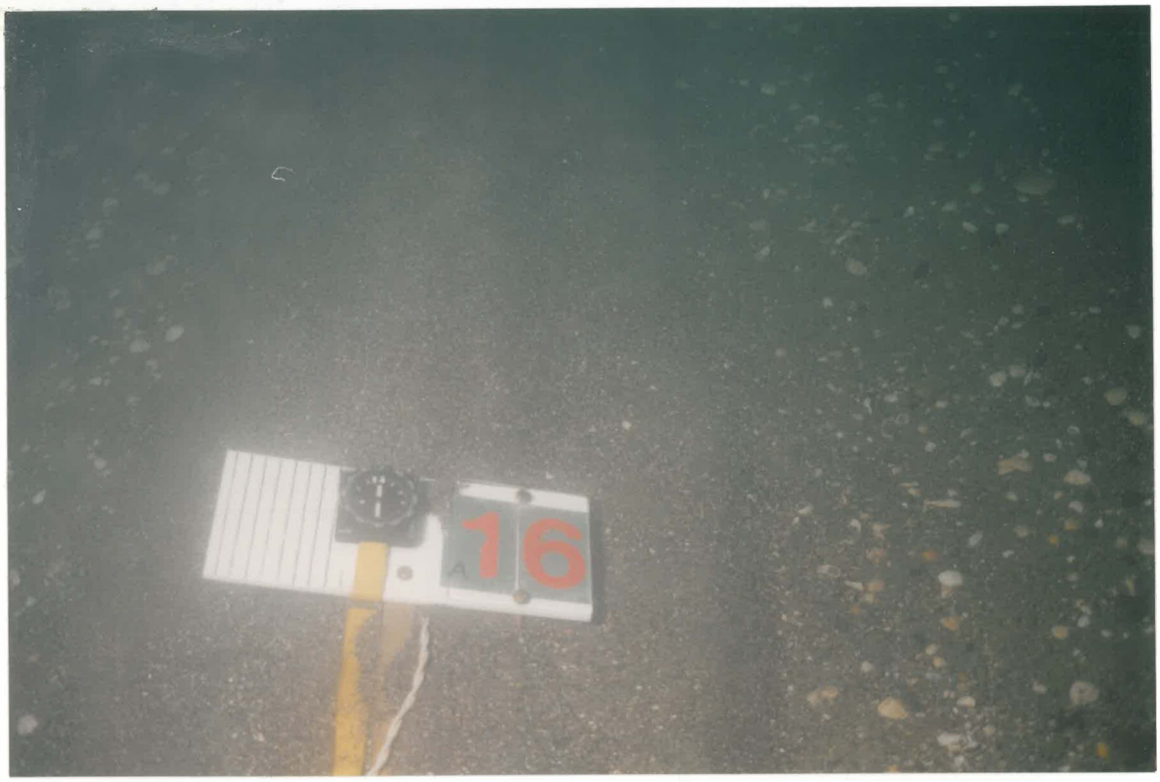


Figure 8.2 Megaripples (λ= 1.0 to 0.9 m, η= 0.15 m, M_Z= 0.62 mm) offshore from Matata (BOPCES 20) in 9.7 m water depth. Coarser shell and rock containing sediments in the troughs, consisting of dark grey sub-rounded greywacke pebbles up to 10 cm, and lighter coloured pumice and rhyolite pebbles. The empty shell species found are abundant *Tawera spissa*, with some *Mactra discors* and occasional *Xenophalium pyrum*. Note that the scale shown on the board is graduated in 1cm intervals.

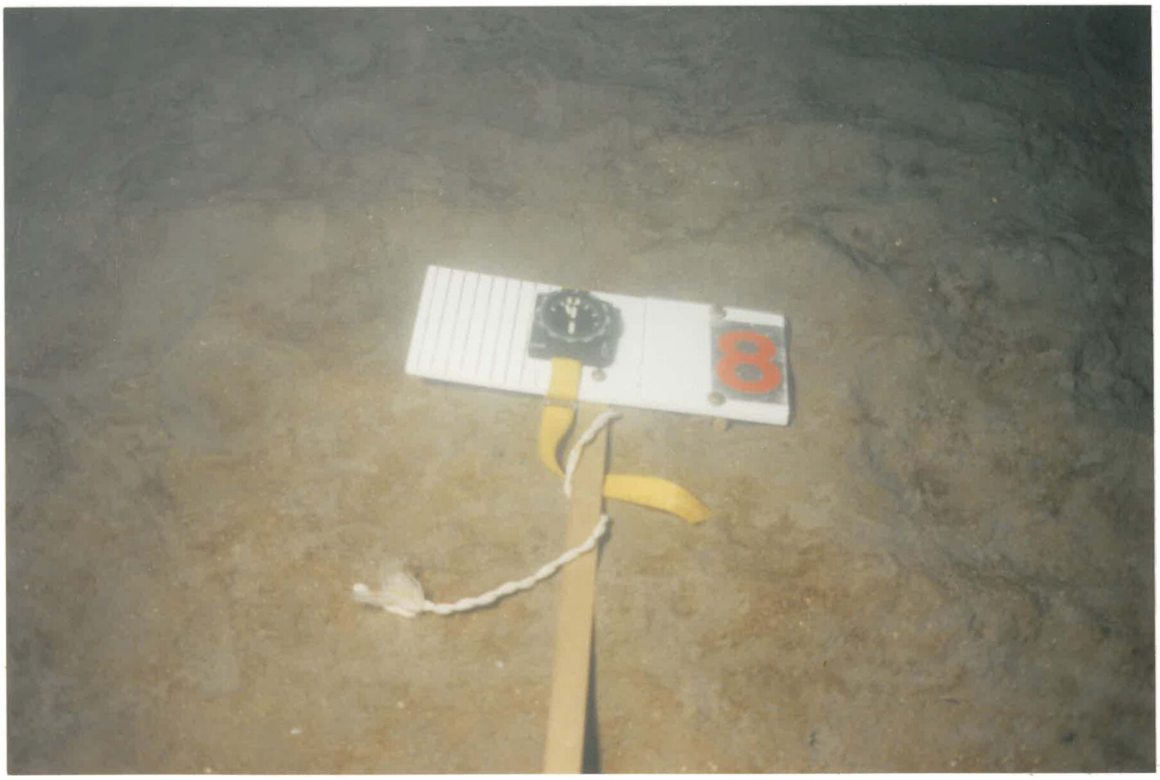


Figure 8.3 Pock marked seafloor with no bedforms offshore from northern Pukehina Spit (BOPCES 29) in 11.7 m water depth. Note the fine yellow-green silt-type layer of 1-2 mm on top, which was found at a number of sites.

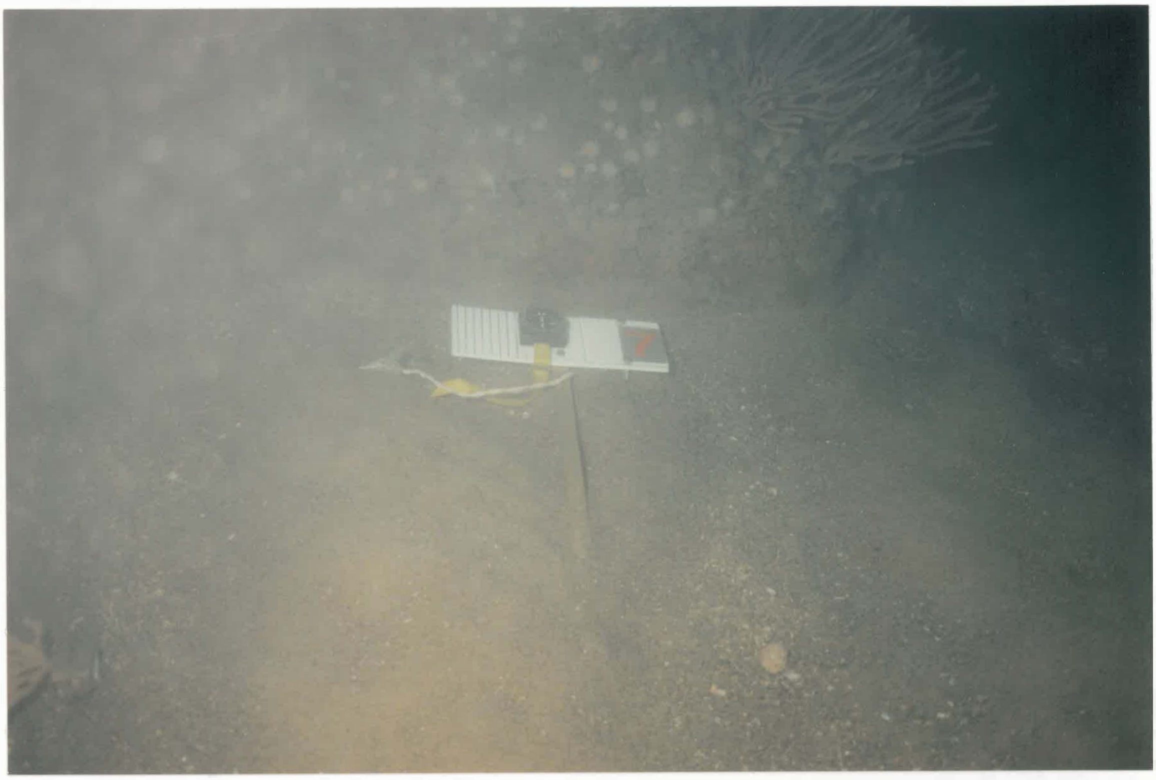


Figure 8.4 Megaripples (λ= 0.7 m, η= 0.13 m, M_Z= 0.59 mm) offshore from Otamarakau (BOPCES 24) in 15 m water depth, which occur amongst rock outcrops of approximately 1m diameter.

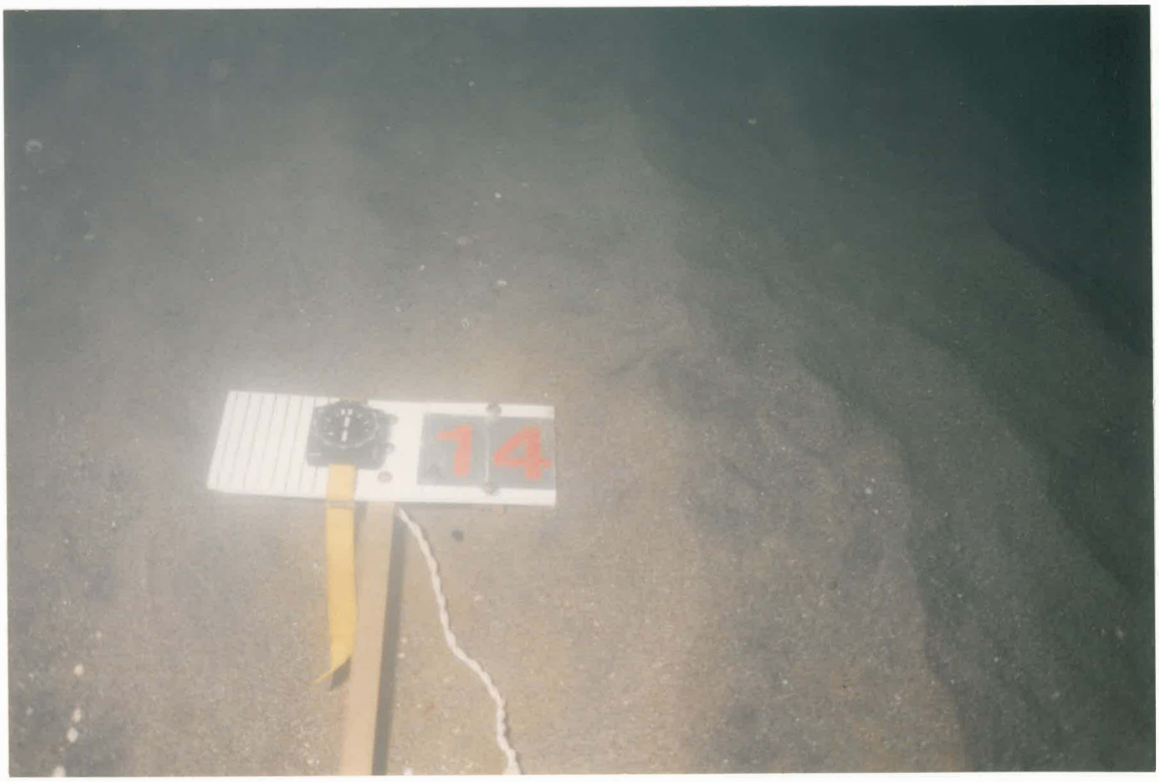


Figure 8.5 Ripples (λ= 0.4 m, η= 0.07 m, M_Z= 0.41 mm) offshore from Matata (BOPCES 20) in 13.9 m water depth.

There is some indication that bedforms in the Pukehina-Matata area are in part a function of water depth within the nearshore zone (Figure 8.6), where wave shoaling effects determine the bottom orbital motions and currents which generate the observed bedforms.

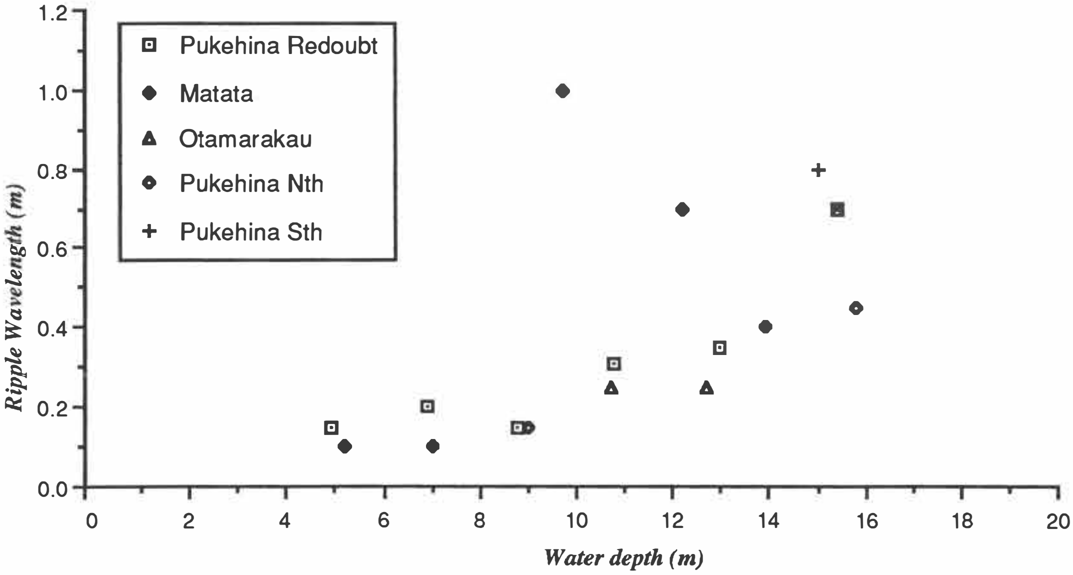


Figure 8.6 Plot of oscillation ripple wavelength at selected sites along the Pukehina-Matata coast versus depth, based on SCUBA measurements.

Kos'yan (1988) found that several relationships exist between bedform parameters of ripple height (η), wavelength (λ), and grain size diameter (D) (Equations 8.1-8.3). Given equations 8.1 and 8.2 and sediment grain size it should therefore be possible to determine the wavelength and height of bedforms anywhere within the Pukehina-Matata coastal sector. However these relationships are only valid if bedforms are dependant on wave orbital diameter for their generation.

$$\lambda = (83.5\pm2)\ D^{1.08\pm0.03} \qquad \textit{...equation 8.1}$$

$$\eta = (17.3\pm0.5)\ D^{1.22\pm0.03} \qquad \textit{...equation 8.2}$$

$$\eta/\lambda = 0.207\ D^{0.14} \qquad \textit{...equation 8.3}$$

Application of these equations is shown in Figure 8.7 where ripple wavelength (λ) is plotted against the mean grain size diameter of the bedform sediments. Bedform spacing does appear to be dependant on grain size, however for sediments with M_Z>0.25 mm (medium sand to gravel), the wave length is greater than that predicted, suggesting that ripple spacing is influenced by factors other than the grain size, and is dependant on the wave orbital diameter (Bradshaw, 1991). The ratio of bedform height to wavelength shows a good relationship with mean grain size at most sites (Figure 8.9) again suggesting that sediment texture has some control on the bedform characteristics within the Pukehina-Matata nearshore.

8.1.4 Predicted Bedform Generation

From the computer program *Mobile*, the wave conditions required to generate the bedforms observed are relatively low from H_S= 1.0 m and T_S= 8.0 s at Pukehina Redoubt in 15.4 m water depth (M_Z=0.67

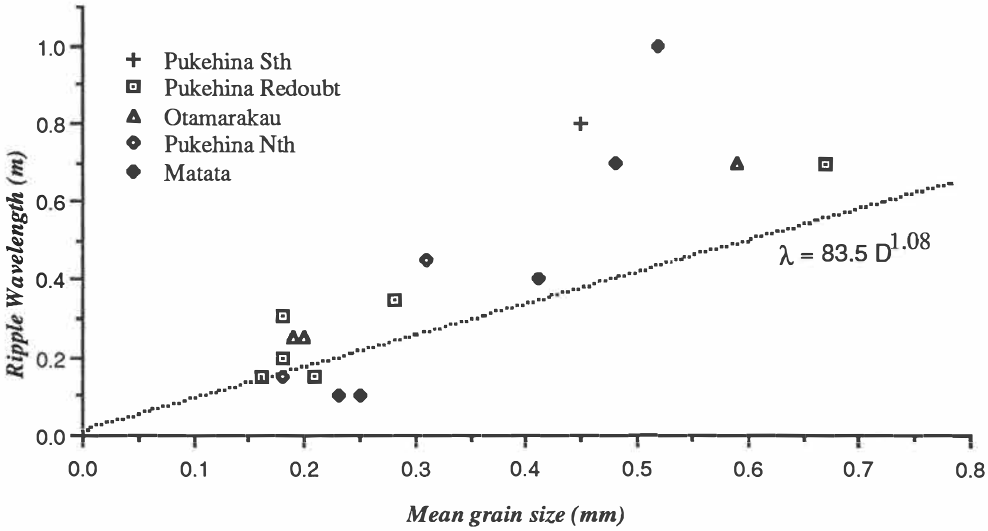


Figure 8.7 Wavelength (λ) of ripples and megaripples measured by SCUBA divers plotted against the associated mean grain size of the observed bedforms. Also shown is the theoretically expected curve of Kos'yan (1988), $\lambda = 83.5D^{1.08}$.

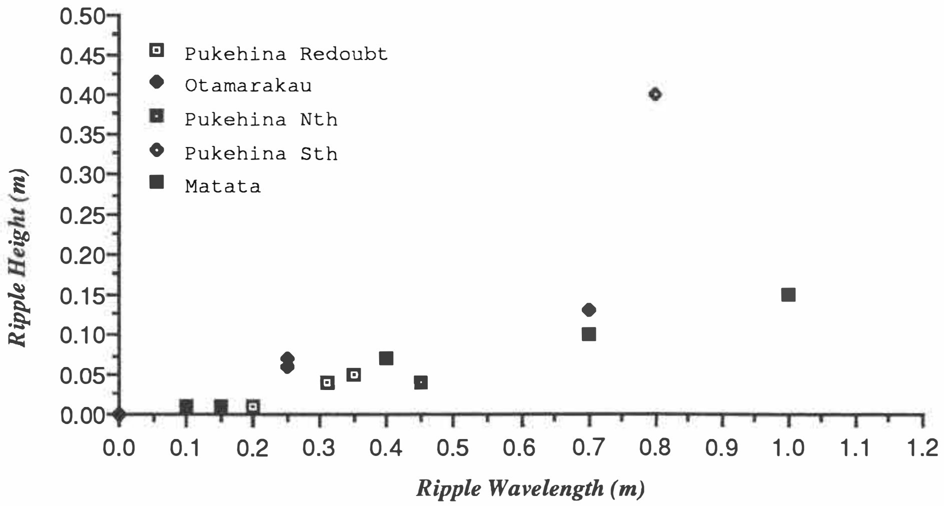


Figure 8.8 Plot of bedform length against height from SCUBA measurements, showing a linear relationship.

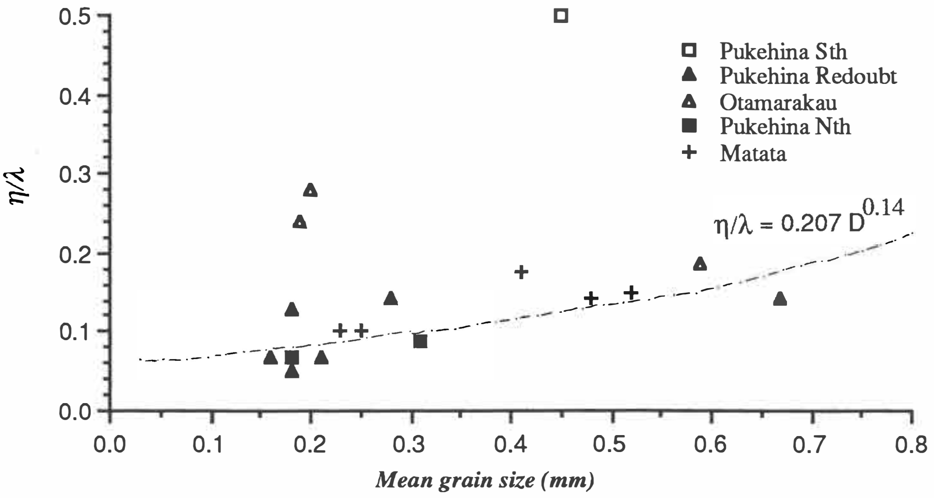


Figure 8.9 Relationship between the ratio of bedform wavelength to bedform height plotted against mean grain size, in association with the theoretically expectable curve of Kos'yan (1988).

mm, λ=0.80 m, η=0.11 m), to $H_S \leq 0.6$ m and T_S= 7.0 s in depths less than 13 m (e.g. Pukehina north, 12.7 m, M_Z= 0.20 mm). From the S4/10 wave recorder data these conditions are present fairly regularly, which would suggest that the sediment composing the bedforms is moved on average once a week at 15 m water depth, and at greater frequencies in shallower water. Larger bedforms tend to develop on coarse grained material, thus in general areas of megaripples should indicate coarser grained sediments composed of coarse sand to gravel sized material.

The predicted bedform sizes for the S4 site sediments (based on the mean grain size), under a variety of wave conditions is summarised from the *Mobile* program in Table 8.3.

Both Warren (1992) and Foster (1992) found that the program did not predict the larger bedforms found, suggesting these differences arise due to:
(i) Bedforms may take some time to respond to changing flow conditions and thus larger bedforms may be relict bedforms from differing flow regimes.
(ii) Theory predicting bedform formation underestimates ripple sizes.
(iii) Shell and pumice are easier to entrain than equivalent sized quartz gravels, upon which the model is based. Thus lower flow regimes would be capable of transporting shell and pumice material more readily which may develop the bedform.

Warren (1992) suggests that finer sediment may be preferentially transported into sand ripples leaving the heavier, gravel sized sediment in the troughs. Thus, the basal layers of the crests would be composed of coarse gravel and shell material, with an accumulation of finer material above (Harms, 1989) as this material is more easily entrained. At the S4 site and SCUBA dived sites within the study area this appeared to be occurring; the coarsest sediments lay in the troughs and finer material on the crests.

8.2 Side-scan Sonar

The recognition, description, and mapping of bedforms over relatively wide areas by obtaining plan views of the nearshore and shelf surface is commonly achieved using side-scan sonar, along with additional information provided from echosounding profiles and diver observations (Belderson *et al.*, 1982). Side-scan sonar is a useful means of determining the broad scale distribution of sediment types and in delineating areas where sediment is suspected of being very mobile. Sonographs can resolve a range of features including megaripples, sandwaves, sandpatches and sand ribbons, and thus indicate potential sediment transport pathways (D'Olier, 1979; Black and Healy, 1983).

Sonographs of the nearshore zone from 7 to 30 m water depth using side-scan sonar equipment were collected in a four day excursion in July 1993, aboard the Port of Tauranga survey vessel, *Kairuri IV*, using personnel from the University of Waikato and Port of Tauranga. Some 239 km of seafloor was scanned along 9 shore-parallel runs from Newdicks Beach to the Tarawera River mouth, providing a good coverage of the study area. The area immediately offshore of Town Point was not covered due to

Table 8.3 Predicted bedform dimensions for the S4 deployment site, in 16.1 m water depth off southern Pukehina Beach, using a site representative mean grain size of 0.68 mm. Shaded areas indicate the conditions present at the site during deployment. R = relict bedform not capable of being formed under thoes wave conditions shown. All bedform measurements are in centimetres.

Wave Height (m)	T = 5 s		T = 6 s		T = 7 s		T = 8 s		T = 9 s		T = 10 s		T = 11 s		T = 12 s	
	λ	η	λ	η	λ	η	λ	η	λ	η	λ	η	λ	η	λ	η
1.0	*R*		*R*		*R*		*R*		*R*		98.93	10.07	74.14	15.53	77.43	15.42
1.2	*R*		*R*		58.89	6.32	80.14	8.12	55.44	10.62	54.76	9.81	54.86	9.49	55.71	9.42
1.4	*R*		43.62	4.89	69.31	7.05	45.15	8.21	41.48	7.00	39.98	6.47	39.92	6.26	40.70	6.22
1.6	*R*		50.27	5.40	41.75	7.82	34.55	5.72	31.54	4.88	30.91	4.51	31.41	4.37	32.50	4.33
1.8	*R*		56.94	5.88	33.37	5.69	27.22	4.16	25.62	3.55	25.79	3.28	26.73	3.18	28.05	3.15
2.0	*R*		39.57	8.06	26.81	4.28	22.67	3.13	22.14	2.67	22.83	2.47	24.03	2.39	25.48	2.37
2.2	*R*		34.16	6.23	22.30	3.31	19.85	2.42	20.02	2.07	21.03	1.91	22.38	1.85	23.90	1.83
2.4	35.16	3.97	28.83	4.93	19.32	2.62	18.06	1.91	18.67	1.63	19.87	1.51	21.31	1.46	22.88	1.45
2.6	38.28	4.23	24.40	3.97	17.33	2.11	16.87	1.54	17.76	1.32	19.09	1.22	20.59	1.18	22.19	1.17
2.8	41.42	4.47	21.01	3.25	15.97	1.73	16.05	1.26	17.13	1.08	18.54	1.00	20.08	0.96	21.70	0.96
3.0	44.56	4.70	18.50	2.70	15.01	1.43	15.46	1.05	16.68	0.89	18.15	0.83	19.72	0.80	21.34	0.79
3.2	47.70	4.92	16.66	2.27	14.32	1.20	15.04	0.88	16.35	0.75	17.85	0.69	19.44	0.67	21.07	0.67

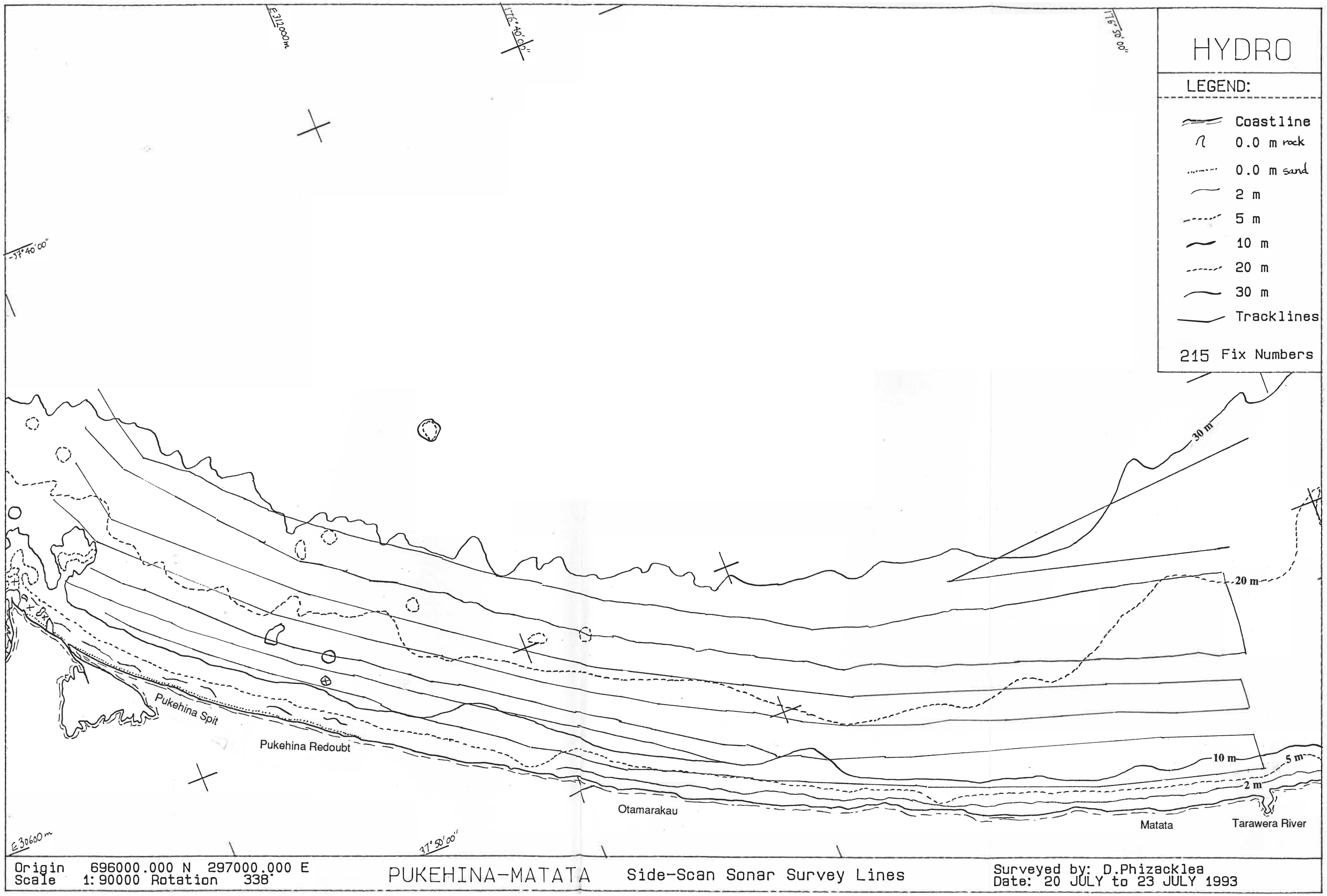


Figure 8.10 Side-scan sonar tracklines from July 1993 (runs 1-9), and bathymetry of the Pukehina-Matata coastal sector, plotted using the computer navigational package HYDRO®.

the numerous reefs and boulders within this area which make side-scan operation hazardous. The side-scan sonar track lines used in this study are shown in Figure 8.10 for the areas covered, and given in detail with fix numbers in Appendix IX, for each of the three sectors into which the sonograph interpretations have been divided.

The side-scan sonar survey utilised a *EDO-Western 706* mapping recorder with a *602* tow fish. Fix positions were determined using a *NavTrac* GPS trimble satellite navigation system. The side-scan fish was towed at a constant speed of 4 knots (9.26 km.hr^{-1}) approximately 20-50 m behind the boat, depending on the water depth. The tow fish was kept at a height of around 5 m above the sea bed where possible or one third of the water depth as this has been found to provide the best resolution (Bradshaw, 1991; EDO-Western, 1985). Bathymetric profiles along each track were obtained using an Atlas Deso 20 33kHz echo sounder and soundings were adjusted to mean sea level relative to Moturiki datum. In order to provide the best resolution possible the total scanning range used in depths less than 15 m was 400 m (runs 1 and 2), and 500 m for all other side-scan runs, except for a 300 m scanning range used towards the end of line run 1.

8.2.1 Sonograph Patterns

Five distinct sonograph patterns were identified from the side-scan sonar survey of the Pukehina-Matata nearshore. Patterns have been determined from the distinguishing characteristics of reflection.

1. Fine Lightly Rippled Pattern
Common pattern characterised by a light tone on sonograph traces, interpreted as a fine sand deposit in which no indication of bedforms is shown. However, from diver observations commonly ripples are present, which are too small ($\lambda < 0.5$ m) to be resolved using side-scan sonar. This pattern characterises most of the upper nearshore zone.

2. Coarse Megarippled Pattern
An easily distinguishable pattern on side-scan sonar traces due to its clear imagery, with a narrow darker tone produced from bedform crests and a white shadow zone in between representative of the trough, resulting in a crenulated pattern. The presence of megaripples is indicative of active bedload transport occurring over the coarse sand deposits (Bradshaw, 1991). The size of the megaripples visible on the sonographs ranged from $\lambda = 0.6$ to 2.5 m dependant on the scanning range used, and resolution of the sonograph.

3. Poorly Defined Megaripples or Rippled Coarse Sediments Pattern
This pattern lies between the first two features, and is characterised by a moderately dark or coarse tone on the side-scan sonar traces, which Bradshaw (1991) interpreted as also part of the Coarse Megarippled pattern (CMR) above, indicative of a medium or coarse grained sand deposit. However this was attributed to the difference in side-scan sonar orientation to the shore, with crenulated features (CMR) associated with this pattern found on shore-parallel traces, but generally absent on

shore-normal runs (Bradshaw, 1991). The absence of the observed bedforms on the shore-normal runs was accounted for as due to the anisotropy of straight-crested bedforms, causing a better reproduction of bedforms if the sonar fish travels along their crests rather than across them (Black and Healy, 1983). Since all the side-scan runs in this study were shore-parallel this would infer that either the bedforms were orientated perpendicular to the shore, or that smaller bedforms are present which are not resolved on the sonographs. Due to the coarse scale on some of the sonographs, this sonograph class pattern may include megarippled deposits which have wavelengths between 0.6 and 0.7 m on the 200 m scanning range and 0.6 and 0.75 m on the 250 m scanning range. Therefore they could not be resolved on the sonographs.

4. *Bedrock Pattern*

Surficial bedrock is a common pattern in the north-western half of the study area, from Town Point to Otamarakau, and virtually non-existent elsewhere. Bedrock patterns in other studies are commonly characterised by strong reflectivity and a rough texture (Belderson *et al.*, 1972), and found in Poverty Bay (Kensington, 1990) and the east Coromandel shelf (Bradshaw, 1991). The interpreted bedrock pattern found here, is characterised mainly by moderate reflectivity, suggesting that the bedrock is composed of ignimbrite type material in which the sonar signal is absorbed more readily than for denser bedrock such as basalt or greywacke (Figure 8.11). This is consistent with the onshore geological manifestations. Bathymetric profiles based on the echosounding traces also indicate these bedrock outcrops.

5. *Isolated Strong Reflectors (Surficial boulders and gravelly sand)*

This last pattern commonly has a strongly reflective coarse granular texture. The rounded nature and appearance of acoustic shadows is interpreted to indicate areas containing scattered boulders and/or a) gravels & coarse sand, or occasionally, b) fine sand dependant on the background tonal variations (Figure 8.11). This pattern is often found associated with the bedrock pattern, and it is possible that these isolated strong reflectors are more denser rocks of a volcanogenic lithology (e.g. rhyolite) which have been weathered out of conglomeritic bedrock, or in some instances may indeed still represent that bedrock.

Other side-scan sonograph patterns were observed which were not natural or 'real' features, but were considered to be reflections from other sources. Most of these are detailed in Belderson *et al.* (1972) and D'Olier (1979). Three were found while undertaking the side-scan sonar survey. In shallow water a 'fizzy' wavy pattern occasionally occurred as a result of reflection from the boat wake where the tow fish was located close to the boat. Also associated with shallow depths was reflection from the sea surface (Lloyd's Mirror Effect) and at times from waves created by the sonar fish. The other main unnatural feature found was occasional thin diagonal lines and dots which appeared on the sonographs due to interference from the 33 khz signal emanating from the echo-sounder.

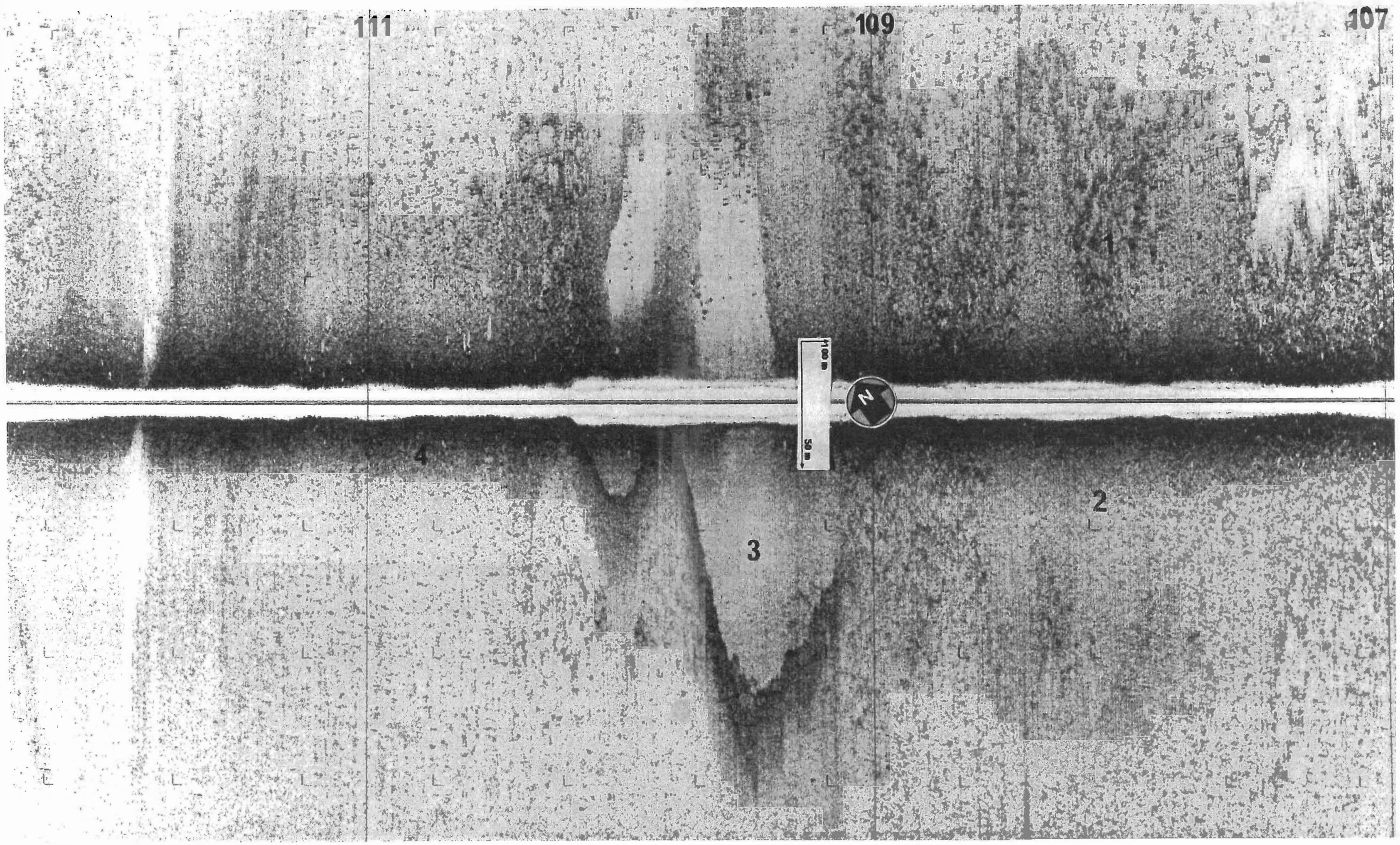


Figure 8.11 Sonograph of the Pukehina Redoubt nearshore in approximately 21 m water depth, run line 4, showing large areas of bedrock (1) and boulder and gravel regions (2), amongst occasional fine sand (3), and coarse megarippled areas.

A final feature which may lead to misinterpretation of the nearshore seabed texture is due to lowering and raising of the sonar fish too quickly causing the fish to dip and dive producing patches or fingers of lighter tones on the sonographs. By noting when the sonar fish was raised or lowered such effects were ignored when interpreting the sonographs.

The side-scan sonographs also enabled the nature of the boundaries between the different patterns to be defined. The two main types of boundaries identified are a *sharp boundary* in which the change from one sonograph pattern to the next is very abrupt, and a *gradational* or *transitional boundary* in which one pattern gently merges with the next. These boundaries may indicate the sonar fish was passing over a topographic feature, the slopes facing the fish giving a strong reflection and those facing away producing a weaker reflection (D'Olier, 1979, pp.63-65). However Bradshaw (1991) for the eastern Coromandel, found that most often this represented a sudden change in textural boundaries associated with erosion, with gradational changes in texture indicative of deposition. This is useful since the occurrence and positioning of these two boundary types may allow for sediment transport pathways to be inferred.

8.2.2 Regional Side-Scan Sonar and Bathymetric Survey

From the above side-scan sonograph interpretations, three regional maps have been compiled for the Pukehina-Matata coastal sector given as: (1) Town Point to Pukehina Redoubt, (2) Rodgers Road to Pikowai, and (3) Kohioawa Beach to the Tarawera River mouth. In addition to the side-scan sonar maps, relevant bathymetric profiles are included to help indicate submarine features. From the nearshore bathymetry provided by the echo sounding traces several bedrock outcrops were found which do not appear on the regional hydrographic charts (NZ 541 and NZ 5411).

Bradshaw (1991) found at Waihi Beach that relatively fine surface sediments dominate in depths of 5 to 22 m, corresponding to a steeply dipping (1:180 gradient) concave-up surface, after which coarser deposits dominate to at least 30 m water depth. This change to coarser sediments at the 22 m depth was found to coincide with a much flatter (1:1000) convex-up feature. For the Pukehina-Matata sediments this change in both sediment texture and profile morphology appears to occur at a shallower depth of 12 to 15 m, with a steeper nearshore gradient of ~ 1:80 to 1:120.

8.2.2.1 Town Point to Pukehina Redoubt (Figure 8.12a)

From the spatial variations in the nearshore sediment texture the area from Town Point to Otamarakau was found to be the most texturally diverse. Comparison of the nearshore sediment textural distribution pattern (Chapter 5) with the sonographs from the Town Point to Pukehina Redoubt region, shows that the large patch of coarse sand with varying amounts of shell and lithic hash material is associated with extensive areas of coarse megaripples (CMR), bedrock and boulder exposures from approximately seaward of the 12 m water depth.

The nearshore pattern of this sector appears as a morphological expression of the onshore geology and

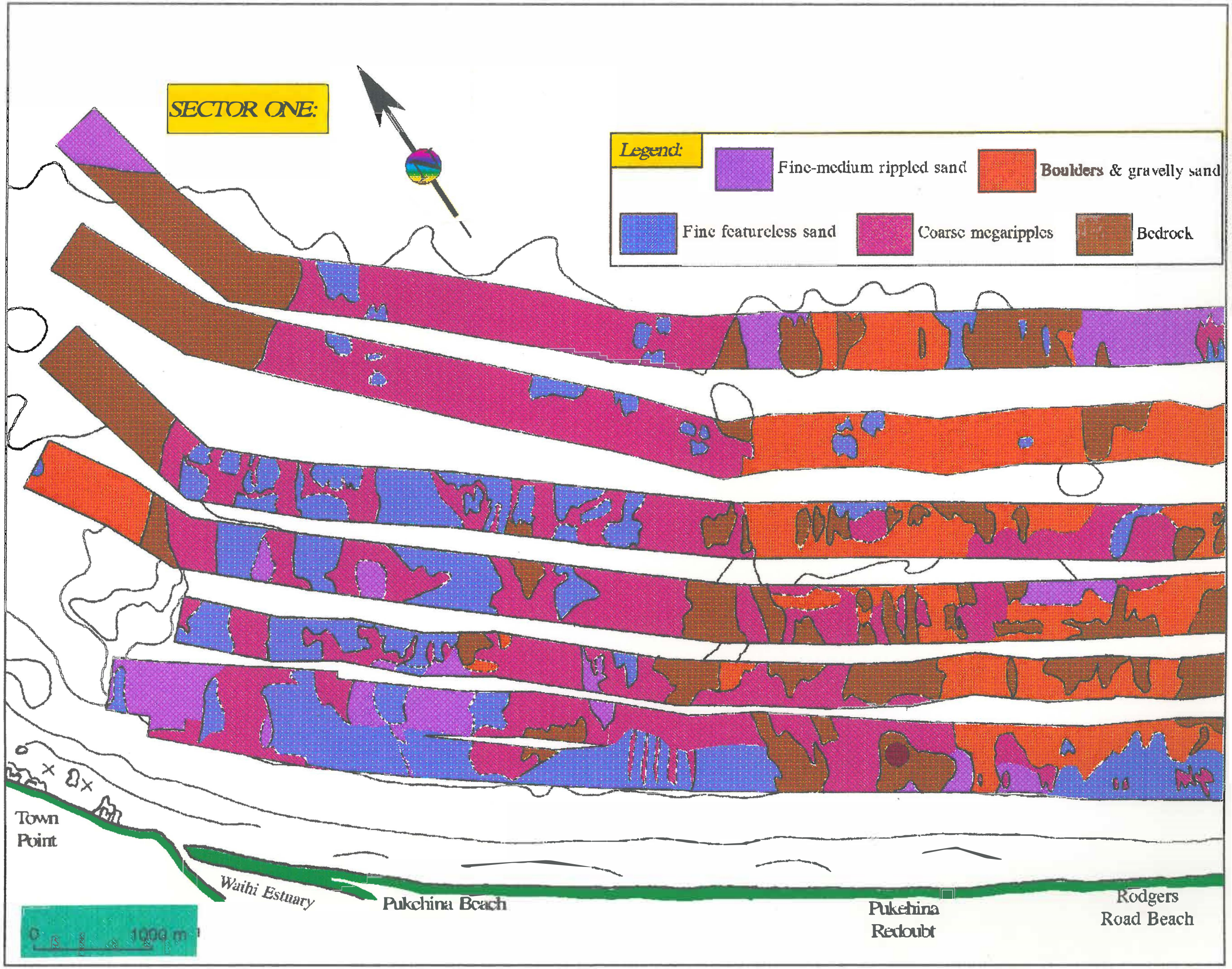


Figure 8.12a Side-scan sonar map of the nearshore between Town Point and the Pukehina Redoubt (Sector 1).

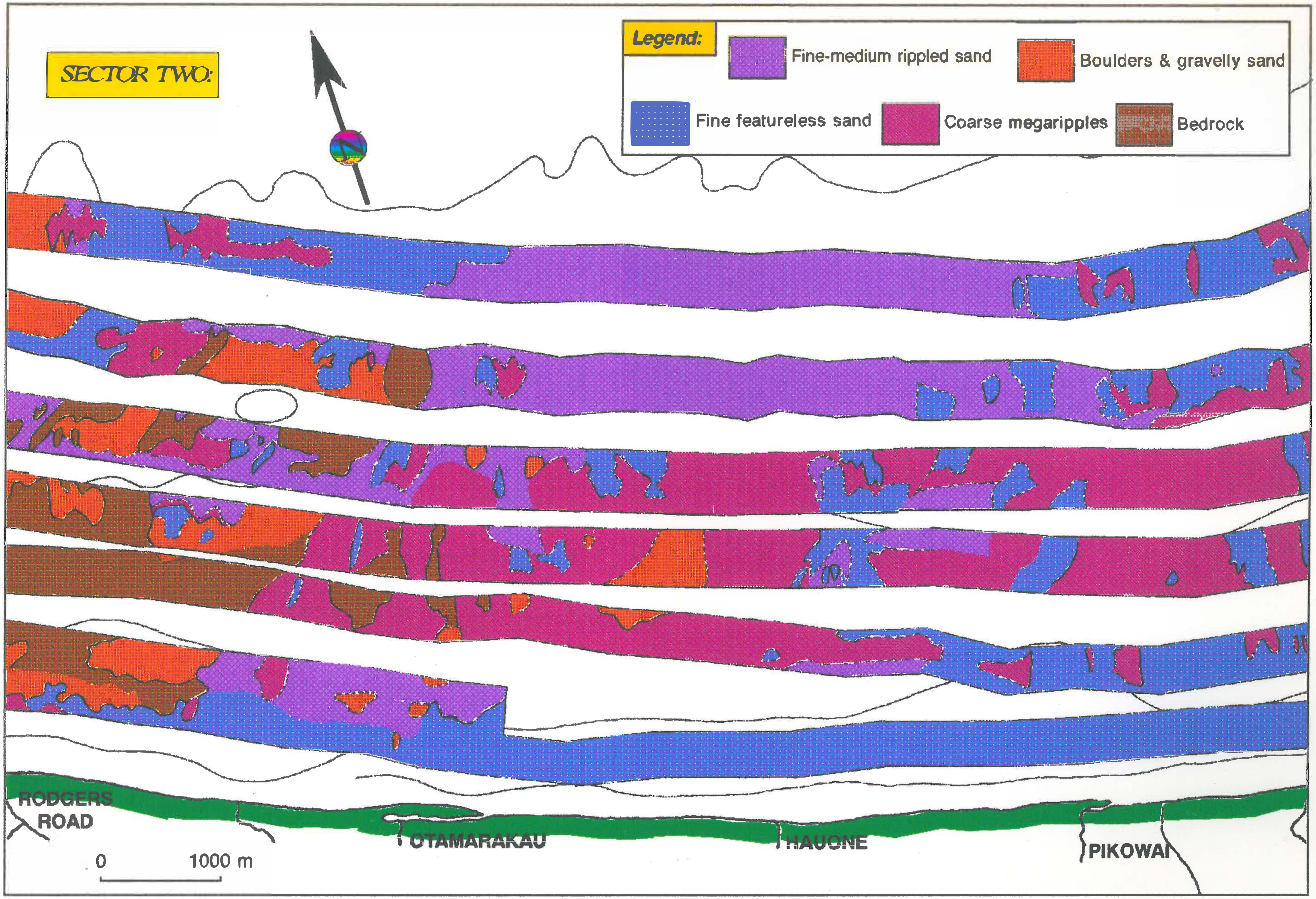


Figure 8.12b Rodgers Road to Pikowai nearshore side-scan sonograph map (July, 1993).

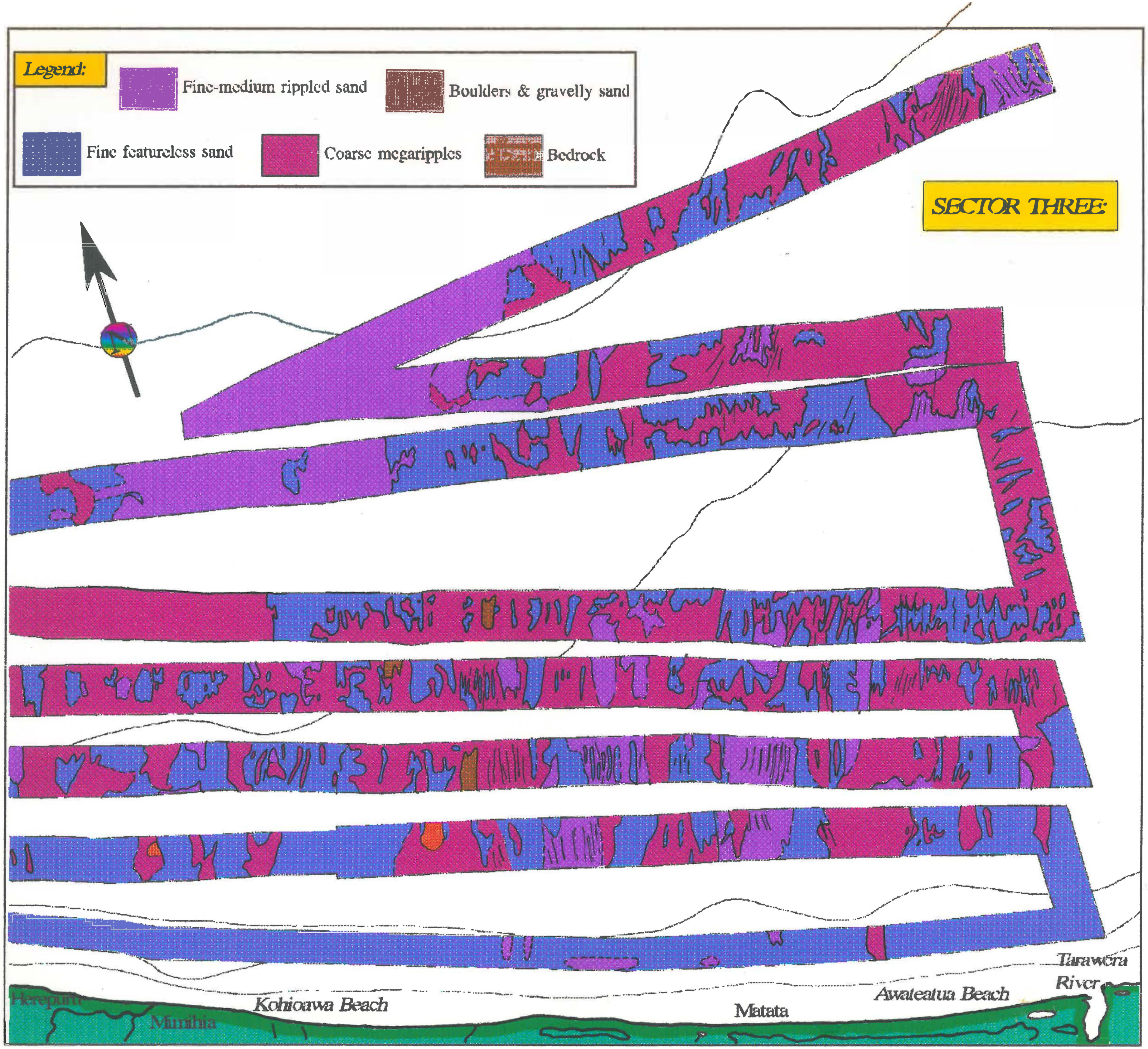


Figure 8.12c Kohioawa Beach to Tarawera River mouth nearshore side-scan sonograph map (July, 1993).

morphology, with the rock outcrops and reef areas offshore corresponding to the Town Point promontory and Pukehina Redoubt cliffs. Within the middle of these are fine featureless sands, rippled sands and coarse megarippled sediments which infer a relationship with Pukehina Spit and sediment input to the nearshore zone from the Waihi estuary outflows of the Pongakawa and Kaikokopu streams.

There is some tendency for the megarippled areas to occur further offshore with the fine featureless sand patches further inshore, however this is complicated by the reefs and submarine rock strata, bathymetry, and local currents.

From the echosounding profiles along various runs it is apparent that there is some current or wave transport of sediments in a north-westerly direction, since the megarippled bands occur predominantly on the south-western or updrift side of topographic mounds and reefs (Figure 8.13). Also the sediments show a strong tendency to 'pile up' on this up-current side, often covering up rock outcrops on this exposed side, whilst on the lee-side there is often a sudden change in bathymetry and increased water depths (Figures 8.14-8.15).

From the accompanying bathymetric profile this region has large fine-medium sand hummocks between CMR areas and boulder-gravel areas which often occur in topographic lows.

The side-scan sonograph patterns for the Town Point-Pukehina Redoubt area help explain the spatial distribution pattern of the nearshore sediments alluded to in Chapter 5, especially the extensive band of shell and lithic hash containing sediments from Town Point to Otamarakau which correspond to areas of bedrock, boulder and gravel material mapped on the sonographs.

8.2.2.2 Rodgers Road to Pikowai (Figure 8.12b)

From Rodgers Road to Otamarakau numerous small and large areas of rock outcrops and boulder covered seafloor occur, interspersed with sandy sediments. Beyond Otamarakau this pattern is absent, suggesting that such rock outcrops have been buried by Late Quaternary fluvially derived sediments from the Waitahanui, Hauone, Pikowai, Mimihia, and Herepuru streams, further evidenced by the fact that there is no onshore suggestion that such geology should not be present. Assuming this to be the case, with no uplift and/or subsidence complications, it would also imply that net littoral drift during present times has been to the south-west, with fluvial output to the nearshore system from the Waitahanui stream covering much of these submarine reefs with sand.

As was found from sediment sampling, the upper nearshore (< 10 m water depth) from Otamarakau to south of Matata is characterised by morphologically similar fine sand sized sediments.

8.2.2.3 Kohioawa Beach to the Tarawera River mouth (Figure 8.12c)

Fine lightly rippled sand dominates most of the upper nearshore zone sediments, with coarser

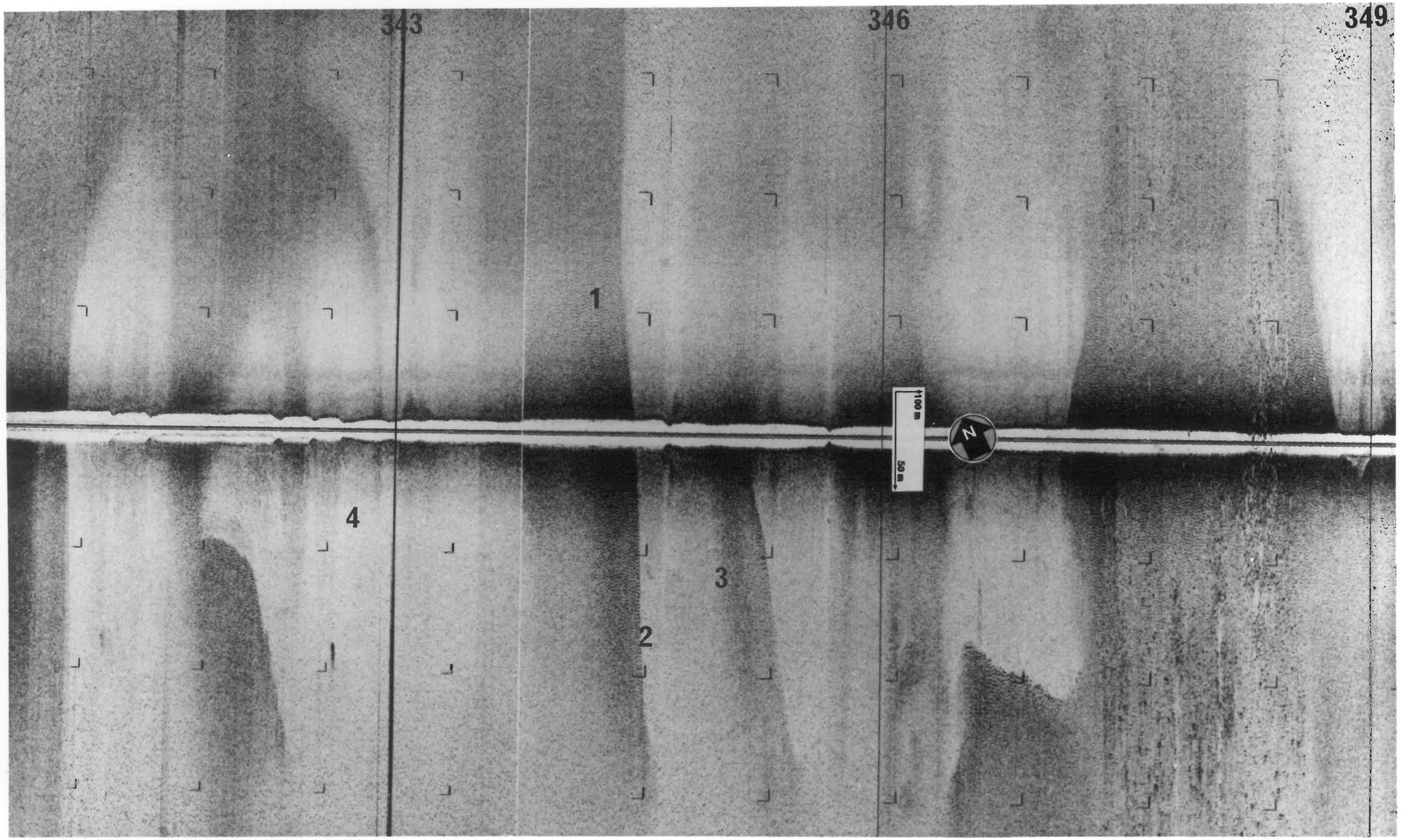


Figure 8.13 Sonograph of the nearshore morphology offshore from Pukehina Spit, runline 2 (approx. 16m water depth). Showing coarse megarippled areas (1), with sharp south-eastern boundaries (2), and gradational north-western boundaries (3) amongst finer featureless sands (4), indicating a north-westerly transport of sediment.

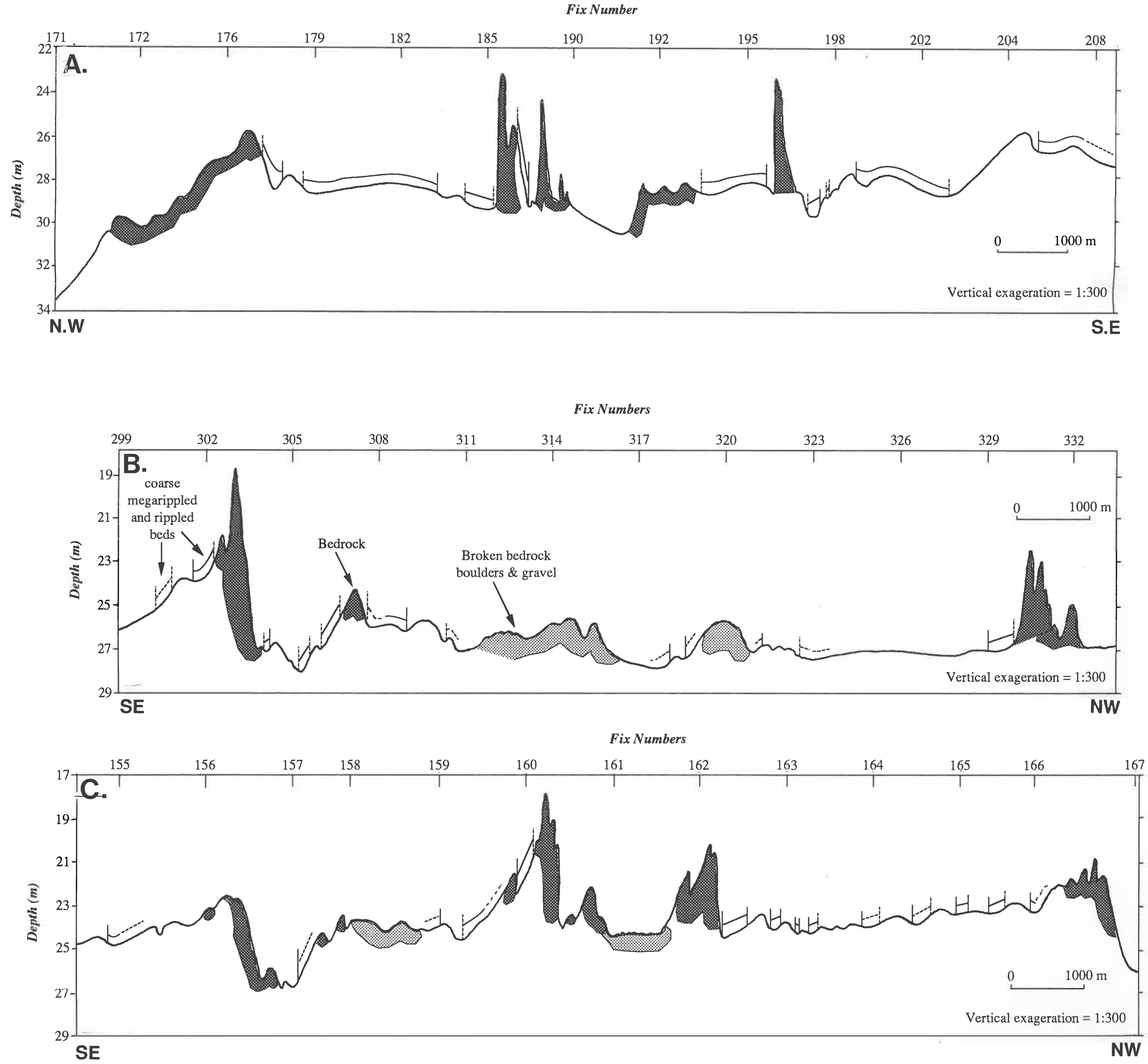


Figure 8.14 Bathymetric profiles from Town Point to Otamarakau, for *a)* runline 7, *b)* runline 6, and *c)* runline 5. Bracketed areas indicate coarse megarippled areas (CMR) of sediment, with a bolded line showing a sharp contact, and dashed line indicating a gradational contact. Both profiles show the irregular topography of this area, and the numerous rock outcrops. The association of the sandy sediments with topographic highs and lows, and the their asymmetry indicates a north-easterly directed transport of nearshore sediments. Note also the localised wave and/or current scouring at the base of the rock outcrops, shown especially in runline 7 between fixes 190-192, and 197-198.

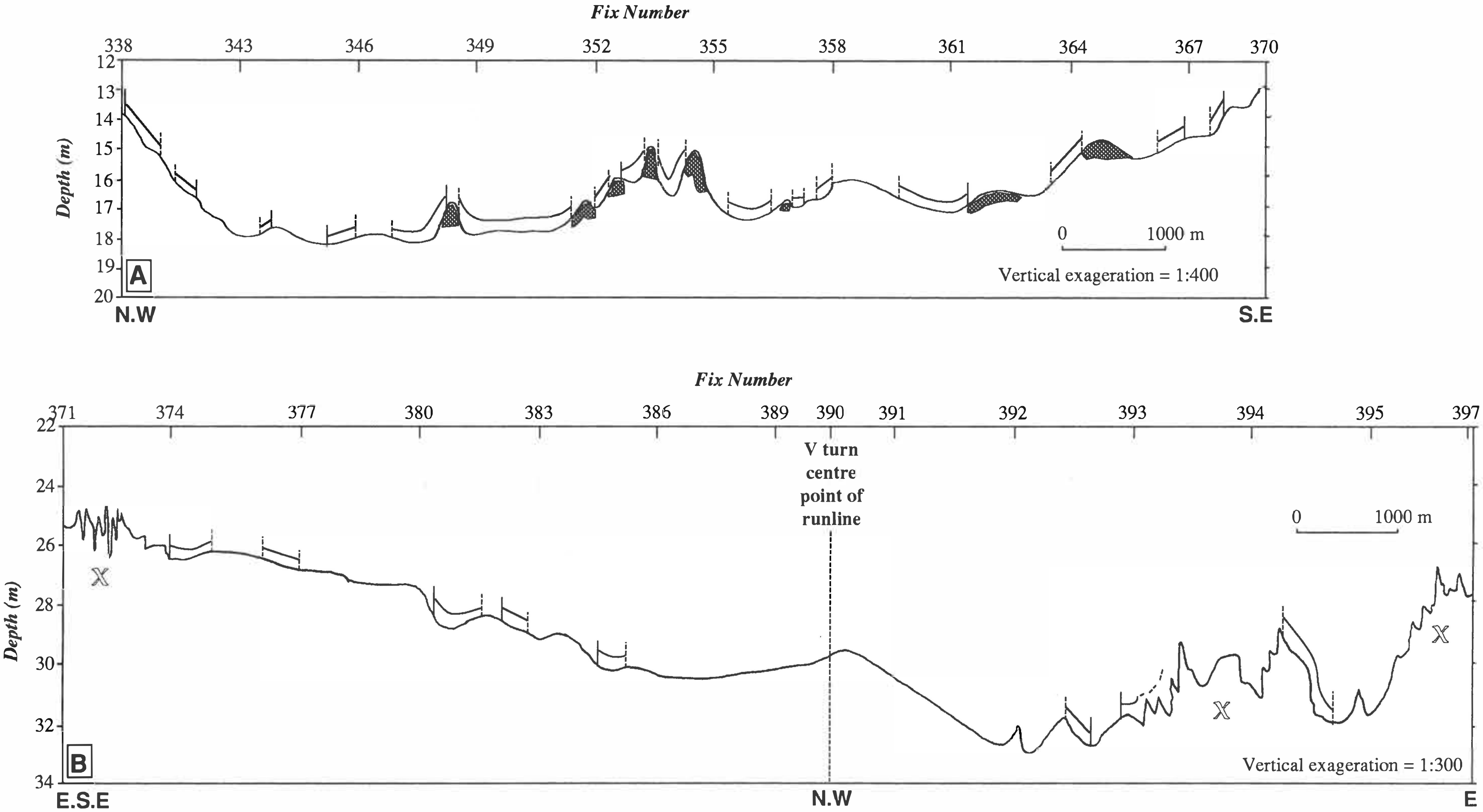


Figure 8.15 Bathymetric profiles for *a)* Town Point to Otamarakau (runline 2), and *b)* Kohioawa Beach to the Tarawera River mouth (runline 8).

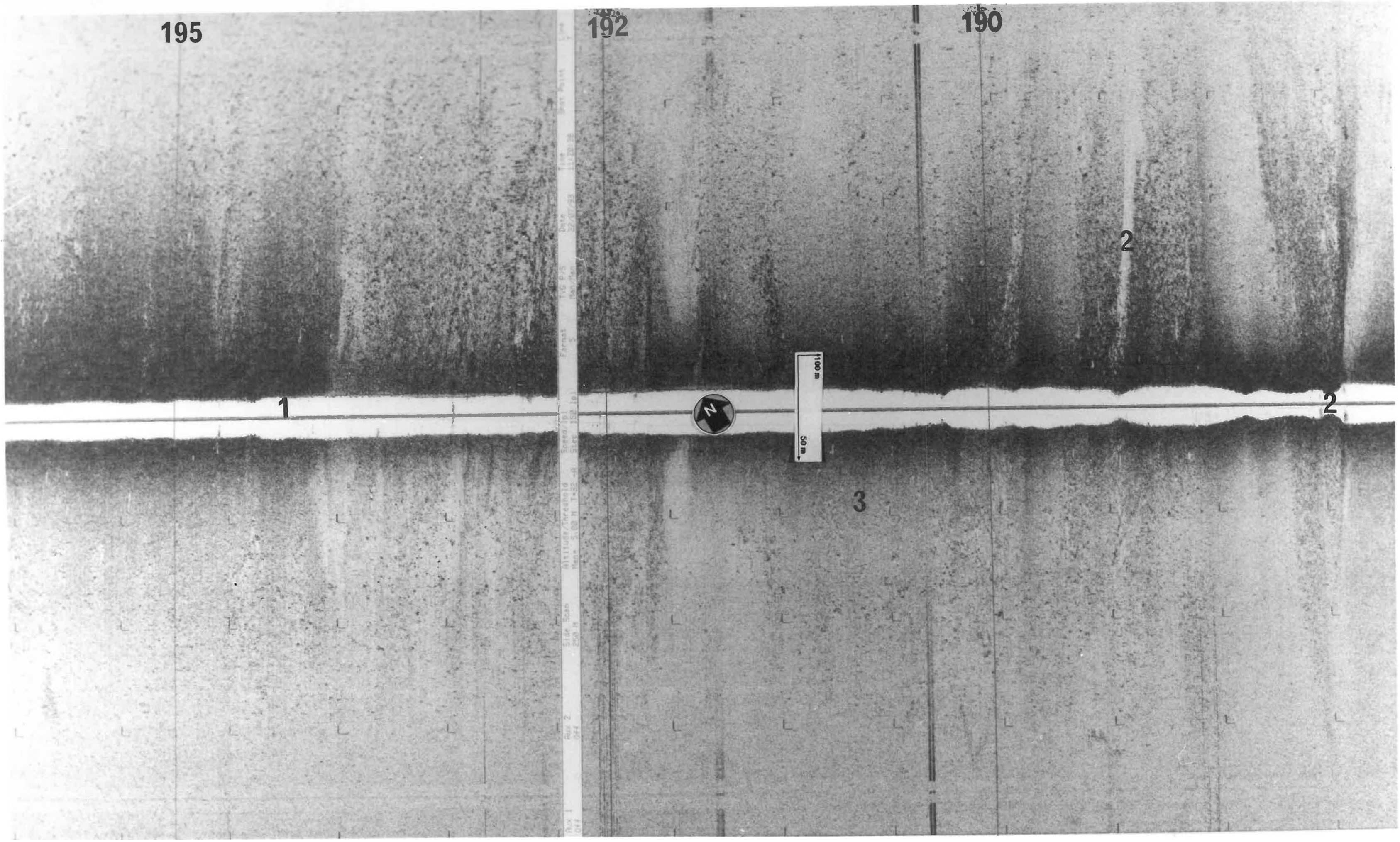


Figure 8.16 Sonograph of the nearshore morphology offshore from Pukehina Redoubt-Rodgers Road, runline 7 (approx. 29 m water depth). Showing coarse megarippled areas (1), rock outcrops (2), and surficial boulders and gravels (3). Note the variable height of the bottom topography shown by the irregular lines on either side of the centre line, caused by reefs, rock outcrops, and gravel areas. The large rocks produce characteristic light shadows.

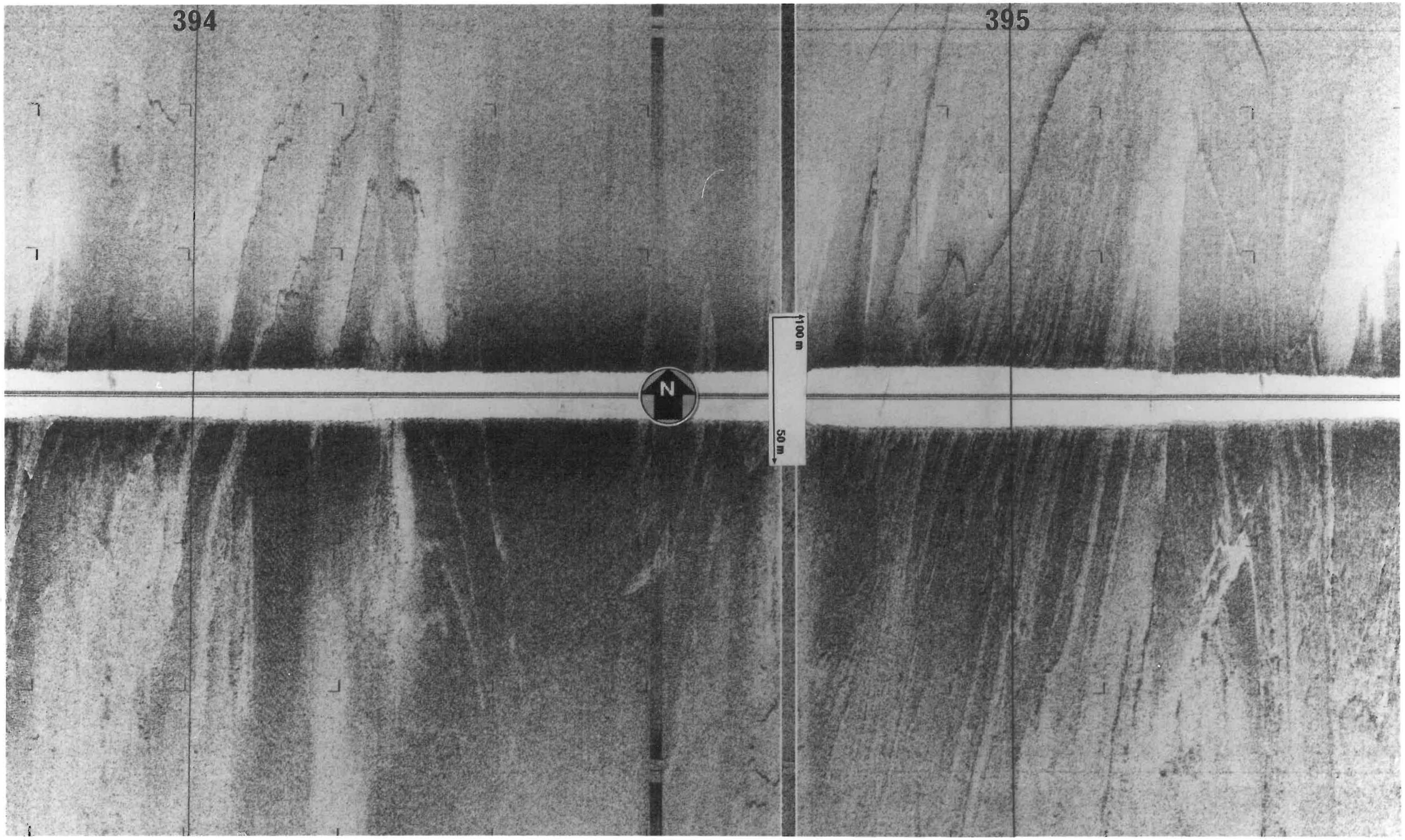


Figure 8.17 Sonograph of the nearshore morphology offshore from the Tarawera River-Matata area, runline 8 (approx. 28 m water depth). Showing rapid fluctuations in sediment texture, corresponding to an irregular sea-floor. This pattern is suggested as due to faulting of either the nearshore sediments or underlying bedrock.

megarippled sands not apparent until beyond approximately the 10 m isobath.

Offshore from Matata-Tarawera River mouth area the sonograph patterns are somewhat unique, characterised by coarse and fine patterns which change rapidly (Figure 8.17), appearing to represent sand wave patterns as found to occur by Bradshaw (1991) on the East Coromandel shelf in > 20 m water depth, and also at Tauranga at similar depths (Foster, 1992). However, from the corresponding echo-sounding traces (Figure 8.15b), there is a rapid vertical offset between 'sand waves', which is suggested as possibly due to the occurrence of wide-spread faulting in the area, either of Holocene deposited sands or Late Pleistocene rock outcrops overlain by veneers of sandy sediments. Evidence for this is provided by Wright (1990) who undertook seismic mapping of Late Quaternary faults of the offshore Whakatane Graben, extending slightly into the side-scan sonar mapped areas of this study. He identified 50 (Figure 8.18) post 18,000 yrs B.P. active faults, correlating to onshore faults such as the Matata Faults. Inferred faulting of the Pikowai-Matata coastal cliffs at Awaateatua Beach by Bailey and Carr (in prep, 1993) (see Figure 2.3), also suggests that some faulting of the offshore in this region could be expected. If these are indeed small scale faults, with vertical displacements of up to 2 m on the echosounding traces (Figure 8.19), then they may have been most recently displaced by the large earthquake shocks of the 1977 Matata and/or 1987 Edgecumbe earthquake sequences. Since Wright (1990) concluded that the offshore faulting within the Whakatane Graben is coseismic in nature. If these faults have been recently activated, i.e. in the last 5-15 years then it is a reasonable for the sandy sediments not to have covered them over, and would suggest that little sediment transport beyond the 15 m water depth is occurring.

The second line of evidence is provided by the sonograph orientation of the observed 'faults', which are predominantly in a northeast-southwest direction, becoming more northerly, and orientated shore-normal at shallower depths. This orientation is consistent with the Whakatane Graben onshore and offshore faults of the Taupo Volcanic Zone, which encompasses nearly all the Pukehina-Matata coastal sector.

8.2.3 Formation of Coarse Megarippled Areas

Foster (1992) notes that megaripples tend to be of coarse sand to sandy gravels, and are commonly poorly sorted. The coarse megarippled bands and patches observed on the sonograph traces, are all approximately shore-parallel, consistent with diver observations. Bedforms at depths beyond 12-15 m are primarily the result of storm waves (Figure 8.20). Few CMR areas are present inshore of this point where the wave orbital velocities affect the seafloor to a much greater extent, with a decrease in grain size to mainly fine sand, in which the bedforms are noticeably smaller. The exact generating mechanism for bedforms within the lower nearshore-inner shelf (*c.f.* nearshore region from diver observation and S4 interpretation) may be either one of several possibilities:

- zones of wave convergence in the nearshore,
- offshore flowing downwelling currents,
- shore-parallel wind-generated currents;

or, • it may involve a complex combination of two or more mechanisms (Bradshaw, 1991).

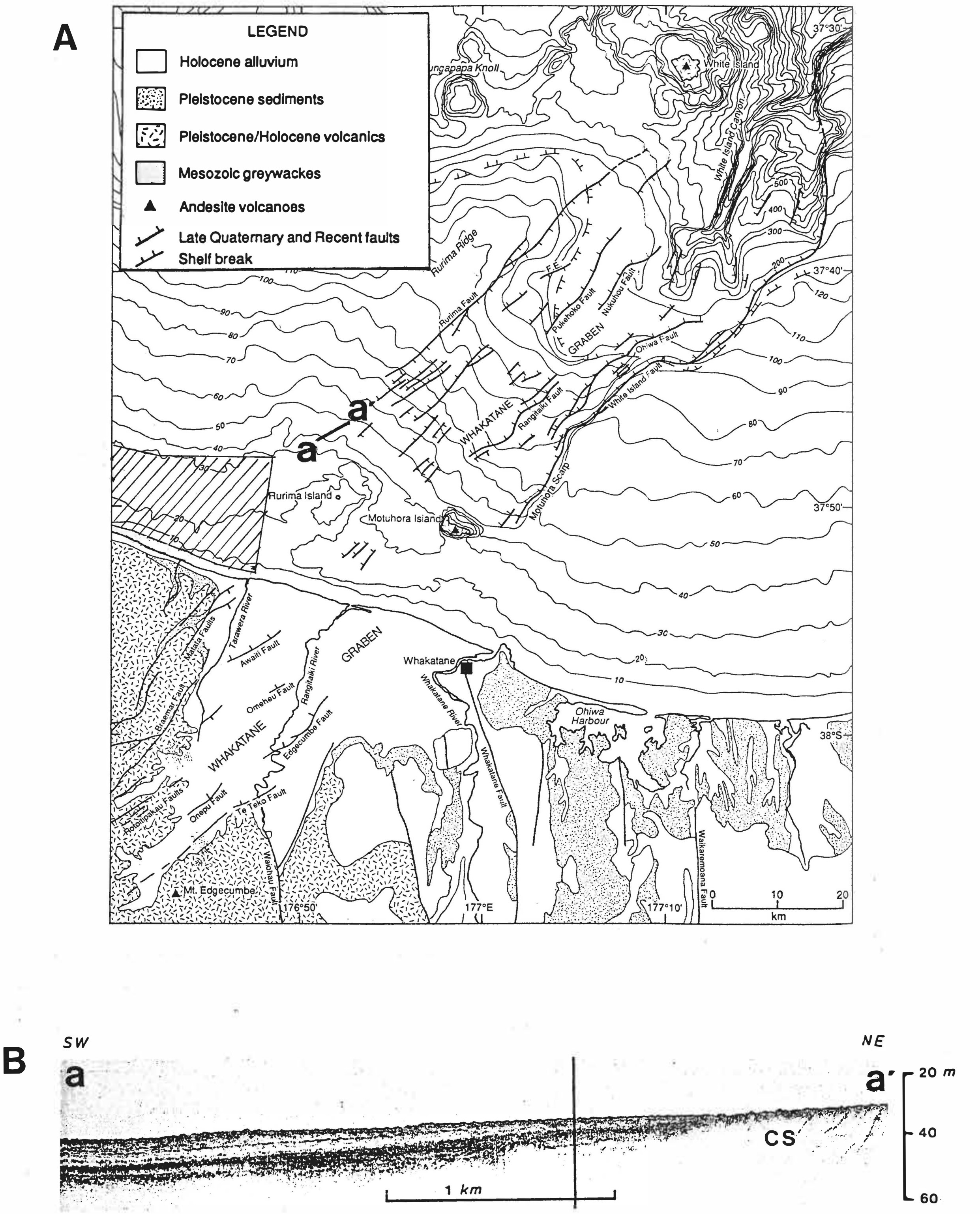


Figure 8.18 a) Late Quaternary (post-18 ka) faults of the offshore Whakatane Graben. Also shown is the area covered by the side-scan sonar survey (hatched area. *b)* High resolution 3.5 kHz seismic profile of offshore Whakatane given along the section marked a to a' in Figure 8.18a. Showing post-18 ka sediments unconformably overlying tilted and folded? Late Cenozoic sediments (CS). *(source: Wright, 1990)*

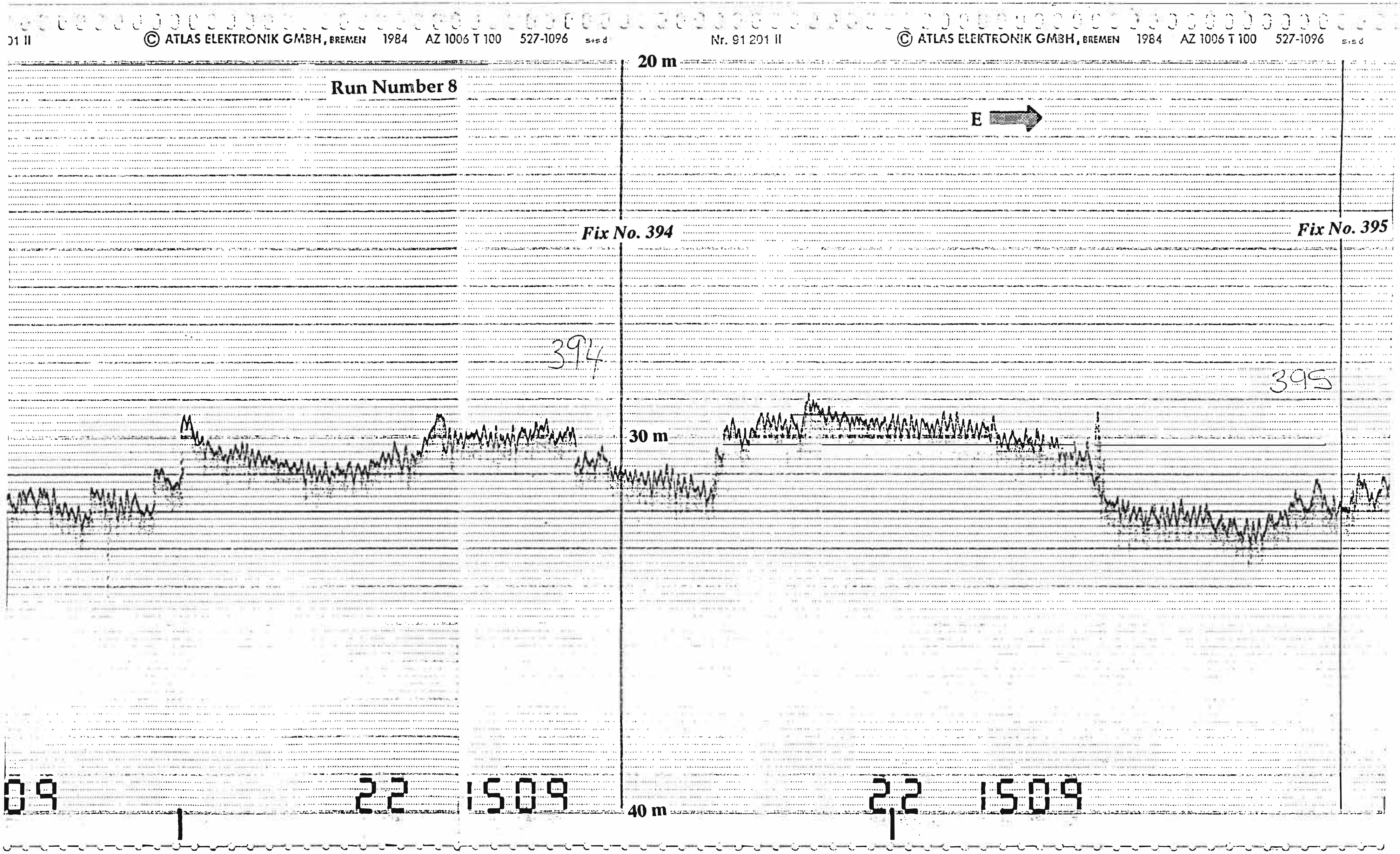


Figure 8.19 Echo-sounding trace from run line 8 corresponding to areas marked X in Figure 8.14b. The bathymetry changes rapidly in these areas, with apparent displacements of up to 2.0 m which are inferred to represent regional faulting offshore from Matata associated with the Whakatane Graben, of either Holocene sands or underlying bedrock.

Bradshaw (1991) found that often zones of wave convergence, where wave height and wave energy reinforcement occur coincided with areas of coarse megaripple bands and patches. Suggesting that for the East Coromandel *"there is strong supportive evidence that wave refraction may play an important role in the formation of these CMR bands, as determined at Whangarei Harbour by Black and Healy (1988)"*. From this study such a mechanism for the generation of coarse megarippled areas of the nearshore is possible for some sections of the Pukehina-Matata coastal sector, but from the wave refraction plots shown it is not possible to accurately determine the zones of wave convergence relative to the CMR bands. The CMR bands are probably formed predominantly by shore-parallel wind-generated currents, as suggested by Swift and Freeland (1978). Evidence for this is the association of CMR bands with down-current flanks of rock outcrops and topographic highs. Also, commonly megaripples occur in topographic lows, with finer featureless sediments at corresponding highs. The bottom currents generated will be greater on the topographic highs causing a higher flow regime than for lower areas and hence a difference in the bedform size. Generation by offshore flowing downwelling currents (Cacchione *et al.*, 1984) may be prevalent in areas where topographic features are present to concentrate flows, such as in the Town Point-Otamarakau area, and offshore from Matata, where isolated areas of intense scouring probably occur.

8.2.4 Sediment Transport Implications from Bedforms

Coupled with direct measurements of bedforms from SCUBA observations, indirect measurements were made from side-scan sonagraphs. Where a clear resolution of bedforms appears on the sonographs the bedform wavelength (λ) is easily measured by dividing the number of acoustic shadows, indicating bedform crests, by the distance over which they occur on the sonograph. To determine bedform heights (η) from sonographs, a technique described by Black and Healy (1983) was used. This involves determining the side-scan fish height from the sea-floor (z), acoustic shadow length of the object (s), and the horizontal distance of the object from the fish (l). Simple trigonometry then resolves the height of the object from the relationship: $h= z.s/l$ (Bradshaw, 1991).

Bradshaw found that areas of shelf erosion are inferred to coincide with the areas of CMR sands, as this sonograph pattern matches those locations in which medium and coarse grained storm-lag deposits were identified from sediment textural analysis. However for the Pukehina-Matata area it is suggested that the presence of some of these coarse megarippled areas are due to sediment input from neighbouring bedrock with finer predominantly pumiceous material easily entrained and transported offshore by wave and current action.

Megaripples are orientated overall slightly to the north-west from Town Point to Pikowai, with a more south-westerly orientation along Awaateatua Beach (Matata to the Tarawera River mouth) (Figure 8.20). The variable directions of inferred sediment transport within the nearshore zone and inner shelf may indicate complex currents and transport patterns are present (Figure 8.21).

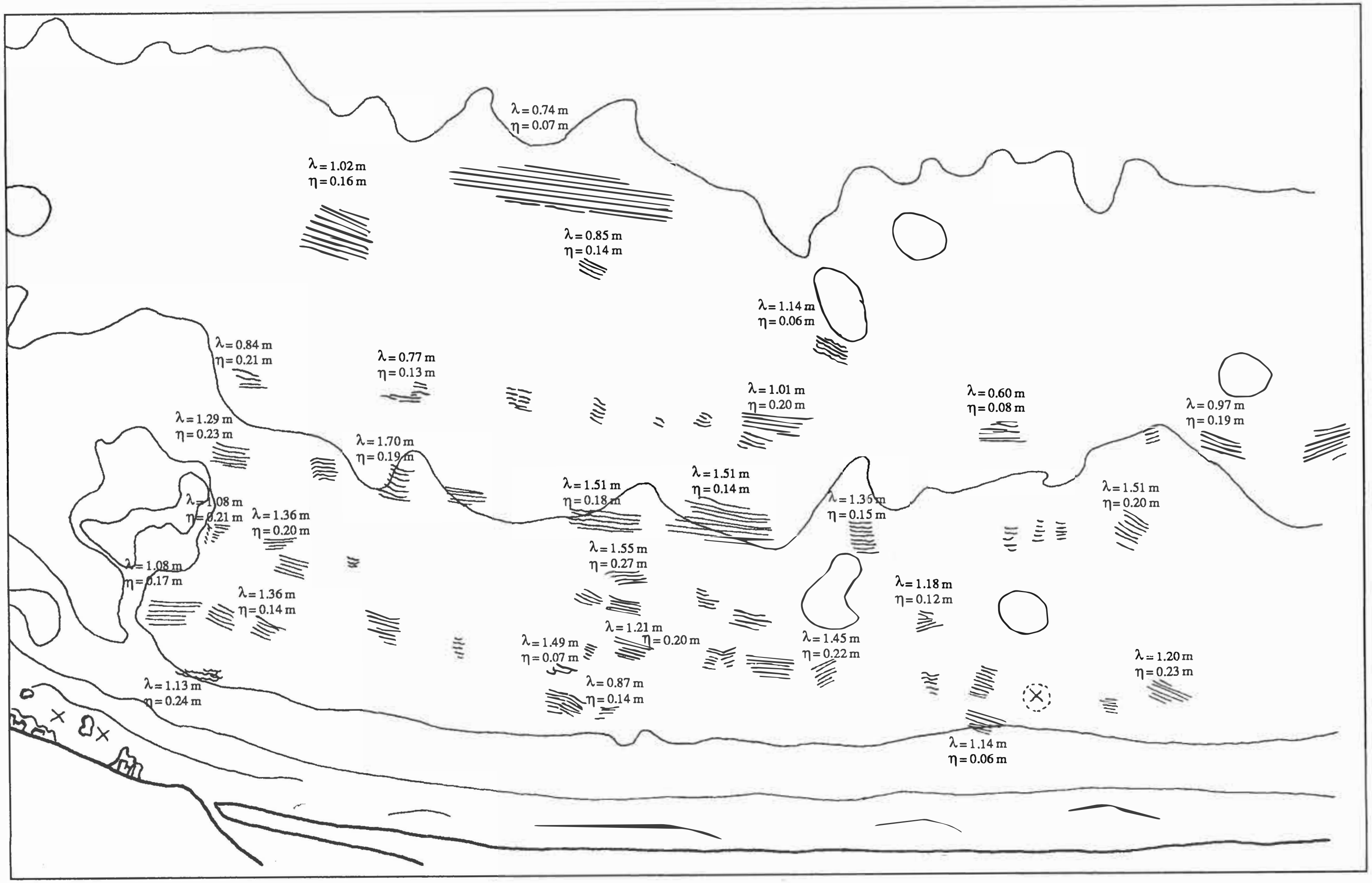


Figure 8.20a Approximated distribution, orientation, and bedform characteristics of megaripples from Town Point to Pukehina Redoubt, based on sonograph measurements of visible bedforms.

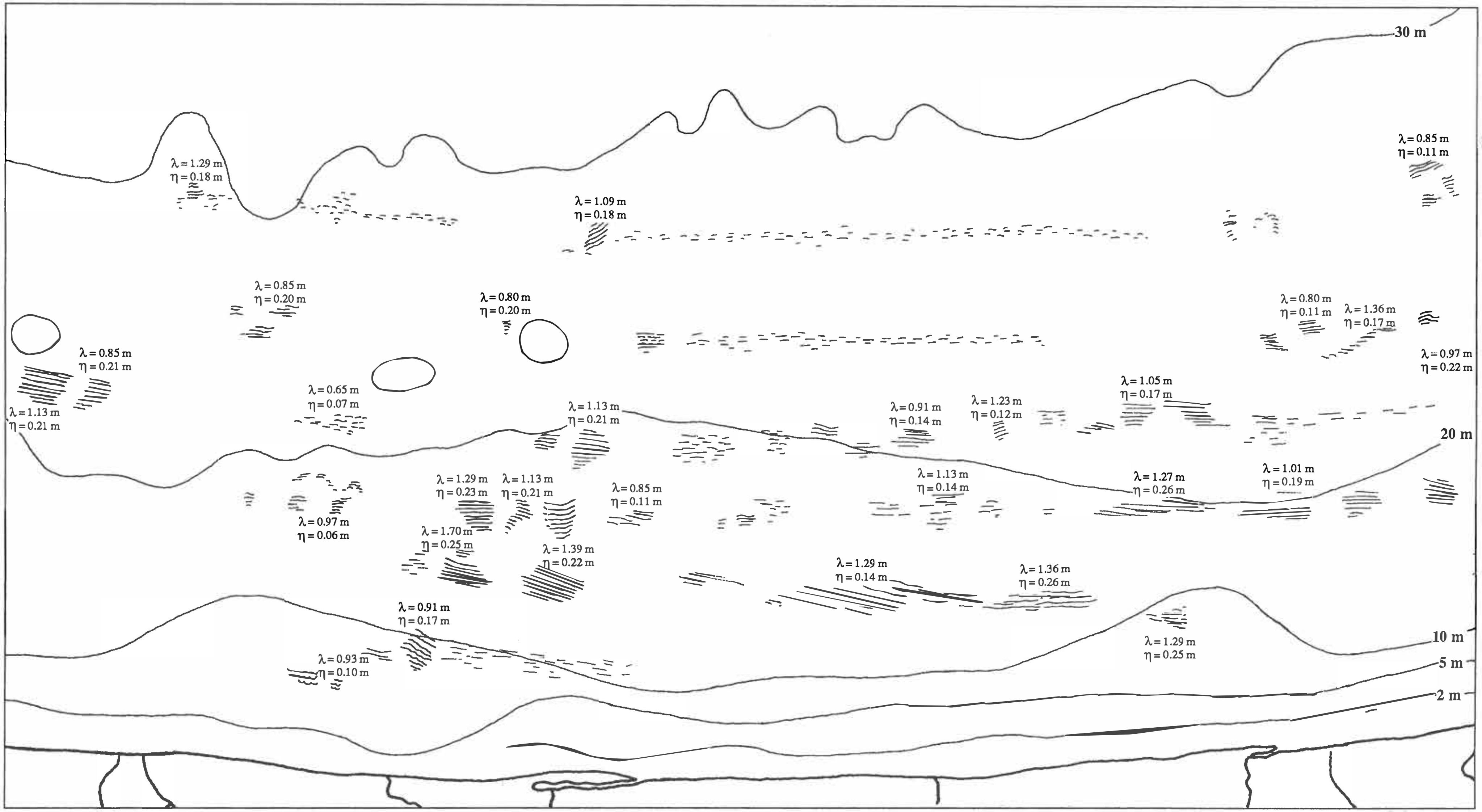


Figure 8.20b Approximated distribution, orientation, and bedform characteristics of megaripples from Rodgers Road to Pikowai, based on sonograph measurements of visible bedforms.

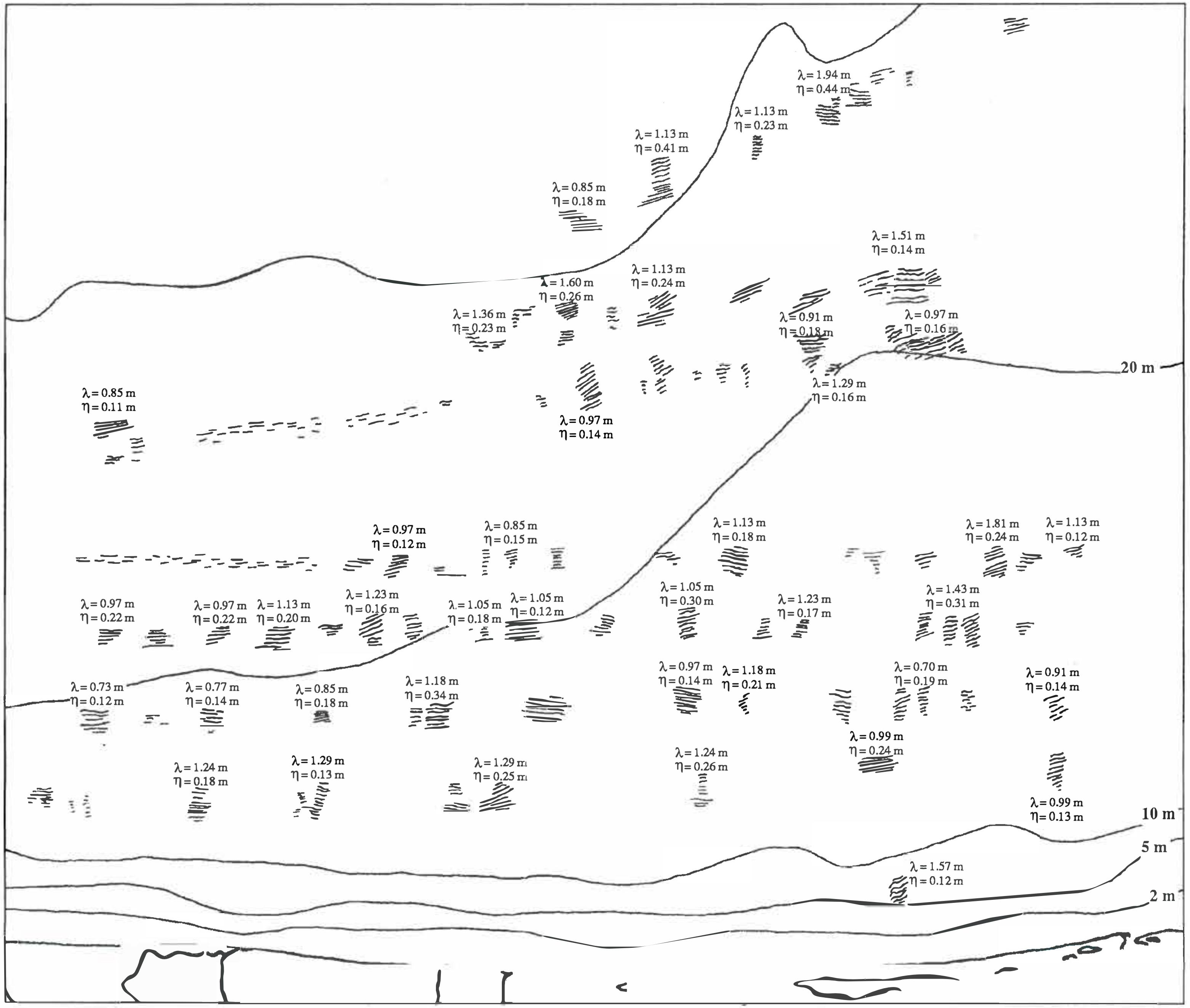


Figure 8.20c Approximated distribution, orientation, and bedform characteristics of megaripples from Kohioawa Beach to the Tarawera River mouth, based on sonograph measurements of visible bedforms.

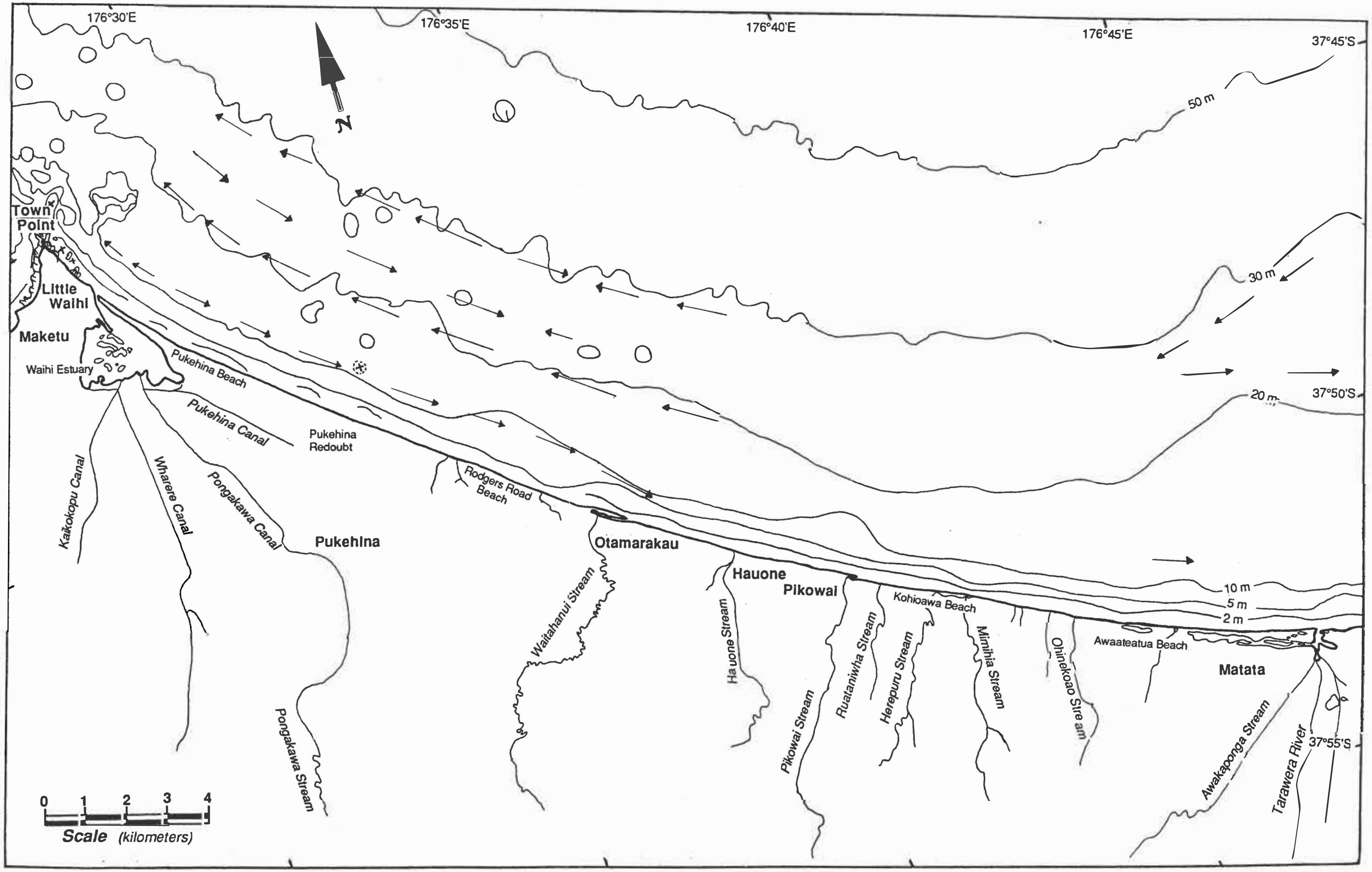


Figure 8.21 Inferred net sediment transport pathways for the Pukehina-Matata coast, based on the morphological association of CMR deposits with sand ridges and rock outcrops.

8.3 Hallermeier Limits

In determining the extent or rate of onshore-offshore sediment transport, it is important to determine at what depth and under what conditions onshore-offshore sediment transport is no longer significant (Warren, 1992). Harris *et al.* (1983) found that for the north-east coast of New Zealand at water depths of 40 m the stirring of 0.22 mm sized sediment (fine sand) by waves should seldom occur, but at 20 m it should be significantly common.

Hallermeier limits have been shown to estimate the maximum depth of significant diabathic sediment transport reasonably well in other studies in the Bay of Plenty (Foster, 1991; Hay, 1991; Warren, 1992). Limits are derived from a formula that calculates the landward and seaward limits of a shoal zone between the littoral (~ shoreface) and inner shelf zones (Hallermeier, 1981; Hay, 1991). The littoral zone extends to the seaward limit of intense bed activity caused by extreme near-breaking waves and breaker-related currents (Hallermeier, 1981). The shoal zone can be defined as one in which the surface waves have neither strong nor negligible effects on the transport of sand in a typical year, with extreme waves carrying some littoral zone sand into the landward section of the shoal zone and common waves carrying some offshore zone sand into the seaward section (Hallermeier, 1981).

The formulae for the Hallermeier limits can be approximated by two equations (Hallermeier, 1981):
Hallermeiers Inner Limit (HIL)- defines the seaward limit of extreme surf-related processes (d_l); and, *Hallermeiers Outer Limit (HOL)*- defines the seaward limit of significant wave shoaling zone processes (d_i).

$$d_l = 2H_s + 11\sigma$$

...equation 8.4

$$d_i = \{H_s - (0.3\sigma)\}\, T_s \sqrt{\frac{9.81}{5000\,D}}$$

...equation 8.5

where: H_s = annual mean significant wave height (m)
σ = annual standard deviation of significant wave height (m)
T_s = annual mean significant wave period (s)
D = median grain size diameter (m)

Significant longshore sand transport and intense onshore-offshore sand transport are restricted to water depths less than d_l. The water depth defined by d_i gives the seaward limit to sand motion by usual waves, and significant onshore-offshore sand transport exists out to this depth. Depths may be approximated to ± 5% when the beach grain density is $2650 kg.m^{-3}$ (Hallermeier, 1981; Hay, 1991). The inner limit depth determines the value of D required, since the sediment grain size used should be at 1.5 d_l (Hallermeier, 1981).

The above equations typically require definition by at least a year's daily wave data (Hallermeier, 1981). However owing to the lack of data for the Pukehina-Matata coastal sector, a composite data set was used. This included wave data recorded at Tauranga (Seaview wave recorder on A-Beacon corrected to actual wave heights equivalent to the *Interocean* S4) (de Lange, 1991), and the average data from the S4/10 wave meter deployed at Pukehina. While not completely ideal for calculating the Hallermeier limits, these provide the best available data.

Hallermeier limits were determined from the program *Hallermeier* run on the Macintosh™, provided by Dr. Willem de Lange, University of Waikato. The program in contrast with the approximated equations (Eqn. 8.4 and 8.5) determines the limits from the full equations given in Hallermeier (1981), and accounts for the both the fluid density and the density of the sediments (taken as 2540 kg/m^3).

8.3.1 Hallermeier Limits for Pukehina-Matata

The results for the Hallermeier limits are given in Table 8.3. The water depth for the sediment measurement used here was 10.7 m for the Tauranga data, and 8.7 m for the S4/10 data. Limits were determined for four locations within the Pukehina-Matata coastal sector: Town Point, Pukehina south, Otamarakau, and Matata, using sediment data contained in Chapter 5.

Table 8.3 Hallermeier Limits (HIL and HOL) calculated for various locations using the mean wave conditions derived from Tauranga (de Lange, 1991), and the S4/10 at southern Pukehina Beach.

Wave Conditions	*Location*	*Mean Grain size values (mm)*	*HIL (m)*	*HIL distance offshore*	*HOL (m)*	*HOL distance offshore*
$H_s = 0.81$ m, $T_s = 9.06$ s, $\sigma = 0.459$	*Town Point*	0.959	7.09	*404 m*	7.62	*542 m*
	Pukehina	0.189		*420 m*	21.27	*2900 m*
	Otamarakau	0.200		*413 m*	20.69	*2640 m*
	Matata	0.186		*476 m*	21.09	*5700 m*
$H_s = 0.642$ m, $T_s = 6.356$ s, $\sigma = 0.4$	*Town Point*	0.582	5.55	*296 m*	6.21	*472 m*
	Pukehina	0.180		*305 m*	11.78	*786 m*
	Otamarakau	0.188		*311 m*	11.55	*794 m*
	Matata	0.219		*343 m*	10.76	*879 m*

From the longer-term Tauranga wave data, the inner limit estimate of intense onshore-offshore sediment transport for the study area is approximately the 7 m water depth, equating to an offshore distance of about 360-500 m measured from MLWS. The Pukehina S4/10 wave data suggests that the HIL is about 5.5 m, which is less than that predicted at Mt. Maunganui (Table 8.4) and may be a reflection of the steeper nearshore morphology or lack of representative wave data. The outer limit calculated shows significant variation depending on which set of wave data measurements are used. The mean grain size at the 8 m and 11 m water depths, except for Town Point, is consistently within ± 0.3 phi units throughout the area, having small bearing on the HOL value. The limit of significant onshore-offshore sediment transport is therefore expected to be similar along most of the Pukehina-Matata coastal sector. Though this also depends on the wave regime being the same over the entire coastal sector, which may not be the case. The limits of 20+ metres water depth given for the Tauranga data appear to be over-estimated, since the wave data utilised in calculating the HOL limit should be site specific. The S4 predicted values by comparison are lower, which may be due to the small duration of the wave data set possibly underestimating the mean annual wave period and wave height.

The Hallermeier outer limit calculated for the Town Point site (BOPCES 30) from the Tauranga data suggests a limit of less than 8 m water depth, caused by the rapid change in grain size within the nearshore. The value obtained from the S4/10 data gives an even lower limit, with the small differences between the HIL and HOL suggesting small amounts of onshore-offshore sediment exchange.

Comparison with results obtained at Mount Maunganui show a range of values for approximately the same area (Table 8.4).

Table 8.4 Various estimates of Hallermeier's Outer Limit (HOL) in the vicinity of Mount Maunganui. Dommerholt (in prep., 1993) is considered the most reliable, due to inaccuracies in the calculations of most of the other authors.

Calculated HOL value (m)	*Author*
13.52	Hay (1991)
13.41 and 17.54	Foster (1991)
11.06 and 9.23	Warren (1992)
22.05	Warren (1992) from data in Harms (1989)
15.10	Dommerholt (in prep., 1993)

An alternative means of calculating the inner limit of sediment transport, equivalent to the parabathic closure depth (D_p) is given by Horikawa (1988) (Eqn. 8.6). As the main controls on parabathic sediment transport (littoral drift) are longshore currents, the seaward limit should be immediately offshore from the breaker line, where the longshore current rapidly drops to zero (Kraus, 1987).

$$D_p = D_b + h_{b\ (max)} \qquad \text{...equation 8.6}$$

where: D_b = berm height above still water level
$h_{b\ (max)}$ = maximum breaker depth.

From the beach profiles (Chapter 4) the berm height value is approximately on average 1.5 m (e.g. 1/5/93). The maximum breaker depth during S4 deployment was 1.92 m (H_s=2.79 m), with wave set-up of 0.19 m, which would yield a closure depth limit of 3.42 m, which is an apparent underestimate due to the wave conditions. Hence for more extreme storm conditions, such as the July 1978 storm (H_b= 4.76 m, Hay, 1991), wave set-up= 0.72 m, the closure depth would be 5.21 m. This figure is in closer agreement with that calculated using the Hallermeier equation, although the Hallermeier limits are derived for wave conditions which are not exceeded for more than 12 hours per year, not extreme storms.

8.3.2 Morphological Comparison

The HOL limit is essentially the diabathic closure depth (D_d) defined as the critical depth for the inception of sediment motion (Horikawa, 1988). As shown above from the differences in HOL limits at Mt. Maunganui, D_d is a very difficult parameter to quantify and is best determined via repeated surveys of the beach profile. Offshore sounding profile results do provide some comparison with the HOL results, with Hay estimating the actual outer limit to be about 0.5 to 3 m less than that calculated based on repeated nearshore profiling of BOPCES sites between Mt. Maunganui and Papamoa. The minimum depth at which no significant change in profile shape occurs over a long period of time may then be assumed to be the closure depth. Although this requires a long record of profile measurements, some indication may be gained from the three profiles sounded for Pukehina south (BOPCES site 27), 300 m to the south-east of the S4 site. The offshore profiles from the BOPRC Beach Profiling Survey 1992 (taken to 15-16 m water depth) and BOPCES 1977 and 1978 profiles (taken to 11-13 m water depth) depicted in Figure 8.22 suggest that the onshore-offshore limit of no significant sediment transport at Pukehina Beach is approximately 12 m, however due to the large time difference between the 1977/78 and 1992 profiling dates and differing exact transect positions in the 1978 profile, a true estimate is difficult. The inner limit calculated above does seem reasonable, with an estimate of 6.0 m probably more accurate.

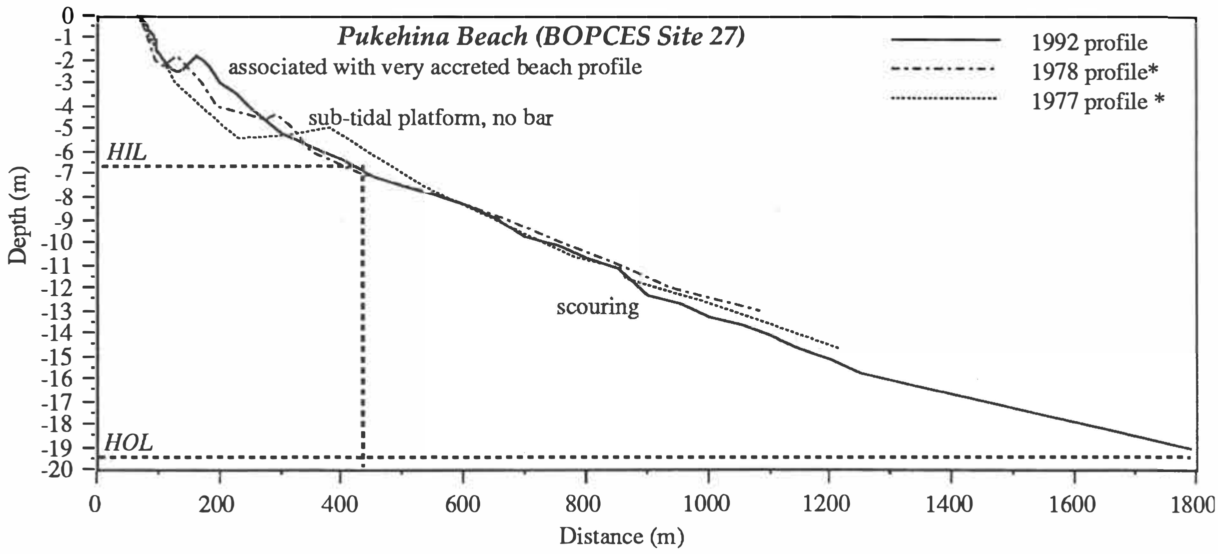


Figure 8.22 Comparisons of the nearshore surveyed profile morphology for 21/4/1977 (Healy *et al.*, 1977), 16/2/1978 (Healy, 1978c), and 1/5/1992 at BOPCES site 27 (Pukehina south). Also shown are the Hallermeier inner (d_l) and outer (d_i) limits based on Tauranga wave data. Profiles are all relative to mean sea level (0.0 R.L.), with the 1977 and 1978 profiles reduced from MLWS to this level.

The difference in the morphologies of the 1978 and 1992 profiles is small, suggesting similar morphodynamic conditions and negation to some degree of the seasonal effects on the profile morphology. However it also infers little overall change in the volume of sand present. A shift in position of the offshore bar is the most noticeable disparity between the three dates, with the development of a sub-tidal platform rather than a bar for the 1977 profile, consistent with a reflective beach state onshore. Wave induced scouring has also occurred at the 11 m water depth, with the small scarp indicated more pronounced on the 1992 profile. This scouring may have occurred as a result of Cyclone Bola in 1988. Bradshaw (1991) has shown from repeated side-scan sonar surveys that similar scouring occurred on the East Coromandel inner shelf following this storm event. The 1977 profile shows a sub-tidal platform 230 m wide, and an offshore gradient of 1:81. The 1978 profile shows two bars, with the outer bar being small, and a gradient of 1:100. Healy (1978) suggests that this change is due to:

(a) the 1977 profile, sounded later in the year, may have reached a summer profile (i.e. some of the sand has moved onshore);
(b) greater wave activity causing erosion of the berm and frontal dune toe in the 1978 profile, may have placed more sand on the bar;
(c) increased littoral drift supply;
or (d) local redistribution of sand by rip currents.

All options are likely and it is probably a combination of all four.

The 1992 profile contains a single bar, but very well developed berm, and an offshore gradient of 1:90. The possible erosion of sediment between 1978 and 1992 at depths beyond 11 m may indicate longer-term erosion of the lower nearshore zone as sediment is transported onshore. An alternative explanation is that this may be the effect of extreme storm-induced change with sediment, particularly fine and medium grained sands, transported in an onshore direction, evidenced by both the well-developed nature of the beach (Chapter 4) and the development of an offshore bar.

For sediment budget purposes Hallermeier (1981) suggests that the ocean boundary of the sediment budget control area be taken at d_l (HIL). Hence, for Pukehina-Matata the depth limit used is suggested as 6 m, equivalent to D_p from Figure 3.9. The outer limit is important in calculating diabathic transfers.

8.3.3 Sediment Textural Evidence of Sediment Transport Limits

At the S4 site the nearshore sediment distribution pattern (Chapter 5) indicates a diabathic closure depth (HOL) of approximately 12 m where the fine sands grade rapidly into coarse sands, with minimal overlap of the grain size distribution curve. Further to the south-east between Otamarkau and Matata no such distinctive boundary was found in the nearshore surficial sediments distribution. This suggests that either a textural change and or morphological change occur beyond the depth of sediment sampling (15 m) at perhaps 18 m, or that the limit of significant diabathic sediment transport does not show any textural change. From side-scan sonar there is some suggestion that coarser sediments occur at about this depth, especially between Pikowai and Kohioawa Beach. If the limit of onshore-offshore movement is greater in this area, this would then suggest that the wave climate for this section of the study area has larger waves.

However, from diver observations a textural change from 7.0 m (Mz=0.23 mm) to 9.7 m (Mz= 0.52 mm), was observed suggesting that the limit of significant onshore/offshore sediment transport at Matata is about 8.5 m. This textural change, from the side-scan sonar mapping, appears to be irregular, suggesting that the SCUBA dived sites may lie in a band of megaripples, due to wave refraction effects from Rurima Rocks, or bathymetric irregularities developed by faulting or wave induced erosion.

8.4 Interaction of the Beach-dune-nearshore system

The Pukehina-Matata beach-dune-nearshore system undergoes continual sediment exchange between its various dynamic units, with distinct diabathic coupling of the beach and upper nearshore zones at most locations. The main exception to this appears to be Town Point, which Smith (1989) suggests is a pocket beach system. This is consistent with probable limited diabathic exchanges at Newdicks beach (Town Point), as indicated by the small Hallermeier limits in this area. Sediment additions at Newdicks Beach are from erosion of the Town Point shoal and rock-strewn inter-tidal zone, from sediment outflow of the Waihi estuary and ebb-tidal delta interactions. Additionally it may receive small volumes of north-easterly directed littoral drift which is not intercepted by the Waihi estuary. The main arterial littoral drift flow to the south-east along the Bay of Plenty coast is suggested as interrupted by the Town Point promontory, with sediment accumulation in the nearshore zone offshore from Maketu, as indicated by the flatter nearshore profiles (Dommerholt, *in prep.*, 1993), and to a limited extent within the Maketu estuary. It is also possible that some sediment is carried offshore and out of the beach-dune nearshore system onto the middle and outer continental shelf. Hence longshore currents in the vicinity of Town Point are probably small to non-existent, although some littoral drift material may by-pass Town Point and get transported onto Pukehina Beach.

Pukehina Beach, from morphological evidence, does not have large quantities of littoral drift material capable of nourishing the beach-dune-nearshore system, as indicated by the numerous submarine rock outcrops and reefs in the area. Offshore from the Waihi estuary these sea-bed irregularities have been mostly covered due to possible downwarping of this area, and/or by sediments originating from the Kaikokopu and Pongakawa streams with ebb-tidal delta deposits reworked to accrete the northern (distal) end of Pukehina Spit. Beach erosion surveys by Healy *et al.* (1981) for the Coromandel showed the distal end of some barrier spit systems (Matarangi, Cooks Beach, Pauanui, and Whangamata) to be characterised by accretion at the point of ebb-tidal delta attachment (Bradshaw, 1991), as appears to be the case with Pukehina Spit. However, the general lack of sediment in the area during historic times is also evidenced by the steeply faceted, transgressive nature of the Holocene dunes along Pukehina Spit, and lack of any true foredune or dune development between the Pukehina Redoubt and Rodgers Road.

Further to the south-east between Otamarakau and Matata, the nearshore zone is nourished by numerous small rivers and streams (e.g. Waitahanui, Pikowai, Herepuru), with a south-westerly directed littoral drift system. This system has increasingly more sediment added to it from initiation north of Otamarakau in the vicinity of Rodgers Road, where the inner-shelf and nearshore zones are dominated by rock outcrops, gravels, and coarse sands, indicative of minimal available sediment, which has been removed via transportation to both the north-west and south-east. From Matata to the Tarawera river the volumes of sediment within the system are increased as wave refraction effects from Rurima Rocks, and sediment input from the Tarawera river and associated ebb-tidal delta transport of sand to the north-east along Awaateatua Beach.

8.4.1 Example: Pukehina Beach

A generalised conceptual model of beach-dune-nearshore interaction for Pukehina Beach, based on the nearshore profiles at BOPCES sites 27 and 28 (Pukehina south to Pukehina central), was developed for fairweather and storm extremes, depicted in Figure 8.23. The ideas and models presented combine the increased understanding of various aspects of the beach-dune-nearshore system gained in this and preceding chapters, and has some limited applicability to the rest of the Pukehina-Matata coastal sector.

Under fairweather conditions (Figure 8.23a), sediments with a mineralogical composition characterised by high amounts of pumice and glass are transported onshore by low swell waves (H_S less than 0.75 m). Transportation of sediment in an onshore direction results in a steady accumulation of sediment on the beachface, and slow onshore movement of the offshore bar developing a ridge-runnel system, which under prolonged periods of calm wave conditions becomes part of the beach berm with a non-existent to flattened offshore bar of less than half a metre in height. Under conditions of persistent long period swell waves where interaction with the sea-bed is more significant, much of the pumiceous material within the nearshore zone, previously eroded by storm waves from the weakly consolidated volcaniclastic reefs in the area, is also moved onshore. In the lower nearshore-inner shelf region a weak, steady bottom current is created, which commonly flows in an easterly shore-oblique direction. This current is capable of entraining only the smallest grains sizes ($M_Z < 0.1$ mm; very fine sands). Littoral drift is negligible or small, depending on the presence of local wind developed choppy seas which increase drift rates within the shortened littoral zone.

Under storm conditions (Figure 8.23b) waves break further offshore, and in deeper water (up to 15 m water depth) entraining sediments at greater depths, with sands continually in suspension. Sediment is removed from the beach and swash zones, transported seawards by strong rip-currents, and deposited in the upper nearshore zone developing a sub-tidal platform at the point where the wave orbital motions can no longer move the coarser sediments. Downwelling bottom return flows transport the fine sands onto the lower nearshore and inner shelf. Localised wave scouring occurs in areas associated with bedrock outcrops, as localised currents are formed and concentrated along areas of the seabed between reef exposures. The wind, wave, current, and sediment interactions between the beach-dune-nearshore system are complex under storm conditions. The lower nearshore inner shelf current is predominantly wind-driven, highly variable, with speeds of up to 25-50 cm/s, and

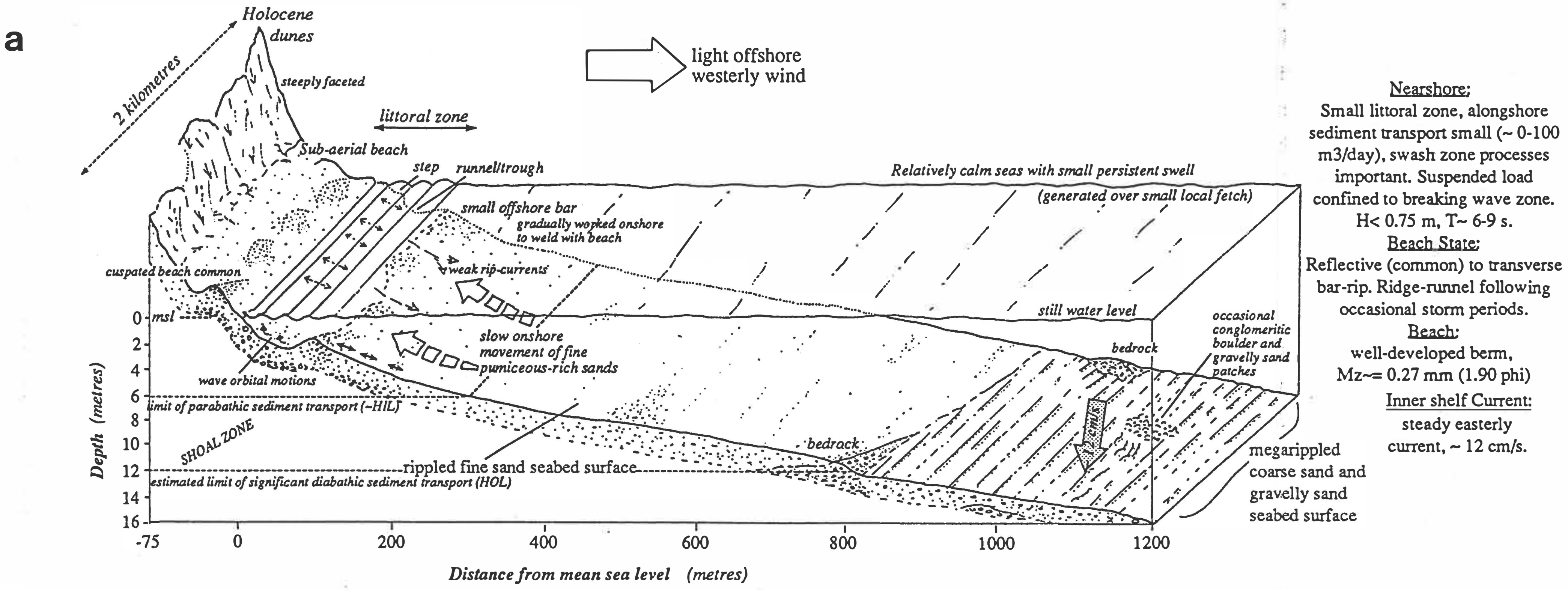
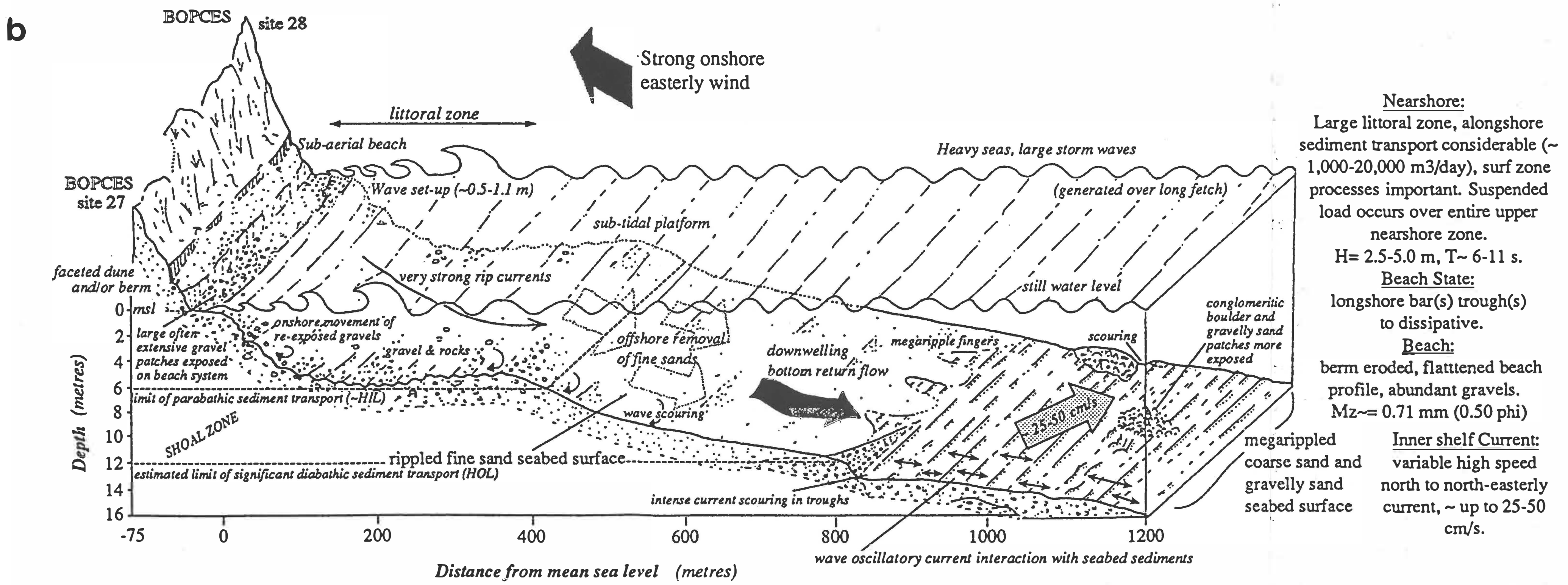


Figure 8.23 Schematic representation of the currents and sediment movements within the Pukehina-Matata coastal sector associated with and in response to *a)* fair weather conditions, and *b)* storm conditions (using storm wave parameters in Hay, 1991, and from this study). Models are the accumulation of wave and wind measurements and observations, side-scan sonar, sediment textural data, aerial photographs, and beach observations and photographs taken by the author. Profile morphology is based on the BOPRC Beach Profiling Survey 1992 (Dommerholt *in prep.*, 1993), Healy *et al.* (1977), and Healy (1978c).



commonly in a northerly to north-easterly shore-parallel to shore-oblique direction.

With larger storm waves wave focussing becomes more prevalent, particularly between Otamarakau and Matata, developing embayments along the beach which concentrate beach erosion. Under extreme storm conditions waves may overtop dunes, causing flooding in swales (e.g. the 1968 Wahine storm), with rapid erosion of the sub-aerial beach.

Littoral drift can be considerable over a large littoral zone of up to 500 m, depending on exact wave conditions (Chapter 9), with parabathic sediment transport under extreme storm conditions (return period ~ 5-10 years) occurring beyond the calculated Hallermeier inner limit. The beach state may vary from extremely dissipative to longshore bar trough depending on the duration of the storm event and the previously existing beach state. Within the littoral zone greywacke, conglomeritic and rhyolitic gravels are re-exposed as the sandy sediments are removed offshore and wave action transports the coarser sediments in an onshore direction, where they may cover extensive areas of the beach, swash and surf zones, or under less extreme conditions exist in localised patches.

8.4.2 Implications for a Conceptual Sediment Transport Model

The gravel patches, initially referred to in Chapter 5, are shown from recent aerial photography of Pukehina Spit (Feb. 1993) to sometimes exist as a dark band of gravel sediments lying just offshore of southern Pukehina Beach, where the gravels appear to be most concentrated. These gravels, in particular the greywacke fraction, periodically appear on the beach as lag deposits, and in terms of sediment transport behave in a different manner to the sand fraction. The gravels have been shown to possess no modern source sufficient to account for the large volumes observed within the beach system, with extensive searches and sediment analysis of the streams and Town Point cliff material finding very minimal quantities of greywacke gravels. Although possible fluvial sources from the greywacke hills inland from Otamarakau, during and prior to the Pleistocene, may have contributed significant greywacke material to the littoral system. However in the authors opinion, it can be reasonably concluded that these gravels originate from Castlecliffian age sediments which consist of *"tuffaceous sediments and greywacke/ignimbrite gravels and conglomerates"* (Nairn and Beanland, 1989), found in the cliffs within the Pukehina-Matata coastal sector. Marine erosion of these previously more extensive cliffs, during the Pleistocene, would have introduced these gravels to the beach-nearshore system. Due to the lack of addition of vast amounts of sediments in the Holocene, such has occurred in developing the Rangitaiki Plains foreshore, some of these gravels have remained active within the littoral environment. This is evidenced by a beach "basement" of sandy gravels which, based on augering of the backbeach between Otamarakau and southern Pukehina beach, underlies a 0.6 to 1.5 m thick sand layer. Such a gravel basement may have some structural control on the morphology of the beach-nearshore system. In terms of sediment transport of these gravels there is little net alongshore transport, from beach observations by the author and local residents between 1991 and 1993, although as suggested in Chapter 5, they may migrate as gravel patches along the beach for up to half a kilometre. The alongshore transport of the gravel fraction is therefore considered oscillatory with no long-term net directional effect. However there does appear to be a significant control on the diabathic transport of these gravels, which when present within the littoral system, have been found to layer either: *(i)* just the beachface, *(ii)* both the beachface and swash zones, or *(iii)* the entire swash-surf zone. These varying states occur when the finer sand layer in these regions is removed by storm wave action, and occur also within the surfzone when the gravels are exposed and moved onshore.

Littoral drift and sediment transport of the sand fraction of the beach-dune-nearshore sediments suggests a bi-directional drift system is operating, with the *net* transport of sediment in a north-west direction from near Otamarakau to the distal end of Pukehina Spit,. In contrast from Otamarakau to Matata the net drift is to the south-east, based on the following lines of evidence:

(i) Pukehina Spit is orientated in a north-westerly direction, with spit orientation commonly found to indicate the net littoral drift direction;
(ii) Beachface sediments show a fining trend from Hauone to the Waihi estuary (distal end of Pukehina Spit), during both erosive and accretionary beach phases, while from Hauone to Matata there is no discernible trend in grain size. Sorting and skewness trends while not statistically significant in terms of an observable trend are not inconsistent with a bi-directional drift system.
(iii) The McLaren model for determining sediment transport on the basis of sediment textural parameters is indicative of a bi-directional drift system, with its origin at Otamarakau.
(iv) Stream orientation between Otamarakau and Matata, based on field observations, aerial photographs, and dune erosion to either side of the stream mouths show the largest frequency of stream migration is to the south-east and that the greatest off-setting occurs in this direction. These streams are all beach impounded and as such act as mini-spits, indicating a net south-easterly longshore drift.
(v) The distal end of Pukehina Spit has been accreting from 1978 to 1993 in comparison with the southern end of the spit which shows some erosion.
(vi) Mineralogical trends show that the peaks of some minerals are off-set relative to their stream sources inferring a south-easterly drift between Otamarakau and Matata. Other mineralogical trends (e.g. amphiboles) for Pukehina Beach show a decrease in a south-easterly direction, which while indicating some sediment is transported in this direction, may still infer a net drift to the north-west.
(vii) Local variations in wave approach angles within the study area. Town Point acts to shelter the littoral zone along Pukehina Beach from westerly generated local waves, with an observable larger wave regime between Otamarakau and Matata when waves are from the westerly quadrants. The nearshore profiles support a larger wave regime between Otamarakau and Matata, with a steeper upper nearshore, indicating more wave energy is impinged onto the beachface in this area (Dommerholt, pers. comm., 1993), than at Pukehina where the waves are dissipated more (Figure 8.24). Also, the offshore islands of Motunau, Motuhaku, and Motiti act to refract waves from the west to northerly quadrants, with the irregular nearshore submarine topography further dissipating some of the wave energy, particularly larger storm waves. Between Otamarakau and Matata the coastline is more exposed to a fuller range of wave directions from the west to the east. The net effect for

Pukehina Spit is for higher frequency westerly waves and corresponding littoral drift, but in small quantities, with opposing occasional north-easterly and easterly storm events, which causes a westerly drift direction with order of magnitudes greater longshore transport rates. The overall balance of gross drift creates a net drift to the north-west along Pukehina Spit. However, the net sediment volumes involved are small, since there is no vast accumulation of sand in the nearshore zone offshore from the distal end of the spit. From Otamarakau to Matata the effect of north-westerly, and northerly waves is greater, with larger amounts of gross drift which are not balanced by easterly events, thereby causing a net westerly transport of sediments.

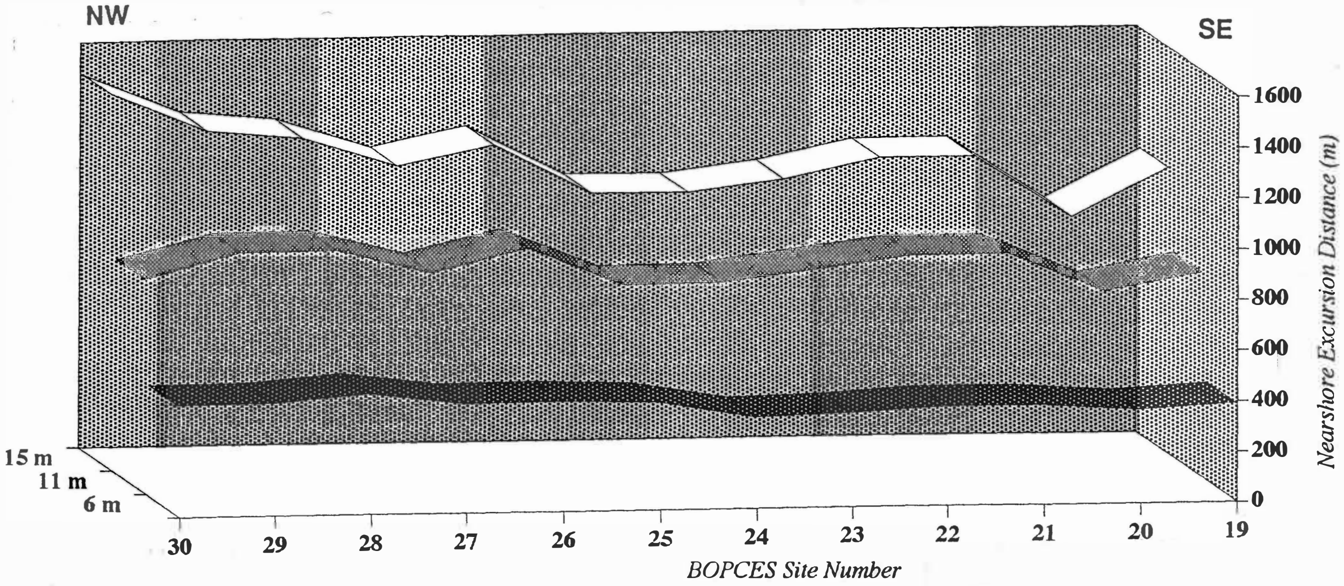


Figure 8.24 Variation in nearshore excursion distances for the Pukehina-Matata coastal sector at BOPCES sites 19 to 30. Distances are based on the May 1992 surveyed nearshore profiles, measured from the crest of the foredune to the three water depths shown: 6 m (approx. HIL, parabathic transport), 11 m (approx. HOL, diabathic tramsport), and 15 m. *(data from Dommerholt in prep., 1993)*

At the northern and southern boundaries of the study area counter drift systems are present in addition to the overall bi-directional drift system. At Pukehina some sediment is transported from the Waihi estuary to northern Pukehina Beach, and south-east of Matata sediment is transported from the Tarawera River in a north-easterly direction along Awaateatua Beach.

Sediment sources are suggested as:

- *streams feeding the Waihi estuary;*
- *sediment loads of the Otamarakau-Matata streams, in particular the Waitahanui, Pikowai, and Herepuru ;*
- *Tarawera River;*
- *onshore transport of sediments from the nearshore submarine rock outcrops, between Pukehina and Otamarakau, under conditions of large swell waves;*
- *cliff and nearshore abrasion of sediments at Newdicks Beach, Town Point;*
- *long-term small-scale erosion of the dune-beach-dune nearshore system in areas where other sources are not present or provide an insufficient volume of sediment.*

The sediment transport directions, sources, and sinks determined above and in the preceding chapters are integrated into Figure 8.25, which forms the basis of transfers involved in determining the littoral sediment budget presented in Chapter 9.

8.5 Summary

- From SCUBA diving observations at Matata, Otamarakau, Pukehina Redoubt, and Pukehina Beach, show that for the nearshore from 7 to 15 m water depth all bedforms are wave generated. From Kos'yan (1988) relationships bedforms are dependant on sediment textures, with the development of megaripples n coarse sediments. Where megaripples occur the sediments consist of finer material on the crests with coarser sands, gravel, and shell in the troughs.

- Five nearshore sediment morphological and textural patterns were identified from mapping 239 km of the nearshore and inner shelf along the Pukehina-Matata coastal sector. From Town Point to Otamarakau the area is dominated by numerous reefs, submarine rock outcrops, and associated boulder and gravel areas. The expanse of these materials between the basal end of Pukehina Spit and Otamarakau corresponds with the area of shell and lithic hash containing sediments in the nearshore zone at depths > 11-13 m found in Chapter 5.

- Within the Pukehina Spit, Redoubt, and Rodgers Road areas bathymetric profiles in conjunction with the morphological associations of coarse megarippled and fine featureless areas indicates north-westerly directed sediment transport, since the coarse megaripple bands occur predominantly on the south-western or updrift side of topographic highs and rock outcrops. Further more topographic asymmetry occurs in this direction, caused by sediment piling-up on the up-current side, and corresponding erosion on the down-current side. However this inferred direction may be complicated by wave refraction and localised current scouring.

Within the Otamarakau-Matata nearshore section, there are no bedrock or associated gravel and boulder patches, suggesting sediment additions to this area are greater from either onshore transport of sands and/or stream sediment discharges, particularly from the Waitahanui, Pikowai, and Herepuru streams.

Offshore from Kohioawa Beach to the Tarawera River in 15 to 30 m water depth, a distinctly different sonograph pattern was found. This consisted of rapid, alternating CMR and finer, featureless bands, developing a 'sand wave type pattern'. However, the orientation of these 'sand waves' in a north-east direction tending more northerly in places, is suggested as due to faulting associated with the Whakatane Graben and Taupo Volcanic Zone. This is indicated by the rapid spatial offsets in the submarine topography in the Matata area, lack of bedrock patterns on the sonographs, and the tectonically active nature of this area, which is known to contain recently activated faults.

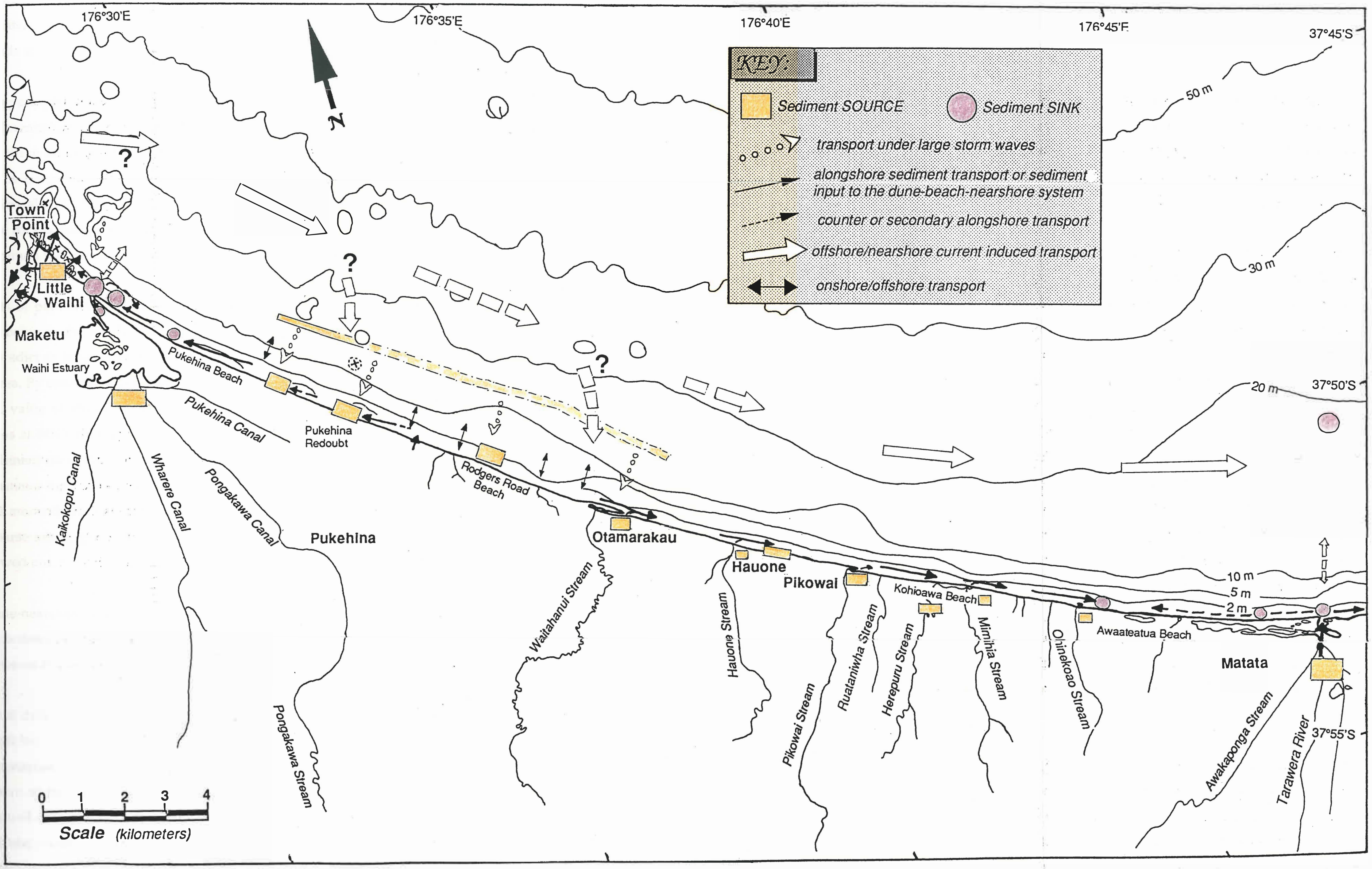


Figure 8.25 Interpreted and suggested sediment sources, sinks, and connecting sediment transport pathways for the Pukehina-Matata coastal sector. Based on results from: sediment textural analysis; inferred transport pathways of the McLaren and Sunamura & Horikawa models; heavy and light mineralogical trends; sediment textural groupings; S4 wave, current and sediment transport interactions; beach-dune-nearshore morphology; combined bathymetric and side-scan sonar mapping associations; beach observations; and the authors own opinions.

- Bedform measurements from side-scan sonographs show that the megaripple bedforms are approximately shore-parallel and primarily due to wave action, although wave focussing may be an important mechanism, shown to occur along much of the study area (e.g. Matata). In areas where bedrock is present (Town Point, basal end of Pukehina Spit to Rodgers Road) downwelling currents may cause intense scouring of bottom sediments where current flows are restricted and intensified, forming bands and patches of coarse grained megaripples, found to be indicative of erosion.

- Coarse megarippled areas of the nearshore and inner shelf indicate regions where erosion of the bottom sediments has occurred, with winnowing of finer material leaving a coarser lag deposit. Commonly these areas occupy topographic lows, and are more prevalent in regions where the bathymetry is irregular. The formation of CMR areas may be due to wave focussing, especially between Pikowai and Matata, and localised current and wave scour in the Pukehina-Otamarakau sector where rock outcrops and associated topographic features concentrate current flows. However the most common mechanism is probably shore-parallel wind-generated currents.

- The limits of parabathic and diabathic sediment transport are important for understanding the interactions between the beach, nearshore, and inner-shelf zones. Hallermeier limits from Tauranga wave data predict an inner limit of 7.1 m and an outer limit of between 20 and 21 m for most sectors of the study area. By contrast wave data from S4 deployment at southern Pukehina Beach (Chapter 7), gives a HIL value of about 5.5 m and a HOL value of about 11.5 m. Based on nearshore profile morphologies at BOPCES site 27 surveyed in 1977, 1978, and 1992, the limit of significant onshore-offshore sediment transport is about 12 m, which shows close agreement with both the S4 calculated outer Hallermeier limit and sediment textural evidence. From the nearshore spatial distribution of surficial sediments there is an abrupt change in sediment texture at 11-13 m water depth, from fine sands, to coarse sands, gravel and shell containing sediments, in which nearly all of the fines have been winnowed out.

- Beach-dune-nearshore interaction for the Pukehina-Matata coastal sector is dominantly the result of diabathic processes, with the parabathic processes, including littoral drift, having more of a longer-term influence on the morphology and sediments of the littoral system.

- Net littoral drift is bi-directional from an origin near Otamarakau, where net drift is oscillatory. Pukehina Spit has a north-westerly directed littoral drift, however the quantities involved are small. Between Otamarakau and Matata net drift is to the south-east, within a system which has increasingly more sediment added to it from initiation near Otamarakau, including sediment additions from the numerous small streams and rivers in this sector. At the northern and southern boundaries of the study area some counter-drift may occur. At Pukehina some sediment is transported from the Waihi estuary to northern Pukehina beach, which acts to nourish the distal end of the spit and Newdicks Beach to the north-west. South-east of Matata sediment is similarly transported from the Tarawera River in a north-easterly direction along Awaateatua Beach.

CHAPTER NINE:

Littoral Sediment Budget

CHAPTER NINE: INTEGRATED SEDIMENT BUDGET

9.0 Introduction

This chapter integrates available information for the littoral sediment budget, in an attempt to arrive at a quantitative estimate of the inputs, outputs, balance and transfers within the Pukehina-Matata littoral sedimentary system. Specific discussion of the fluvial inputs, diabathic sediment transport, and littoral drift is given, prior to presentation of the littoral sediment budget, which entails estimation of the identified components of the sediment budget.

9.1 Fluvial Inputs

Fluvial inputs for the Otamarakau-Matata sector in particular, are a significant contributor to the beach-dune-nearshore system. Data has been published for sediment loads of major New Zealand rivers, including the Tarawera River. No data exists though for the smaller streams and rivers in the study area, although some spot discharge rates are estimated from measurements in 1974 and 1975. By using discharge rating curves and associated data it is possible to estimate the sediment loads of these other streams and rivers from predictive formulae similar to that of Thompson and Adams (1979), and used in other sediment budget studies (Gibb and Adams, 1982; Carter, 1986).

Empirical equations to determine the sediment yields for rivers are often the only means of determining annual fluvial inputs to the coast in the absence of direct measurements. Nevertheless direct measurements are required to calibrate predictive equations. Such equations are given in Griffiths (1982), Thompson and Adams (1979) and Gibb and Adams (1982) for the major rivers in the North and South islands. These equations however require some sediment measurements of sediment concentrations as well as long-term flow records. For the streams and rivers in the study area much of this information is unknown. The results of sediment yield equations tend to overlook two assumptions. Firstly, the amount of sediment that the flow is capable of transporting is assumed to be available for transport, hence results are maxima for the given sediment sizes. And secondly, the formulae are derived for steady flow conditions, and it is not possible to take into account the effects of the rise and fall in stage during floods, when more or less material is transported. Sutherland (1979) states that on large catchments and rivers (e.g. Tarawera) this effect is probably minimal, but on smaller rivers that have rapidly rising, short duration floods, some errors, probably over estimates, can be expected.

Another method which may be used is given in Griffiths (1982) who used multiple regression analysis of eight elementary functions fitted to measured concentration and flow data to obtain the sediment yields. He then developed regional equations based on linear regression of all data, with mean catchment rainfall found to be the only significant variable. While the Tarawera river is not included in his work, it is contained in the regional boundaries of one of the predictive equations, given as:

$$G = -1382 + 1026P \qquad (r^2=0.80) \qquad \text{....equation. 9.1}$$

where: G = specific annual suspended sediment yield in t/km^2/yr; P = catchment mean rainfall in metres.

Equation 9.1 is based mainly on catchments of the eastern Bay of Plenty where erosion rates and sediment yields are substantially higher (Griffiths and Glasby, 1985) than the sediment loads of the streams within the Pukehina-Matata coastal sector.

9.1.1 Tarawera River

Table 9.1 summarises known estimates of suspended load and bedload for the Tarawera River. Differences in estimates between sources appears mainly due to the distinction in defining suspended load and bedload. Griffiths and Glasby (1985) define bedload as the gravel class range given on the Wentworth scale (Folk, 1968 p.25) i.e. greater than 2mm, and suspended load as all else. Bedload is estimated at 2-5% of the total suspended load in any given river, which includes the greywacke braided rivers of the South Island (Griffiths and Glasby, 1985).

In contrast other authors dealing with *sediment budgets* have vastly different definitions. Carter (1986), makes a distinction between river bedload and shelf (ocean) bedload. River bedload includes medium sand, coarse sand and gravel, and suspended load fine sand and mud. Whereas shelf bedload is fine sand to gravel, and suspended load mud and possibly very fine sand. Gibb and Adams (1982), give bedload as *"coarser sand and gravel"* and suspended load as *"finer sand and mud"*. Their overall sediment budget defines bedload as fine, medium, coarse sand, and gravel, with very fine sand and mud contributing to the suspended loads.

Murray (1976) using a bedload sampler to determine the sediment load for the Tarawera river mentions that the device was designed to measure bed material 2-10 mm in diameter. From particle size analysis of bedload material from the Awakaponga flow gauging site, 40% by weight was in this size range (gravel) and another 25 % in the 1-2 mm diameter range (very coarse sand), with a mean grain size of approximately 2.05 mm. This compares favourably with Healy (1978) and results from this study which show that the mean grain size for the lower Tarawera is 1.29 mm (-0.37ϕ, very coarse sand),and for the estuary Tarawera 1.60mm (-0.68ϕ, very coarse sand). Hence while only 3-5% of the total sediment load of the Tarawera river which enters the coast annually is expected to be bedload, as proposed in Griffiths and Glasby (1985), the actual sediment texture of the river is predominantly bedload material (Figure 9.1).

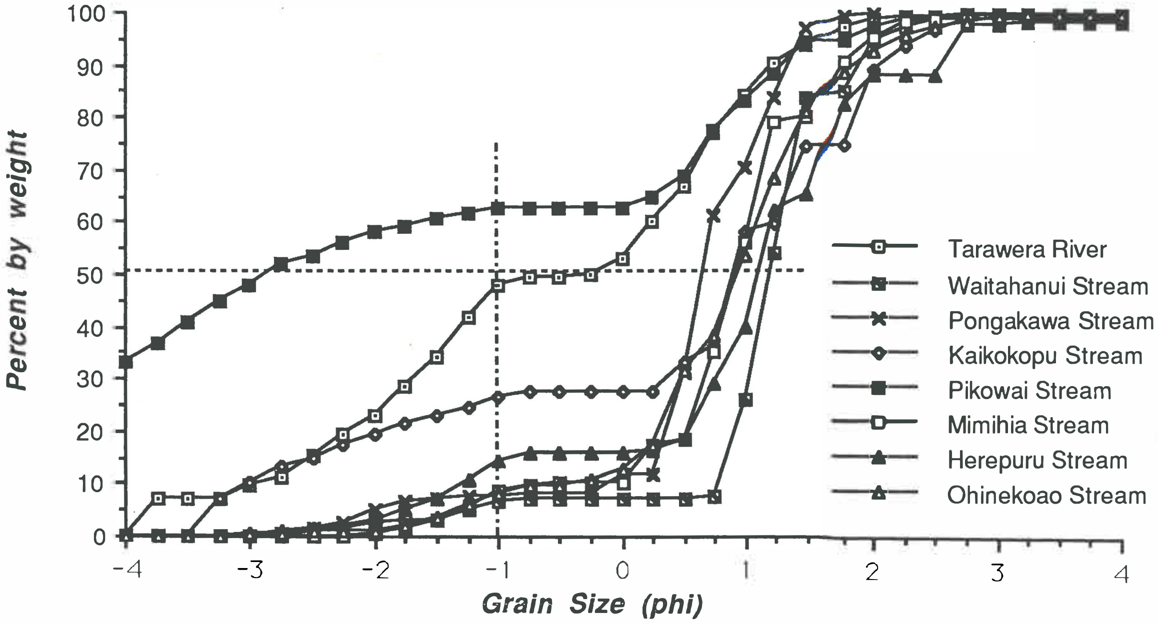


Figure 9.1 Cumulative frequency curves for the stream and river sediments within the Pukehina-Matata coastal sector, from results in Chapter 5. Note the predominance of river bedload material in the streams, and the 47 % gravel sized material of the Tarawera River.

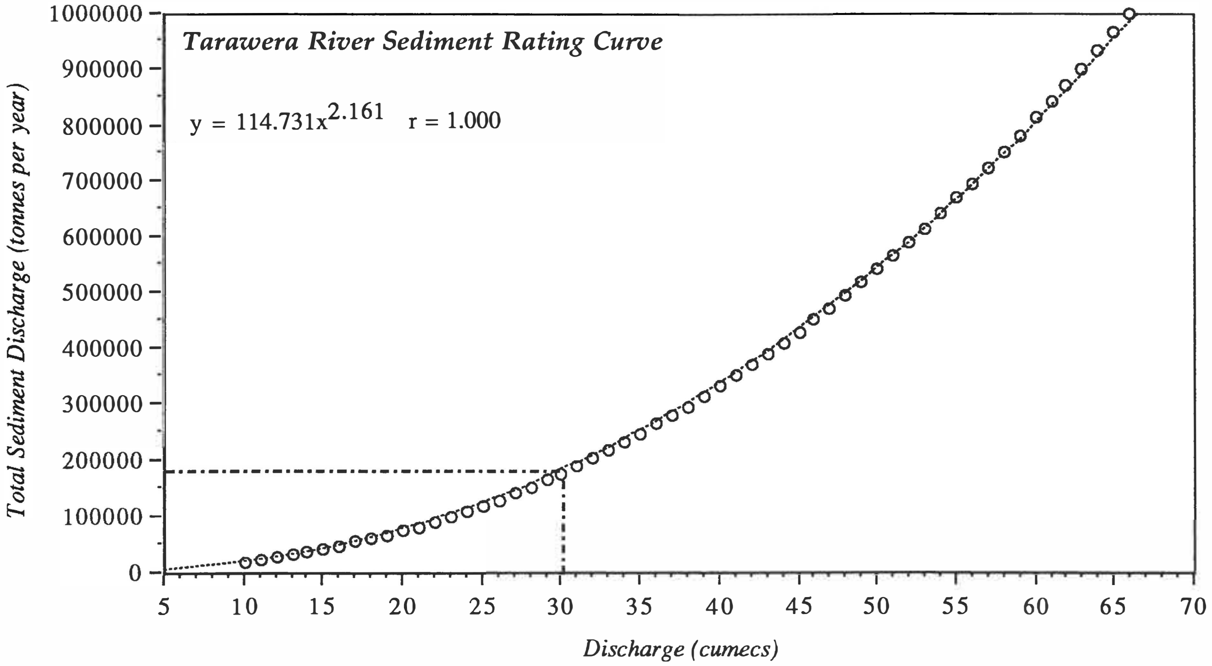


Figure 9.2 Derived sediment discharge rating curve for the Tarawera River *(source: MWD, 1978)*

Total sediment discharges were calculated for the Tarawera river by the MWD (1978) based on 20 gaugings carried out between 19 September 1962 and 15 September 1976, however, the actual methods involved and analysis of the results is unknown. From these estimates a sediment discharge rating curve was produced (Figure 9.2).

Table 9.1 Estimates of Sediment loads for the Tarawera River.

Total load (tonnes per year)	*Bedload estimate (tonnes/yr)*	*Suspended load estimate (tonnes/yr)*	*Method Used**	*Source*
195,640	149,285	46,355	1	Murray (1976) *(1974 data)*
228,000	149,000	79,000	2	Murray (1976) *(1976 data)*
365,200	273,900	91,300	3	MWD Records (1960-1969)
331,760	12,760	319,000	3	Griffiths & Glasby (1985)

* 1. Determined from sediment traps using Helley-Smith and baffle type samplers
2. Combination of sediment traps and discharge rating curves
3. Predictive formulae relating sediment yield to flow rating curves.

The total load estimates of Murray (1978) appear the most accurate suggesting a value of 228,000 t/yr from 1976 data which are more representative of the typical flow conditions. The Murray 1974 estimate is based on flow discharge levels which were the third lowest in twenty years, and hence the sediment load would be underestimated on an annual basis. Also, the derived sediment discharge rating curve for the Tarawera River (Figure 9.2) shows close agreement with the Murray 1976 figure, which equates to 149,000 m^3 per year of total sediment load, by assuming a density value of 1.52 tonnes per cubic metre. This density value is calculated from the average density of the beach sediments (2540 kg/m^3) multiplied by the particle density (1-porosity) of 0.6.

In considering the supply of bedload material to the Tarawera river, the lake acts essentially to block all material, and hence the Tarawera valley is considered to be the main contributor of bedload to the Tarawera river (Murray, 1976). Large amounts of pumice are supplied to the Tarawera river during storms from tephra layers and poorly consolidated pumiceous strata, with 41 % of the Tarawera bedload material found to consist of pumice (Chapter 6).

9.1.2 Calculation of Stream Sediment Loads

Griffiths and Glasby (1985) while not discussing the sediment yields for streams and rivers that occur between the major rivers, have estimated (in Figure 2, p. 780) the fluvial sediment loads for the streams between the Kaituna River and the Tarawera River. The sum total of these streams amounts to a suspended load figure of 180,000 tonnes/yr, with 7,200 t/yr assumed to be (estimated as 4 % of the suspended load). These sediment loads seem ridiculously high.

Smith (1986) gives an approximate estimate of the sediment load from the streams draining the Kaharoa Plateau along the Otamarakau-Matata coast, by relating known sediment loads to the catchment area. Using a figure of 218 km^2 for the total catchment area, Smith's estimated average annual input of new material is 4,000 m^3, based on the Waipaoa River in Poverty Bay, which discharges an average of 18 m^3/km^2 of *sand sized* material. Smith (1986) also estimates the sediment input to the beach could be between 4,000 m^3 and 5,000 m^3 given estimated sediment yields from the Waioeka and Motu rivers of 21 and 23 m^3/km^2. However he concluded that *"These estimated volumes are lower than the rates of deposition on the coast at different periods, which could indicate that these estimates are an underestimation or there are other sources of beach sediment" (Smith, 1986)*. O'Shaunessy (1993) suggests that these sediment rates are *over-estimated* and the actual sediment loads are less than 5,000 m^3, as the discharge volumes estimated are based on inappropriate sediment production characteristics of the Motu, Waioeka, and Waipaoa rivers, which are dissimilar to the Waitahanui stream, and other streams in the area. BOPRC soil conservation staff familiar with the area suggest that a lower value would be more appropriate (BOPRC, 1993). Also the estimate of 5,000 m^3 is for sand sized material only, of which the Motu, Waioeka, and Waipaoa rivers have high suspended loads. Hence, for the sediment budget determination here it is considered that the use of a conservative calculated estimate of the sediment yield per kilometre for the Tarawera River of 33.8 m^3/km^2, for sand sized sediment based on the estimated bedload figure of 59,000 tonnes/yr (Healy, 1983) would be more appropriate. The sediment characteristics of the streams and rivers within the Otamarakau-Matata coastal area are very similar, as shown in Chapters 5 and 6, with similar sediment provenance and hence texture and composition. Estimated volumes for the streams discharging into the Pukehina-Matata coastal sector are therefore higher than stated in Smith (1986; 1992) with 5,200 m^3 of material estimated to discharge at the coast within the Otamarakau-Matata area. The summarised results of given in

Table 9.2, and ignores the mud fraction in each stream, found to be a very small to non-existent part of the stream sediments and which would be rapidly removed out of the littoral system upon reaching the coast. This method though does not allow for the discharge flow rates, which determines transportation of material to the coast.

Table 9.2 Calculated annual sediment load for each stream or river contained in the Pukehina-Matata coastal sector boundaries, based on Figure 9.3. *(source: discharge, and catchment area data obtained from the BOP Regional Council)*

River	Catchment Area (km^2)	Average Discharge ($m^3/sec.$)*	L/sec. per km^2	Total Sediment Load (tonnes/year)	Annual Sediment Load (m^3)#	**Annual Sediment Load (m^3)+**
Kaikokopu	115.5	3.03	26.2	3,900	2,560	**2,560**
Puanene	13.0	0.16	12.5	430	280	**280**
Wharere	30.8	0.53	17.2	1040	680	**680**
Pongakawa	118.6	5.18	43.7	4,000	2,620	**2,620**
Pokare	3.1	0.05	15.4	100	60	**60**
Waitahanui	96.1	5.74	59.7	3,240	3,110	**3,110**
Hauone	14.0	0.33	23.4	470	300	**300**
Pikowai	28.8	1.18	41.0	973	630	**410**
Herepuru	49.0	1.37	28.0	1,650	1,080	**700**
Mimihia	18.9	0.39	20.8	630	410	**410**
Ohinekoao	5.2	0.11	21.0	170	110	**110**
Awakaponga	12.2	0.27	21.9	412	270	**20**
Tarawera	906.0	33.01	42.5	59,000	38,710	**19,330**

* Based on relating Tarawera flow annual measurements to spot discharges for all other streams.
\# Volumes are converted from masses by assuming a density of 1.524 t/m^3.
\+ Volume calculated to exclude the pumice lost from the beach system, by comparing the ratio of pumice in the streams with pumice on the beach.

The only known available data on stream flow measurements within the study area are spot discharges taken in 1974 and again in 1975 as part of the Tarawera River-Pongakawa River Water Resources Survey, and a water resources study conducted on low-flow water resources in the Hamilton, Whakatane, and Tauranga Districts (MWD Internal Report). The mean flow for the Tarawera River at Awakaponga is 33.128 m^3/s which is exceeded 41 % of the time, with a flow of 31.640 m^3/s exceeded 50 % of the time. The 33.128 m^3/s value is similar to the flow value recorded in 1974 of 33.006 m^3/s, and can therefore be related to the stream flow discharges taken at the same time. In calculating the stream sediment loads the Tarawera River sediment discharge curve was used in the region of the stream flow rates (Figure 9.3), and the spot discharge rates assumed to represent the mean flow conditions. In comparing the Tarawera River and the streams in the Pukehina-Matata region several assumptions are made. It is assumed that the rainfall in the region is the same, which is more or less true, and that the geology through which the streams pass is the same. As shown in Chapter 6 and Figure 2.1 in Chapter 2, the geologic materials are similar for all the streams in the area. At the extreme lower end of the rating curve it is possible that the curve function fitted for higher flow rates does not apply to very low flows. As flows below 15-20 m^3/s do not occur for the Tarawera River, and the predicted sediment loads for streams with flow rates of less than 5 m/s may be underestimated. The calculated loads using this method are given in Table 9.3.

The sum total load of all streams except the Tarawera River and Awakaponga is 6,790 m^3 per year compared with Griffiths and Glasby's (1985) estimate of 187,000 m^3. Based on the above the Waitahanui (46 %), Pongakawa (38 %), Kaikokopu (12 %), Herepuru (2 %), and Pikowai (2 %) streams contribute 99.1 % of the sediment load to the coastal system. However, the Kaikokopu and Pongakawa streams, along with the Wharere and Puanene, flow into the Waihi estuary rather than directly into the beach system, and much of this material will be lost to the estuary system, through sedimentation in the estuary and storage within the ebb and flood-tidal delta system. From areal changes to the Waihi estuary between 1943 and 1981, and estimating an average sedimentation depth of 0.5 m, it is estimated that approximately 1,450 m^3/yr of sediment remains within the estuary. The remaining 1,800 m^3 is either encorporated into the ebb-tidal & flood-tidal delta system or enters the beach-dune-nearshore system.

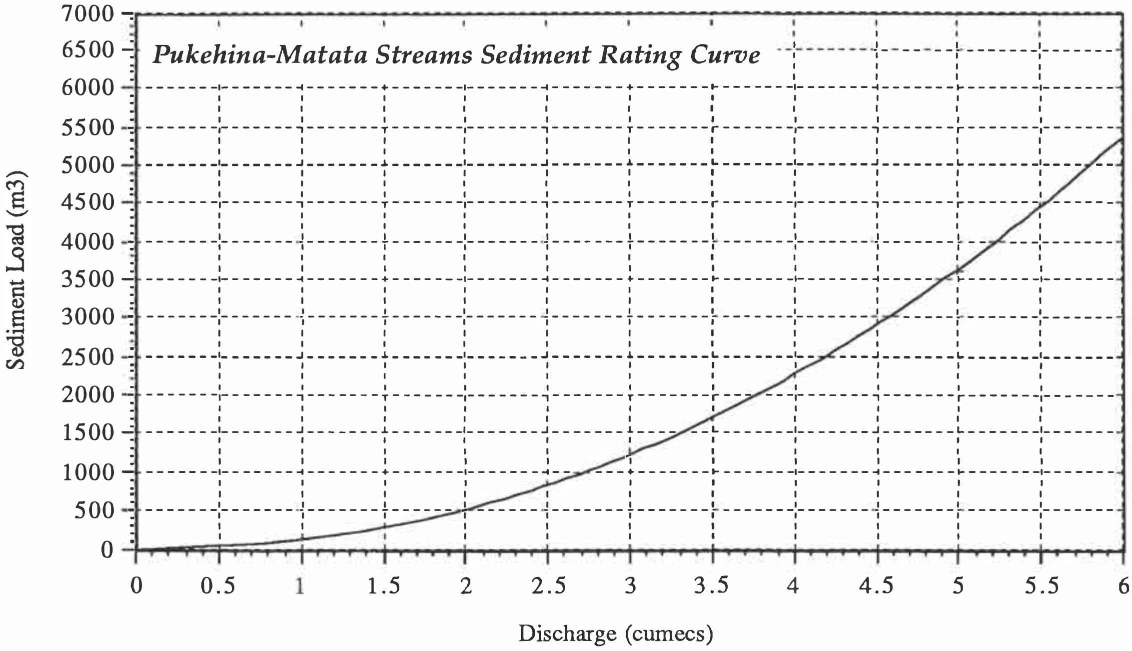


Figure 9.3 Predicted sediment discharge curve of the Tarawera river applied in the range of the spot discharges available for the Pukehina-Matata coastal sector streams. *(based on Figure 9.2, derived from data in MWD, 1978)*

Table 9.3 Calculated annual sediment load for each stream or river contained in the Pukehina-Matata coastal sector boundaries, based on Figure 9.3. *(source: discharge, and catchment area data obtained from the BOP Regional Council)*

River	*Catchment Area (km^2)*	*Average Discharge (m^3/sec.)**	*L/sec. per km^2*	*Total Sediment Load (tonnes/year)*	*Annual Sediment Load (m^3)#*	***Annual Sediment Load (m^3)+***
Kaikokopu	115.5	3.03	26.2	1,200	790	**790**
Puanene	13.0	0.16	12.5	10	6	**6**
Wharere	30.8	0.53	17.2	40	26	**26**
Pongakawa	118.6	5.18	43.7	3,900	2,560	**2,560**
Pokare	3.1	0.05	15.4	1-2	0.8	**0.8**
Waitahanui	96.1	5.74	59.7	4,750	3,110	**3,110**
Hauone	14.0	0.33	23.4	20	13	**13**
Pikowai	28.8	1.18	41.0	180	120	**77**
Herepuru	49.0	1.37	28.0	220	145	**94**
Mimihia	18.9	0.39	20.8	25	16	**16**
Ohinekoao	5.2	0.11	21.0	8	5	**5**
Awakaponga	12.2	0.27	21.9	30	20	**20**
Tarawera	906.0	33.01	42.5	149,000	97,760	**48,880**

* Based on relating Tarawera flow annual measurements to spot discharges for all other streams.
# Volumes are converted from masses by assuming a density of 1.524 t/m^3.
+ Volume calculated to exclude the pumice lost from the beach system, by comparing the ratio of pumice in the streams with pumice on the beach.

9.2 Littoral Drift

An estimate of the littoral drift contribution to the sediment budget can be made, by taking into account the assumed directions of littoral drift within the study area, the beach volume differences between adjacent survey profiles, envelope of change in beach volume, and previous estimates of littoral drift. Net littoral drift estimates for the Bay of Plenty coast are thought to be in the order of 50,000-100,000 m^3 per year (BOPRC, 1991). Healy *et al.* (1977) estimate littoral drift within the Bay of Plenty is 70,000 ± 20,000 m^3. For the Otamarakau-Matata sector of coast an unexplained estimate by Smith of 22,000 m^3 is suggested (BOPRC, 1993). However, perhaps the best estimate for the Pukehina-Matata area is given by Healy (1983), where a net drift of 25,000 was calculated based on the sediment loads delivered to the Rangitaiki Plains foreshore and progradation rates of this section of coast.

For the Pukehina-Matata coastal sector it is possible that a small amount of sediment enters the study area at its northern boundary from around Town Point, estimated as 2,000 (± 2,000) m^3. Some of this is accumulating offshore of Newdicks Beach, and some is lost to the Waihi estuary. Littoral drift to the north west along Pukehina Spit from Otamarakau, consists of input from the

Waitahanui stream (estimated as 40% of the stream material, based on stream orientation) and beach, nearshore, and cliff erosion at Rodgers Road to the basal end of Pukehina Spit. This amount is small in terms of littoral drift rates for the Bay of Plenty, and hence no major accretion has been noted along Pukehina Spit. However there is some suggested long-term accretion of the dune and beach, with suggested sedimentation in the nearshore zone offshore from the Waihi estuary. South of the Waitahanui stream net littoral drift appears to be to the south-east, and assuming no storage within the littoral system, this consists of stream inputs of sediment and onshore transports of material, which related back to mineralogy would mean littoral drift is approximately 15,000 m^3 at Matata, given that the rest of the sediment which is abraded is removed offshore as fines. However, sand extraction at Matata, of 6,700 m^3/yr, resulted in a deficit of sediment at this site, suggesting that littoral drift is lower than 15,000m^3, with Healy (1983) estimating littoral drift to the east along the Rangitaiki Plains foreshore as 25,000 m^3. Hence, an error of ± 10,000 m^3/yr is provided for.

9.2.1 Calculation of the Littoral Drift Rate

From beach wave observational data of breaking wave heights and breaking wave angles, and S4 wave data (Chapter 7) the net littoral drift rates over the period of record was determined. Calculation of the littoral drift rate for the Pukehina-Matata coastal sector was undertaken using two empirical methods. The first is based on an energy flux equation for deepwater wave conditions (CERC, 1984; Leenknecht *et al.*, 1991) utilising the S4 data collected in Chapter 7, to obtain an estimate of the probable net littoral drift rate. The second is an energy flux equation for breaking wave conditions (CERC, 1984; Leenknecht *et al.*, 1991) calculated from beach observational data of the breaking wave height and breaker angle.

9.2.1.1 Wave Data Deep-water Based Rate

The method used is based on the empirical relationship between the longshore component of wave energy flux entering the surf zone and the immersed weight of sand moved (Leenknecht *et al.*, 1991). The model makes the following basic assumptions and limitations: conservation of energy flux in shoaling waves, linear wave theory, evaluation of the energy flux at the breaker position, breaker characteristics described by solitary wave theory, and straight bathymetric contours parallel to the shoreline. The accuracy of the longshore transport rate (Q) found using the energy flux factor is estimated to be ± 50 % (CERC, 1984).

$$P_{ls} = 0.05\,\rho g^{3/2} H_{so}^{5/2} (\cos\alpha_o)^{1/4} \sin 2\alpha_o \qquad \text{...equation 9.2}$$

where: P_{ls}= longshore energy flux
p= fluid density (1025 $kg.m^{-3}$)
g= acceleration due to gravity (9.81 $m.s^{-2}$)
H_{so}= deepwater root mean square wave height (from H_s=1.414 H_{rms})
α_o= angle of wave approach in deepwater, taken as the angle of onshore approaching wave from 90° to the shoreline.

The longshore transport rate is then:

$$Q = K\,P_{ls} \qquad \text{....equation 9.3}$$

where K is an empirical coefficient, taken as 0.77 for H_{rms} data (Komar and Inman, 1970).

Equation 9.2 is a modification of the simplified longshore energy flux factor for breaking wave conditions (Eqn. 9.5), with the local wave height (H_b) related to deepwater height (H_o) by refraction and shoaling coefficients, where the coefficients are evaluated at the breaker position (Eqn.'s 15 and 16, Leenknecht *et al.*, 1991).

$$P_{ls} = 0.0884\ \rho g^{3/2}\, H_{sb}^{5/2} \sin 2\alpha_o \qquad \text{....equation 9.4}$$

Two variations of this method were applied using different deepwater wave approach angles from the data recorded by the S4/10. In the first instance the wave angle is based on the those given by the S4/10 for the total wave spectra. However since a 2.79 m 'storm' wave is suggested by this method not to be causing any littoral drift at the beach, the wave directions were recalculated based on the swell wave direction only of the wave spectra. Wave direction in both cases are based on approach to the coastline at Pukehina from 311° to 131°.

9.2.1.2 Observed Data Breaking Wave Conditions Rate

Using the Komar and Inman (1970) relationship:

$$Q_l = \frac{0.77\,P_{ls}}{(\rho_s - \rho)\,g\,a'} \qquad \text{...equation 9.5}$$

$$\textit{and:}\quad P_{ls} = (ECn)_b\, \mathrm{Sin}\alpha_b \mathrm{Cos}\alpha_b \qquad \text{...equation 9.6}$$

$$h_b = H_b/0.78 \qquad E = 0.125\rho g\, H^2 \qquad C = gh^{0.5} \qquad \text{...equation 9.7}$$

where: ρ_s = density of sediments (2600 kg.m^{-3})
H_b= root mean square of the breaking wave height
h_b = depth at breaking
E = wave energy
C = wave celerity
a' = packing coefficient of grains (0.6)

The breaking wave angle and wave height converted from observed breaking wave height to root mean square wave heights, were substituted into the above equations, and the longshore transport rate calculated for each day over the three and a half month data period for those days in which the breaker angle was > 0°.

9.2.2 Results:

Results from both the deepwater S4 method (41 days) and beach observational data (108 days) is given in Appendix X. Summarised results are presented in Table 9.3. It must be stressed however that both sets of results are for only part of one year, and the calculated net littoral drift rates are therefore only for that period. Nevertheless they do provide some indication of the littoral drift rates for the Pukehina-Matata coast, although rates may vary slightly between sectors of the study area, if the effects of longshore sediment transfers, wave refraction, wave shoaling, and the differing orientations of the coastline were to be considered. Extrapolated annual net drift values indicate rates of sediment transport which are unlikely in comparison with other lines of evidence. For example, from the beach profile morphology and the envelope of change, a value of less than 30,000 m^3 per year moving through the littoral system is indicated.

Table 9.3 Calculated littoral drift rates for *a)(i)* deepwater S4 wave data (Eqn. 8.6) & *(ii)* deepwater S4 wave data using wave angle based on the swell wave component, and *b)* breaking wave observational data (Eqn. 8.9). Rates given are calculated for the time period of the data used, for the S4, 41 days and for the beach observations, 67 days *(dataset 1)*, 41 days *(dataset 2)*, and 108 days for the entire record (both datasets). Also given is the extrapolated net littoral drift on an annual basis from the time periods covered, assuming net drift to represent the annual rate, which due to seasonality of wind and waves is invalid.

Littoral Drift Rates	Total Gross Drift (m^3) *to South-east*	Total Gross Drift (m^3) *to North-west*	Net Drift for period (m^3); +ve= to SE, -ve= to NW	Annual Littoral Drift ($m^3.yr^{-1}$); +ve= to SE, -ve= to NW
S4 (i) (eqn. 9.4)	5,039	-699	**+ 4,340**	**+ 38,630**
S4 (ii) (eqn. 9.4)	39,842	-1,0821	**+ 29,020**	**+ 258,360**
Observations eqn. 9.5				
Data Set 1	51,565	-9,905	**+ 41,660**	**+ 140,790**
Data Set 2	5,766	-23,213	**- 17,440**	**- 58,960**
Entire Record	57,330	-33,120	**+ 24,210**	**+ 81,830**

From Table 9.3 there is some difference in the littoral drift rates depending on the data used. Using the S4 data a small net drift rate is obtained, since as shown in Chapter 7 the wave direction is given by the wave recorder as commonly offshore, particularly during the two 'storm' periods, when longshore sediment transport is at its greatest. Hence, the S4 wave swell direction was utilised for the same period, since 2 m breaking waves observed at the beach must be contributing to longshore sediment transport even if the S4 records these waves as in an offshore direction. The differences is suggested as due to the pronounced effect of offshore winds on the nearshore wave spectra. The variation in gross and net littoral drift rates over the data periods from which the calculations are based is shown in Figure 9.4. The effects of storms are pronounced, with order of magnitudes greater gross littoral drift rates during these periods, in comparison with fairer weather periods in which the calculated drift rates are small. The rates measured over the 41 day and 108 day periods are therefore suggested as probably larger than the annual littoral drift rate might be, as the extreme storm periods and seasonal effects of wave direction are averaged out.

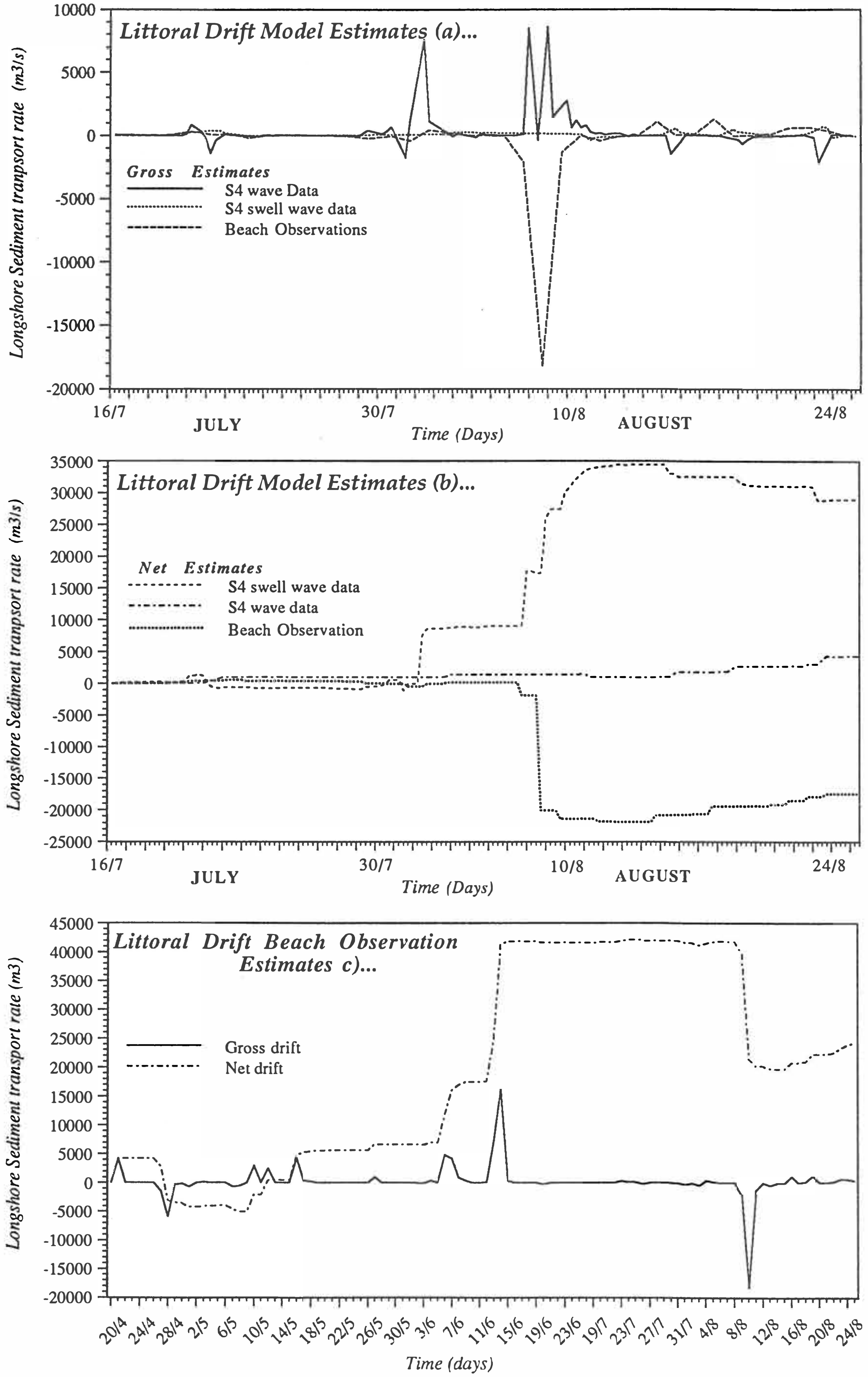


Figure 9.4 Calculated littoral drift estimates from S4 wave data and beach observations showing *a)* Gross littoral drift from 16/7 to 25/8 (41 days) for all methods, *b)* Net littoral drift from 16/7 to 25/8 (41 days) for all methods, and c) Gross and net drift rates from beach observational data between 20/4 to 23/6 and 16/7 to 25/8 (108 days).

The calculated drift rates also assume that all the volume of sand calculated is available to be transported, which may not be the case. In some sections of the coast, the presence of gravel layers which appear to armour the beach, swash, and surf zones during storm events may limit the amount of sand transported during these periods and thereby limit the overall net littoral drift.

9.3 Diabathic Sediment Transport

Onshore-offshore sediment movement, and transfers between the beach, nearshore, and inner-shelf zones is considered an important process of the Pukehina-Matata coastal sector (Chapter 8). However, with the nature of the beach sediments and catchment geology, it is expected that a lot of the pumiceous sediments will be removed offshore during storm periods, due to the ease with which this material can be entrained. Similarly material derived from the erosion of the offshore rock outcrops in the Pukehina-Otamarakau area would be brought onshore during fairweather periods.

During storm periods the beach erodes and during fairweather periods it accretes, thus the way in which the sediment budget operates during these two extremes varies (Figure 9.5).

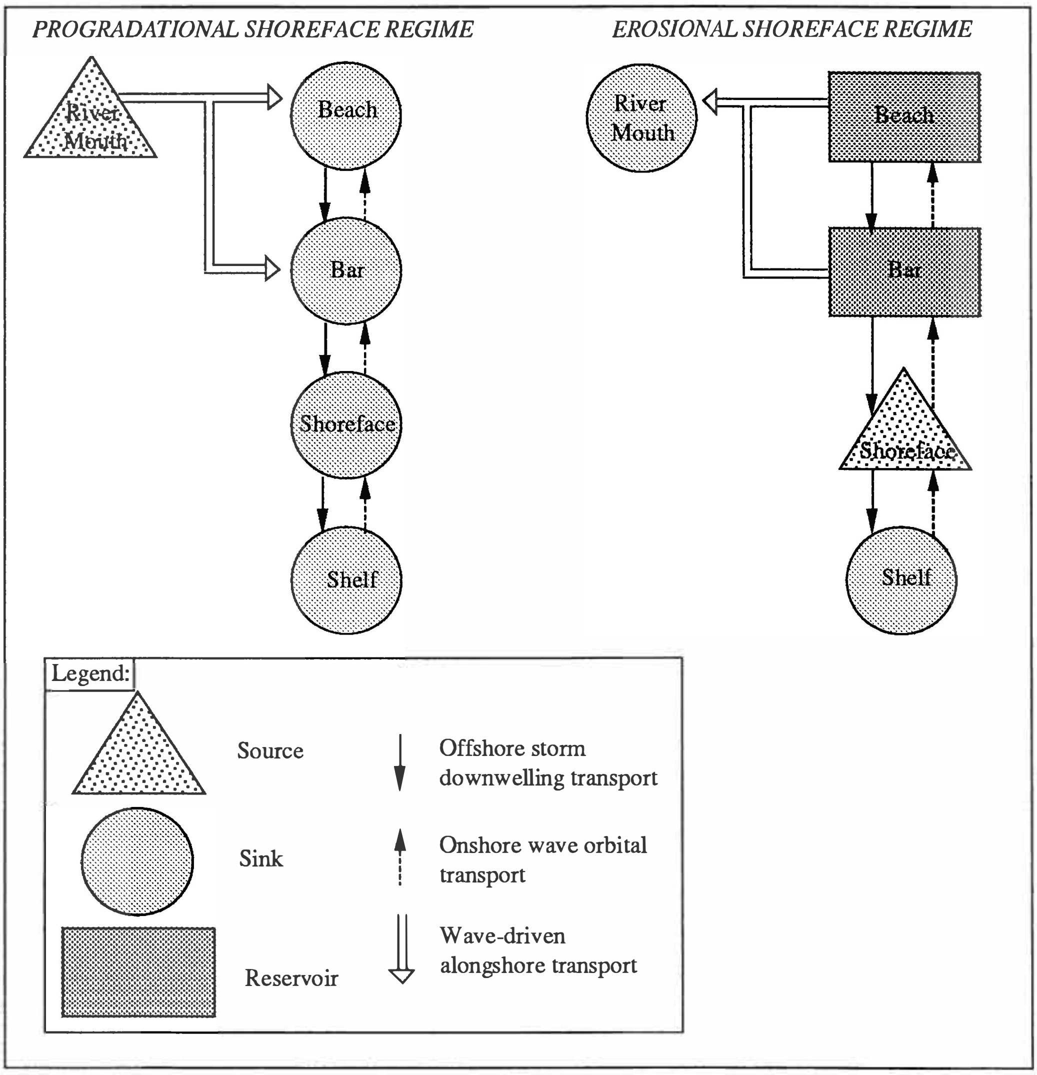


Figure 9.5 Schematic representation of general coastal sand budgets in prograding and eroding shoreface regimes. *(source: Niedoroda et al., 1984)*

Warren (1992) found that while bedload moves onshore under storm conditions, under fair-weather conditions it is likely that it simply oscillates with no net shoreward movement. Conversely suspended load is predominantly transported offshore except during times of strong offshore winds, accounting for the presence of pumice on Mount Maunganui and Papamoa beaches.

The net onshore-offshore suspended load sediment transport was estimated as 0.05 m^3/m in an offshore direction. Warren (1992) demonstrated that there is a gradual decrease in suspended load transport with increasing wave height, as opposed to an increase in bedload transport rate. With suspended sediment transport possibly ceasing at the peak of large storm events due to the formation of a planar bed (Warren, 1992).

Diabathic sediment transport for southern Pukehina Beach in the vicinity of the S4 site was calculated using the computer program *Mobile* (obtained from Dr. Willem de Lange, University of Waikato), which calculates the potential predicted bedload and suspended load transport (Heuristic suspended load model used). Wave conditions utilised were those recorded by the S4/10 which were capable of causing sediment motion (see for example Table 7.7 and Figure 7.23), using the site mean grain size of 0.68 mm (coarse sand) (Appendix X). Both the S4/1 and S4/10 currents were analysed to determine the current direction during the period of wave-induced sediment motion, either in an onshore (positive) direction or offshore (negative) direction.

The potential net onshore-offshore bedload sediment transport over the period of S4 deployment (41 days) was 2.30 m^3/m in an onshore direction. However since this is only the volume entrained by wave orbital motions, the actual amount moved either onshore or offshore depends on the bottom currents present. For the S4 site as shown in Chapter 7, the residual currents are only capable of transporting very fine and fine sands, which constitute about 1 % of the site sediments. Hence, the actual bedload directionally transported during the deployment period was 0.0253 m^3/m, of fine sand, moving in an onshore direction. The onshore movement of only fine sand from 16.1 m water depth further accounts for the general coarseness of the nearshore sediments beyond 12 m water depth, as there are insufficient bottom currents to transport the coarser sediments, unless distant storm wave conditions are generated. Under these conditions the coarser sediment may move onshore or offshore. Hence if only fine sands are capable of transport then based on the spatial distribution of the nearshore sediments, and assuming the bottom current recorded to represent both the annual and spatial currents then perhaps 30-40,000 m^3 of fine sand is transported from outside the diabathic limits of sediment exchange, within the 31 km Pukehina-Matata coastal sector.

9.4 The Sediment Budget

9.4 .1 Sand Extraction

The current sand mining at Otamarakau by J.W. Patterson and Sons is removing 15,000 m^3 annually from the dune-beachface region of the beach, although it is thought that this could be as high as

50,000 m^3 (Brett O'Shaunessy pers. comm.) which would have expected depletion effects on the beach sediment budget both at Otamarakau and areas downdrift. A recent coastal permit was granted by the Bay of Plenty Regional Council in May 1993 to allow the operator to increase the amount of sand removed at this site to 36,000 m^3 along a four kilometre stretch of beach from Otamarakau to Pikowai. The new mining strip is divided into four sections in which a maximum of 9,000 m^3 in each section can be removed annually (Figure 9.6). A general formula was proposed, in the conditions pertaining to the coastal permit, as to the volume of sand that is able to be extracted at any given time:

$$A - (62 + B + 15) = \text{balance of sand available to mine } (m^3/m) \qquad \text{...equation 9.8}$$

where: A = volume of sand present at the time of survey as calculated from survey measurements
62 = a constant, 100 yr return period storm erosion buffer zone along the toe of the foredune
B = beach variability factor (= std. dev. of the beach volume)
15 = constant, 5 yr erosion factor

From Table 9.2 and 9.3 above, the total annual sediment load for the Waitahanui stream is approximately 3,110 m^3. Given such a value, the sand extraction in the immediate vicinity of the stream mouth should have some measurable effect on the dune-beach-nearshore system. This may explain the decrease in beach volume at BOPCES site 24 (Otamarakau) and downdrift implications at Pikowai (BOPCES site 23) (Chapter 4), as sediment is removed from the beach-dune-nearshore system by natural processes to bring the littoral system back into equilibrium.

9.4.2 Budget of Littoral Sediments

The simplified littoral sediment budget is derived from examining the Pukehina-Matata coastal sector as a whole, as has been used in determining a sediment budget for Pakiri (O'Brien and Associates, 1992), in comparison with a more complex budget in which the study area is split into several budget compartments.

Komar (1976) states: "*For a given littoral compartment the total volume of sand added to the beach (credits) from the various sources can be balanced against the total losses (debits). If the losses are greater than the gains, then there will be a net deficit, which will be reflected as a decrease in the total volume of beach sediment: beach erosion will occur. Similarly, if the credits outweigh the debits, there will be beach deposition....*

....If there is beach erosion or deposition, it can generally be evaluated by comparing series of beach profiles. Therefore, the balance in the budget of littoral sediments is known beforehand."

Thus from Chapter 4, the overall balance for the 31 km Pukehina-Matata coastal sector from Newdicks Beach, Town Point to the Tarawera River mouth (thereby excluding the sediment accretion at BOPCES site 19) is +20,470 m^3 per year (i.e. 660 m^3/km) based on the net volume change above mean sea level (Moturiki R.L. 0.0) between 1978 and 1993, and including sand extraction volumes during this period.

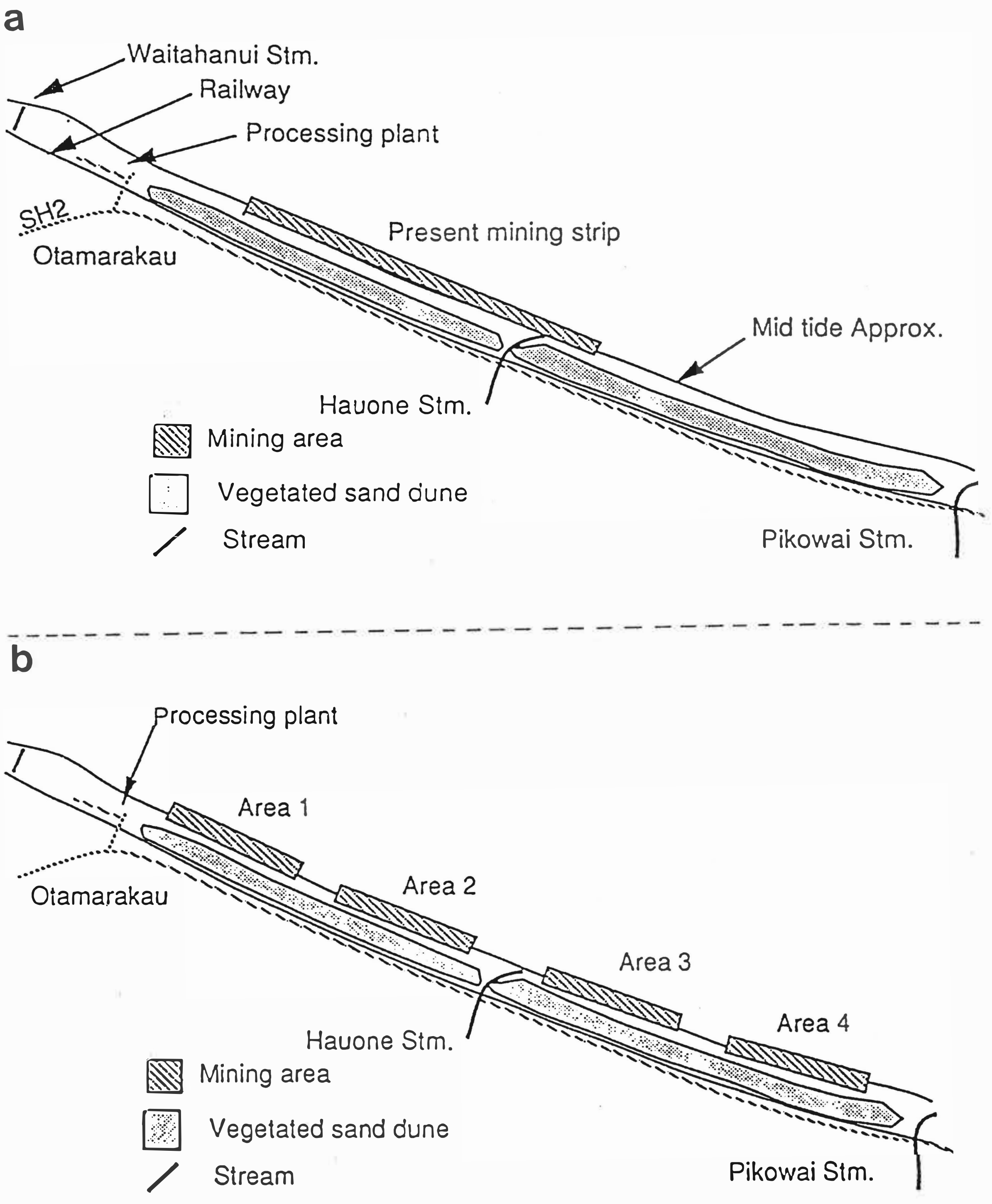


Figure 9.6 Schematic location map of the Otamarakau-Hauone-Pikowai mining strip, a*)* existing 2.4 km mining strip from Otamarakau to Hauone as at May 1993, and b) mining strip as proposed by Smith *et al.* (1992). *(source: Smith et al., 1992)*

Inputs to the Pukehina-Matata littoral zone are determined as follows:

- *Net Littoral Drift:* The amount of net drift into the system is estimated as less than 2,000 (± 2,000) m^3, since the directions of net drift for the study area, infer littoral drift out of the southern boundary. Net drift at Town Point is close to zero, due to the rocky nature of the coast preventing nearly all sediment supply from the north via the Bay of Plenty littoral conveyor system.

- *Fluvial Inputs:* From the calculations provided above the amount of sediment available to the beach-dune-nearshore system from the streams is approximately 6,000 ± 2,000 m^3 per year, depending on fluctuations in sediment yield during high-flow and contrasting low flow years. For the Tarawera river, based on a bedload figure of 48,880 m^3 per year (accounting for a loss of 50% of sediment load due to pumice abrasion and removal offshore), and net littoral drift to the south-east at this point, it is estimated that about 40 % of the sediment from this river would enter the southern budget boundary, equivalent to about 19,550 m^3.

- *Cliff Erosion:* Since the northern budget boundary lies outside most of the active cliff area of Town Point, cliff erosion in the weakly consolidated pumiceous materials is small. Based on a cliff retreat rate of 5.49 mm/yr calculated by Gordon (in prep., 1993) for Waitemata Group sediments within the Waitemata Harbour, which are similarly in structural lithology, and applied to the area of interactive cliff face then the input rate is about 30 m^3 per year. Some cliff input similarly occurs in the vicinity of the Pukehina Redoubt, although the length of interactive cliff is small, with an estimated input rate of 5 m^3 per year from this source.

- *Biogenic Inputs:* Addition to the system from biogenic input is small and is based on Hilton (1990) and O'Brien and Associates (1992) for the Pakiri coast. Hilton (1990) calculated for the Pakiri coast that the annual production of carbonate shell is 530 tonnes, equating to about 460 m^3 (O'Brien and Associates, 1992). For the Pukehina to Otamarakau area the carbonate contents in the beach and nearshore sediments is comparable to Pakiri (Hilton, 1990), with an estimate of 299 m^3 for this area. For the Otamarakau-Matata region the carbonate contents are approximately one third of those for Pukehina and hence the estimated biogenic input from this sector is 145 m^3 per year.

- *Net Onshore Transport:* The amount of net onshore transport from beyond the limit of significant diabathic sediment transport is unknown.

Sediment losses from the system have been estimated as follows:

- *Net Littoral Drift:* Net drift out of the system is estimated as approximately 15,000 (± 10,000) m^3 per year, confined to movement out of the southern boundary. This figure is consistent with Healy (1983) of 25,000 m^3, allowing for the bi-directional littoral drift system within the study area, which thereby limits the net drift to the south-east.

- *Estuary Infilling:* Both the Waihi estuary and Tarawera river mouth act as sediment traps intercepting alongshore sediment transport, which is added to by the effects of storms washing sediment into the estuary system. From analysis of the areal change in the estuary between 1943 and 1981 (Chapter 4) and assuming a sedimentation depth of 0.5 metres in these areas then the approximate amount of estuarine infilling is estimated as 1,420 (± 1,000) m^3 for the Waihi estuary. The amount of sediment which is trapped by the estuary inlet is unknown but is estimated to be small, possibly 2,000 (± 2,000) m^3 per year. For the Tarawera river estuary infilling and sediment trapping is estimated at 2,000 (± 2,000) m^3 per year (low value due to the large freshwater input which flushes most of the sediment out of the estuary system, relying mainly on the ebb-tidal delta system to trap littoral drift movements).

- *Aeolian Sediment Loss:* The loss by wind processes is unknown but is estimated as a small component of the littoral sediment budget since vegetation is present on most of the foredunes, acting to trap wind-blown sands during periods of onshore winds. However an estimate of less than 2,000 (±1,000) m^3 is provided for here.

- *Offshore losses* out of the seaward budget boundary. This is mainly due to sediment abrasion of pumice sediments into fine sands and silts which are easily removed offshore by downwelling currents generated by storm wave action, and periods of strong onshore winds.

- *Sand Mining:* Losses due to sand extraction activities are based on the annual licensed rate of sand removal of 15,000 m^3 per year. This has since been permitted to increase to 36,000 m^3 per year (BOPRC, 1992), however the beach profile period for sediment balance is only until May 1993, corresponding to the effects of the first level of sand extraction.

The existing simplified sediment budget is therefore given as:

Inputs - Outputs ± Onshore/Offshore sediment supply or loss = Net erosion/accretion rate

Inputs:

2,000 + 6,000 + 444 + 35 + 19,550 = 28,029 m^3

Outputs:

15,000 + 15,000 + 4,000 + 2,000 = 36,000 m^3

28,029 - 36,000 ± onshore/offshore = 20,470 m^3

Hence, in order to balance the above budget approximately 27,400 m^3 of annual onshore sediment transport must occur. This onshore supply may come from erosion of the nearshore reefs and submarine rock outcrops and abrasion of pumiceous gravels in the nearshore zone (Town Point-Otamarakau region), particularly from beyond the 11-13 m depth contour where the surficial sediments are commonly coarse sands and gravelly sands. Finer sands are capable of onshore transport under fairweather conditions, and coarser sands may be transported from the lower nearshore and inner shelf during extreme storms. The estimated rate of onshore sediment transport required to balance the simplified budget given is small in comparison with Mangawhai-Pakiri which has an estimated onshore rate of 160,000 to 235,000 m^3 per year (O'Brien and Associates, 1992; Tonkin and Taylor, 1992), and has a similar morphodynamic setting to the Pukehina-Matata coast. The differences may be attributed to two factors. Firstly, sand mining at Pakiri is far greater than at Otamarakau, and secondly, due to the pumiceous nature of much of the beach, nearshore and stream sediments a great deal more material will be lost to the offshore region, so that while the gross onshore transport may be higher than the figure given, the net onshore rate is comparatively small. Some onshore sediment additions may also come from possible BOP littoral drift intrusion into the Pukehina Redoubt-Otamarakau sector.

This budget may be expanded based on the morphological differences in sectors of the Pukehina-Matata coastal sector identified in earlier chapters, in which the net longer-term rates of erosion and accretion vary in response to the differing sediment inputs and outputs within each sector or budget compartment, illustrated in Figure 9.7.

An alternative littoral sediment budget estimate can be determined using figures from Smith and Ovenden (1992) who give estimates of 22,000 m^3 for the net littoral drift and 5,000 for the annual fluvial sediment inputs. Sand extraction of 36,000 m^3 between Otamarakau and Pikowai, would therefore result in a sediment deficit of 9,000 m^3 annually over this area, which would therefore have to come from the sand supply of the nearshore zone, commonly resulting in depletion of the offshore bar and beach, as has been found at other sites in the Bay of Plenty, such as Papamoa and Matata where the natural outputs resulting from sand extraction are imbalance with the inputs (Healy *et al.*, 1977; Healy, 1978c; Smith, 1990a). This would neglect biogenic inputs which are not applicable since they are not required in commercial sand supplies, and presumably are sorted out at the mining operations site. Moreover the carbonate levels in the beach and nearshore sediments are low and have been shown above to contribute little to the sediment budget (~40 m^3). Similarly there is no sediment input from cliffs in the Otamarakau-Pikowai area. A deficit of 9,000 m^3 would therefore have to be met from net onshore transport in order to balance inputs and outputs, equating to 2.25 m^3/m of beach over the 4 km mining section, assuming even removal of sand by Patterson and Sons Ltd. over this area as proposed in BOPRC (1993). This amount would therefore seem small, but it is suggested that the amount of sand available to the system from offshore and nearshore sources is in itself small, and that over a period of some years there will probably be increased erosion of the beach in the mining section and reduction of the offshore bar, which will not immediately become evident. Also it has been demonstrated that the Pukehina-Matata coastal sector of the Bay of Plenty is in a quasi-dynamic equilibrium, which infers that the natural sediment inputs and outputs are in balance with each other so that erosion and accretion trends are only short-term or seasonal effects. There is evidence that at Otamarakau and downdrift at Pikowai (Chapter 4; BOPRC, 1993) the beach sediment volumes are decreasing relative to the rest of the coastal sector, which may be due to the continued removal of unknown quantities of sand by Patterson and Sons Ltd., who are licensed to annually extract 36,000 m^3, up from 15,000 m^3 prior to 1993. Also if the net littoral drift through the Otamarakau-Pikowai sector is reduced or cut-off to downdrift areas, beach and nearshore erosion will be enhanced as the beach-dune-nearshore system readjusts to a new equilibrium.

9.5 Summary

The sediment inputs and outputs for the Pukehina-Matata beach-dune-nearshore system were estimated and presented in this chapter utilising previously determined sediment transfers within the system. The balance of sediments should be equivalent to the net beach volume change calculated in Chapter 4.

- Sediment loads for the streams and rivers that discharge into the Pukehina-Matata coastal sector were determined from two methods. The first utilises the known sediment load from the Tarawera River catchment to then calculate the loads of the smaller streams and rivers, based on a sediment discharge volume of 33.8 m^3/km. Estimated sediment volumes into the Waihi estuary are therefore 6, 140 m^3 per annum, with approximately 5,040 m^3 /yr entering the dune-beach-nearshore system between Otamarakau and Matata.

The second method calculates sediment loads from the sediment discharge rating curve for the Tarawera River, estimated to discharge 48,880 m^3 of sediment which remains in the littoral system. Sediment loads from this method are comparable to the first and existing estimates, with 3,380 m^3/yr of material entering the Waihi estuary, and 3,330 m^3/yr entering the Otamarakau to Matata sector of coast. Due to the high amounts of pumice within many of the streams, the volumes calculated for both methods reflect the relative abundances of pumice within the streams and beach system. This therefore assumes loss of pumiceous sediments to the offshore regions, out of the sediment budget boundaries.

- Littoral drift rates were calculated for Pukehina Beach for the period of S4 deployment (41 days) and from beach observational data (108 days). Both data sets showed an overall south-westerly net littoral drift. For the S4 data two methods were used, producing net drift of 4,300 m^3 and 29,000 m^3 in 41 days. The net drift for the period of beach observational data was 24, 200 m^3 in 108 days. Gross littoral drift volumes are shown to be small for most of the time, except during stormy periods when rates are orders of magnitude higher. Hence, extrapolation of the above rates to an annual rate is inaccurate, as seasonal and directional storm effects have a marked influence on the net littoral drift rate.

- From several lines of evidence the annual net littoral drift for the Pukehina-Matata coastal sector at Matata is estimated as about 15,000 m^3 moving in a south-easterly direction. However due to the difficulty in accurately quantifying the drift volume, this may be as much as 25,000 m^3 or as little as 5,000 m^3.

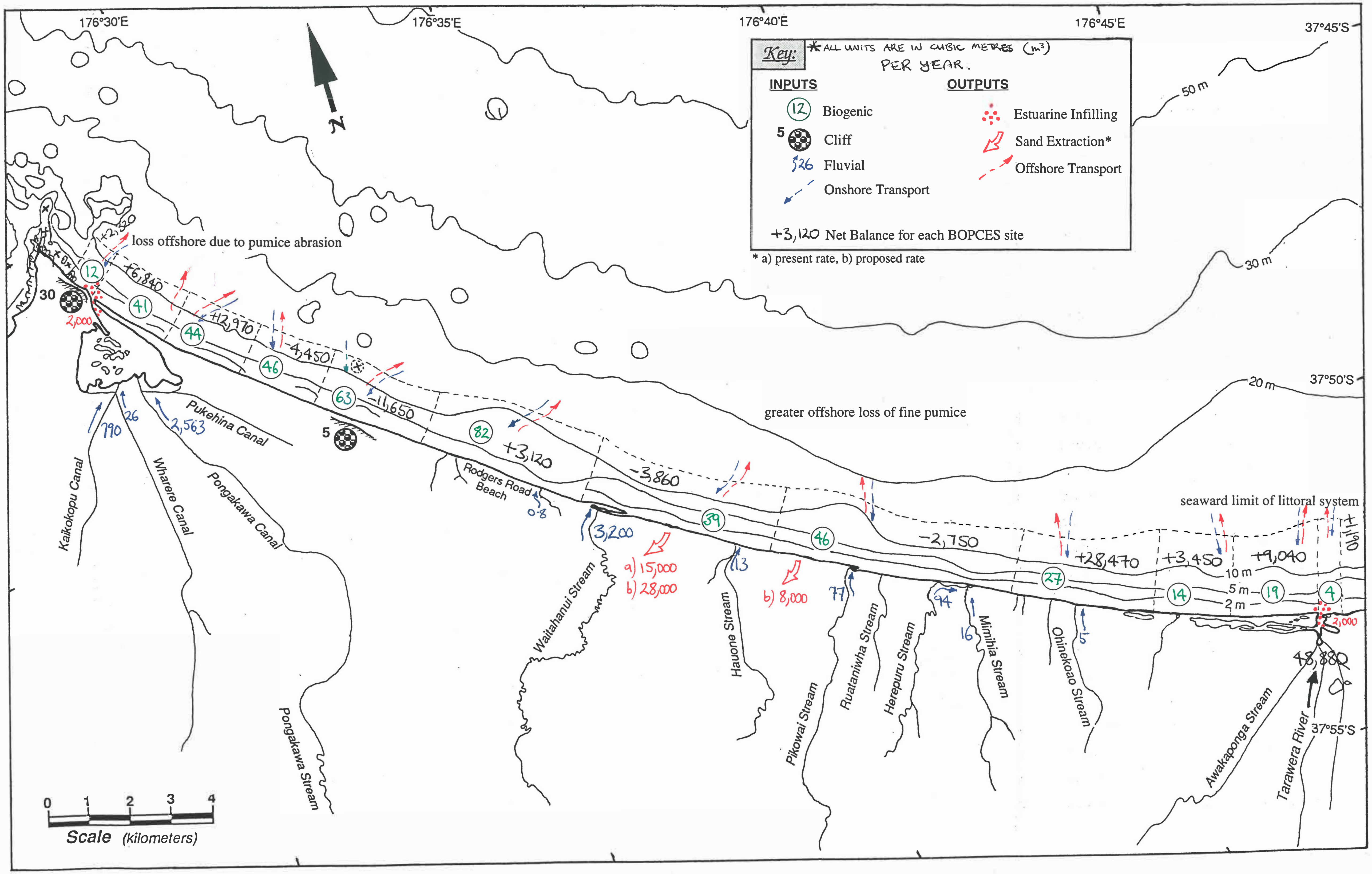


Figure 9.7 Littoral sediment budget for the Pukehina-Matata coastal sector. Beach volumes are from Chapter 4, for the net change between February 1978 and April 1993, and are suggested to represent the net balance between inputs and outputs.

- Diabathic sediment transport in 16.1 m water depth offshore from Pukehina Beach was calculated as 2.30 m^3/m for the 41 days period of S4 deployment. However this rate requires a bottom current to actually move the sediments, which are sufficient to only entrain very fine and fine sands. These sediments are scarce at the S4 site and hence the actual amount of sediment moved was estimated as 0.025 m^3/m in an onshore direction. Extrapolation of this result for the Pukehina-Matata coastal sector gives a possible amount of 30-40,000 of m^3 of material transported onshore from outside the limits of diabathic sediment exchange.

- The littoral sediment budget presented shows that in order to balance the inputs and outputs within the system, approximately 27, 400 m^3 of annual onshore sediment transport must occur.

Due to the effects of sand extraction, the sediment budget between Otamarakau and Pikowai is in deficit, and hence the longer-term erosion of the beach-dune-nearshore system, shown to be occurring in Chapter 4, is likely to continue as sources of sediment are sought within the system to restore the natural equilibrium.

CHAPTER TEN:

Summary and Conclusions

CHAPTER TEN
SUMMARY AND CONCLUSIONS

10.1 Introduction

Owing to the lack of information regarding the Pukehina-Matata coastal sector, a research study was undertaken to further the understanding of the beach-dune-nearshore system in this section of the Bay of Plenty coastline, particularly in regard to the Resource Management Act (1991), and current sand extraction activities at Otamarakau.

The stated aims of this study were to:

(i) Investigate the origin of the beach sediments and their mineralogy, in particular the terrigenous fraction of greywacke.

(ii) Investigate the beach morpho-sedimentary units, in terms of texture and morphology, to determine possible sediment transport pathways, and areas of long-term change in the Pukehina-Matata coastal sector.

(iii) Assess the nature of the nearshore zone sedimentary-morphodynamic pattern, to provide information on sediment sinks and sources particularly in comparison to the beach, as well as general background data.

(iv) Produce information on the nearshore oceanography and currents using S4 current meters to monitor the interaction of the beach and nearshore in terms of sediment transport.

(v) From available survey data, including beach profile records, and calculations of source and sink volumes, attempt to refine a sediment budget for the Pukehina-Matata coastal sector.

10.2 Summary of the Major Findings

10.2.1 Beach sediments

Light minerals were found to constitute between 92.1 to 98.5 % of the beach sediments, heavy minerals 0.2 to 5.6 %, with the remainder due to biogenic production of carbonate material. The mineralogy reflects the high input of quartzo-felspathic sediments from the Okataina volcanic centre.

The heavy mineral trends suggest that the streams in the Otamarakau-Matata sector provide much of the sediment to this area of the beach, however along Pukehina Spit and in the vicinity of the Pukehina Redoubt the mineralogy of the streams implies additional sediment sources are present adding material to the beach system. The suggested source is nearshore reefs which are geologically similar to the coastal hinterland.

Within the beach sediments the overall trend observed in the heavy minerals is for an increasing abundance from the Waihi estuary towards Otamarakau, culminating in a peak at Hauone. Towards Matata abundances decrease with small peaks where streams add new sediment.

While some of the alongshore mineral trends support a bi-directional sediment transport system, varying sediment source volumes, and stream-beach-nearshore interaction complicates this. The suggested low rates of littoral drift along the Pukehina-Matata coastal sector, may indicate mineralogical trends which are in part at least due to diabathic sediment transfers and storm wave versus fairweather effects on the littoral sediments.

The stream and river sediments are predominantly coarser and more poorly sorted than those found at the beach, with variable interaction with the beach and nearshore sediments. The source of beach sands is at least partially derived from erosion of local catchment material, which may be supplemented by littoral drift, erosion of submarine rock outcrops in the Town Point-Otamarakau region, and possible onshore reworking of pre-Holocene sediments.

Although there are greywacke gravels present within the beach system the mineralogy of the beach, nearshore and stream sediments is consistent with their derivation from Okataina Volcanic Centre eruptives which constitute the majority of the Pukehina-Matata hinterland. The greywacke pebbles while numerous on the beach are not an active source of sediment *input* to the littoral system and contribute little to the sand fraction in terms of abrasion. No greywacke unique minerals were found that could not also have been derived from acid volcanics.

10.2.2 Beach Morpho-sedimentary Units

The Pukehina-Matata coastal sector is at best a stable coastline with localised small amounts of long-term accretion. However, historically there has been a tendency for the some coastal erosion of between 0-0.2 m per year. Imposed on these longer-term trends it was found that shorter-term erosion-accretion cycles occur, with prominent seasonal cut and fill cycles.

While the beach system has accreted in the vicinity of the many beach impounded streams within the Otamarakau-Matata region, the foredune is eroded to either side due to stream migration along the beach, which is associated with littoral sediment transport. The overall south-easterly migration tendency of the Waitahanui, Pikowai, Hauone, and Herepuru/Mimihia streams suggests a south-easterly littoral drift.

Beach sediment volumes at surveyed BOPCES sites, indicate that the beach buffer zones can cope with most single storm events without significant erosion of the dune sand reservoir, but that a series of closely-spaced events, between which the beach does not have time to recover and accrete, may cause significant beach and dune erosion.

The beach sediments along Newdicks Beach and Pukehina Spit to the Pukehina Redoubt are medium to fine grained under accretionary conditions, with a statistically significant change in texture to medium and coarse sands under erosive conditions.

From the alongshore transport models the following conclusions can be made:
(i) The Sunamura & Horikawa (1972) model infers bi-directional alongshore transport to the north-west and south-east from a centre-point near Otamarakau. The north-west directed littoral drift along Pukehina Spit is suggested as in part due to the lee effect created by the Town Point promontory, combined with wave refraction, reducing the influence of north and north-easterly generated waves, thereby causing a more complex current pattern than that which occurs further down the coast between Otamarakau and Matata.

(ii) The McLaren (1981) model found that there was a trend for sediment transport to the south-east from Otamarakau to Matata, and to the north-west to Pukehina, although this depends slightly on the beach and wave conditions. Inferred source sectors of the study area are north-west of Rodgers Road to the Pukehina Redoubt, Otamarakau, Kohioawa Beach, and southern Pukehina Spit (basal end). Conversely inferred sectors of the beach which may act as sediment sinks are northern (distal end) and central Pukehina Spit, Newdicks Beach, and Matata.

(iii) The Waihi model, suggested sediment transport pathways inconsistent with other lines of evidence.

Net littoral drift is determined as bi-directional, from an origin near Otamarakau, where net drift is oscillatory. Pukehina Spit has a north-westerly directed littoral drift, however the quantities involved are small. Between Otamarakau and Matata net drift is to the south-east, within a system which has increasingly more sediment added to it from initiation near Otamarakau. This includes sediment additions from the numerous small streams and rivers in this sector. At the northern and southern boundaries of the study area some counter-drift may occur. At Pukehina some sediment is transported from the Waihi estuary to northern Pukehina beach, which acts to nourish the distal end of the spit and Newdicks Beach to the north-west. South-east of Matata sediment is similarly transported from the Tarawera River in a north-easterly direction along Awaateatua Beach.

10.2.3 Nearshore Sedimentary-morphodynamic Pattern

Carbonate percentages in the beach surficial sediments indicate two distinct areas of marine species diversity, linked to differences in sediment texture and substrate, and possibly wave energy. Between Newdicks Beach and Rodgers Road the carbonate content is between 3-5 %, with a decrease to 1-2 % from Otamarakau to the Tarawera River mouth. In the nearshore zone a similar pattern is apparent, with higher amounts of carbonate in the shell and lithic hash containing sediments offshore from Pukehina to Otamarakau. The highest carbonate contents are associated with the presence of rocky substrates in this area identified from side-scan sonar.

SCUBA diving observations at Matata, Otamarakau, Pukehina Redoubt, and Pukehina Beach, show that for the nearshore from 7 to 15 m water depth bedforms are wave generated, and that the bedforms characteristics are dependant to a large extent on their sediment textures.

The nearshore sediments in the region show an overall offshore fining trend, with sediments becoming more poorly sorted and more coarsely skewed in an offshore direction. Imposed on this general pattern is a distinctive area of coarser sediment in 12-20 m water depth from Town Point to Otamarakau, with localised areas of slightly coarser sediment, offshore from the Tarawera River, and small pockets of coarser (Pikowai) or finer (Pukehina) surficial sediments. Cross-shore variations can be partly correlated to changes in profile morphology, associated with submarine rock outcrops in the nearshore zone which are possibly remnants of the Late Pleistocene wave cut terraces formed prior to the last sea-level rise of 6,000 yrs B.P.

The nearshore and inner-shelf zones from Town Point to Otamarakau are dominated by numerous reefs, submarine rock outcrops, and associated boulder and gravel areas. The expanse of these materials between the basal end of Pukehina Spit and Otamarakau corresponds with the area of shell and lithic hash containing sediments in the nearshore zone at depths > 11-13 m.

Within the Pukehina Spit, Redoubt, and Rodgers Road areas, bathymetric profiles in conjunction with the morphological associations of coarse megarippled and fine featureless areas, indicates north-westerly directed sediment transport. Topographic asymmetry occurs in this direction, caused by sediment piling-up on the up-current side, and corresponding erosion on the down-current side. However this is complicated by wave refraction and localised current scouring.

Within the Otamarakau-Matata nearshore section, there is no bedrock or associated gravel and boulder patches, suggesting greater sediment additions to this area, from either onshore transport of sands and/or stream sediment discharges, particularly from the Waitahanui, Pikowai, and Herepuru streams.

Offshore from Kohioawa Beach to the Tarawera River the nearshore zone consists of rapid, alternating CMR and finer, featureless bands, developing a 'sand wave type pattern'. This pattern is suggested to be associated with faulting of the Whakatane Graben and Taupo Volcanic Zone.

Bedform measurements from side-scan sonographs show that the megaripple bedforms are approximately shore-parallel and primarily due to wave action, although wave focussing may be an important mechanism. In areas where bedrock is present (Town Point, basal end of Pukehina Spit to Rodgers Road) downwelling currents may cause intense scouring of bottom sediments where current flows are restricted and intensified, forming bands and patches of coarse grained megaripples, found to be indicative of erosion.

Beach-dune-nearshore interaction for the Pukehina-Matata coastal sector was found to be dominantly the result of diabathic processes, with parabathic processes, including littoral drift, having more longer-term influence on the morphology and sediments of the littoral system. The limit of significant onshore-offshore sediment transport is about 12 m, based on Hallermeier limits, nearshore morphologic changes, and sediment textural separations. The limit of parabathic transport was found to be less than 6 m.

10.2.4 Nearshore Oceanography:

During a six week period (16/7/93-26/8/93) the mean wave conditions recorded at southern Pukehina Beach were H_s= 0.64 m, T_s= 6.36 m, with an averaged wave approach direction of 192°. Maximum conditions were H_s= 2.79 m and T_p= 11.13 s. Two small duration storm events (30/7-2/8 and 6/8-10/8) were recorded.

Wave refraction has some significant impact on the beach-dune-nearshore system particularly along Pukehina Spit and Matata. Wave approach directions from the north-east at Matata may be effected by wave refraction processes from Rurima rocks and Whale Island, lessening the effects of north-westerly littoral drift, causing an alongshore variation in breaking wave heights and hence greater or lesser alongshore sediment transport.

Daily beach observational data at Pukehina Beach over a three and a half month period from 20-April to 23-June 1993 and 15-July to 25-August 1993, gave an average breaking wave height of 0.58 m and period of 9.26 s. Winds were predominantly westerly (21 %), with the greatest wind speeds estimated for winds from the north-west, north, and north-east.

Bottom currents in the Pukehina-Matata nearshore and inner shelf were found to be due primarily to wind-driven currents, with rip currents and coastal currents having some possible effect at shallower (littoral zone to middle shoreface) and deeper (lower inner shelf to middle shelf) depths respectively. Analysis of the nearshore seabed bottom currents offshore from Pukehina Beach, showed that the average current speed during S4 deployment was 12.95 cm/s directed overall at 192° in a southerly direction. Current speeds attained a maximum bottom current of 25.4 cm/s (8/8/93), with a brief bottom return flow developed to the north-west, however this was of a minimal duration due to the short wave periods having a lessened effect on the bottom currents than for longer period waves of similar wave height (2.4 m).

10.2.5 Sediment Budget

The net change in sediment volume for the entire beach system within the Pukehina-Matata coastal sector between 1989 and 1993, produced a calculated deficit of sediment within the beach system of 90,570 m^3. In comparison a longer-term change between 1978 and 1993, showed a sediment surplus of 218, 560 m^3. Inclusion of the volumes of sediment removed by sand extraction at Otamarakau showed overall accretion during this period of 329,500 m^3. Over the Pukehina-Matata coastal sector these volume changes are reasonably small and their variability reflects both the dynamic nature, and the delicate state of equilibrium, of the beach-dune-nearshore system.

Estimated sediment volumes into the Waihi estuary are 3,380-6,140 m^3 per annum, with approximately 3,330-5,040 m^3 /yr entering the dune-beach-nearshore system between Otamarakau and Matata. These volumes allow for sediment loss to the offshore from abrasion of the high pumice content sediments.

Calculation of diabathic sediment transport at Pukehina Beach showed that 0.025 m^3/m of fine sand is transported in an onshore direction from 16.1 m water depth under average wave and current conditions. This transport of only the fine and very fine sands may explain the coarse nature of the nearshore zone between Pukehina and Otamarakau beyond 12-13 m water depth.. Extrapolation of this result for the Pukehina-Matata coastal sector gives a possible amount of 30-40,000 of m^3 of material transported onshore from outside the limits of diabathic sediment exchange.

Annual net littoral drift for the Pukehina-Matata coastal sector at Matata is estimated as about 15,000 m^3 moving in a south-easterly direction. Calculated littoral drift rates for Pukehina Beach showed an overall south-westerly net littoral drift. Net drift from S4 data was estimated as 4,300 m^3 and 29,000 m^3 in a 41 day period, and from beach observational data as 24, 200 m^3 in a 108 day period. Gross littoral drift volumes within the Pukehina Spit littoral zone are shown to be small for most of the time, however during stormy periods rates are orders of magnitude higher.

The derived littoral sediment budget shows that in order to balance the inputs and outputs within the system, approximately 27, 400 m^3 of annual onshore sediment transport must occur.

10.3 Investigations in Relation to Sand Extraction

The beach-dune-nearshore system at Otamarakau is in a delicate state of quasi-equilibrium, with continual natural net transfers of small sediment volumes within both the beach-dune-nearshore system and between the various sections of the Pukehina-Matata coastal sector. Under these conditions removal of any sediment will alter the balance of the system. The recently approved increased sand extraction rate of 36,000 m^3 per year (BOPRC, 1993), may over a period of years cause long term erosion problems not only at Otamarakau and within the mining strip but also at downdrift locations such as Pikowai and Kohioawa Beach.

In the short-term sand extraction will probably have little noticeable effect on the beach-dune-nearshore system of the area, other than the current aesthetic one, provided the guidelines set down in the coastal permit regarding sand extraction are adhered to (BOPRC, 1993), particularly concerning sand removal over the entire 4 kilometre mining strip and not just near the operations plant at Otamarakau. Also of vital importance is stringent monitoring of the actual volumes of sand removed is required, to better assess the extent of likely impacts.

However, the assertion that the beach between Otamarakau and Pikowai can sustain removal of 36,000 m^3 per year, is at best sceptical. Results from this study show that since 1988 the available beach sediment volume has decreased in comparison with neighbouring areas, and that some downdrift depletion of the beach sand reservoir may have occurred. This depletion is notably prevalent after the current operators started mining at this site. Therefore the longer-term erosion trend in this area is likely to continue, with the increased extraction rates placing the system into further deficit as sources of sediment are sought within the system to restore the natural equilibrium. Despite this the dynamic nature of the littoral system will probably insure that publically observable impacts are likely to remain masked by natural processes, such as storm cut & fill.

10.4 Future Research

Although this study seeks to provide background information on the coastal environment of the Pukehina-Matata coastal sector, and address some of the concerns within it, further research is suggested, particularly:

- investigation of the sedimentation history and geomorphological development of the Waihi estuary and environs;
- detailed geological information of the coastal cliffs, petrology, and the geological inter-relationships of the area from Town Point to the Rangitaiki Plains, including the devlopment of the Pukehina-Matata coastline;
- more frequent profile surveys of the nearshore zone at selected sites, coupled with beach profiling to determine volumetric changes, in terms of holistic beach-nearshore interaction. This would also provide a far greater indication of sediment losses or gains within the beach-dune-nearshore system, and provide better information to assess any impacts from sand extraction at Otamarakau.

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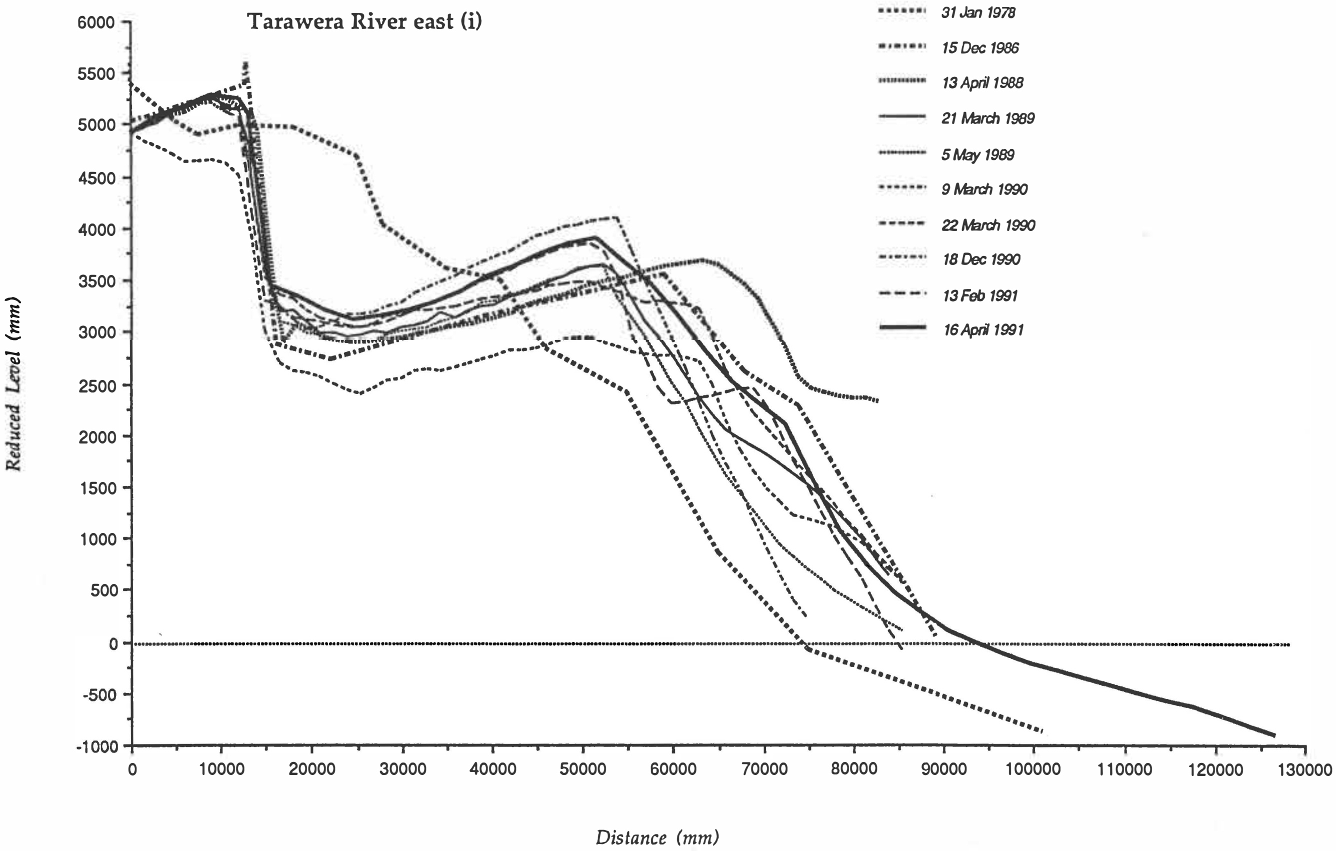
Appendices

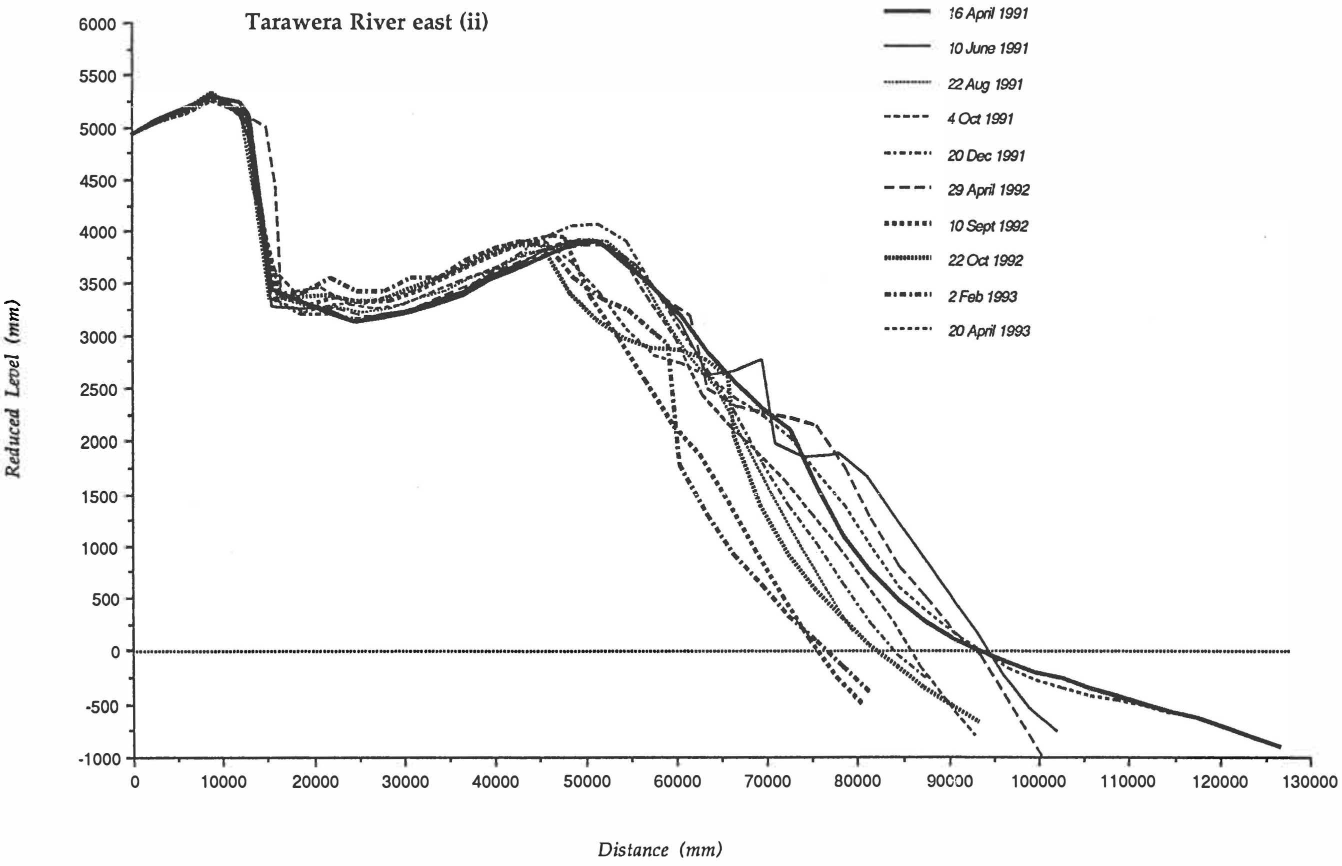
Appendix I: Beach and Nearshore Profiles

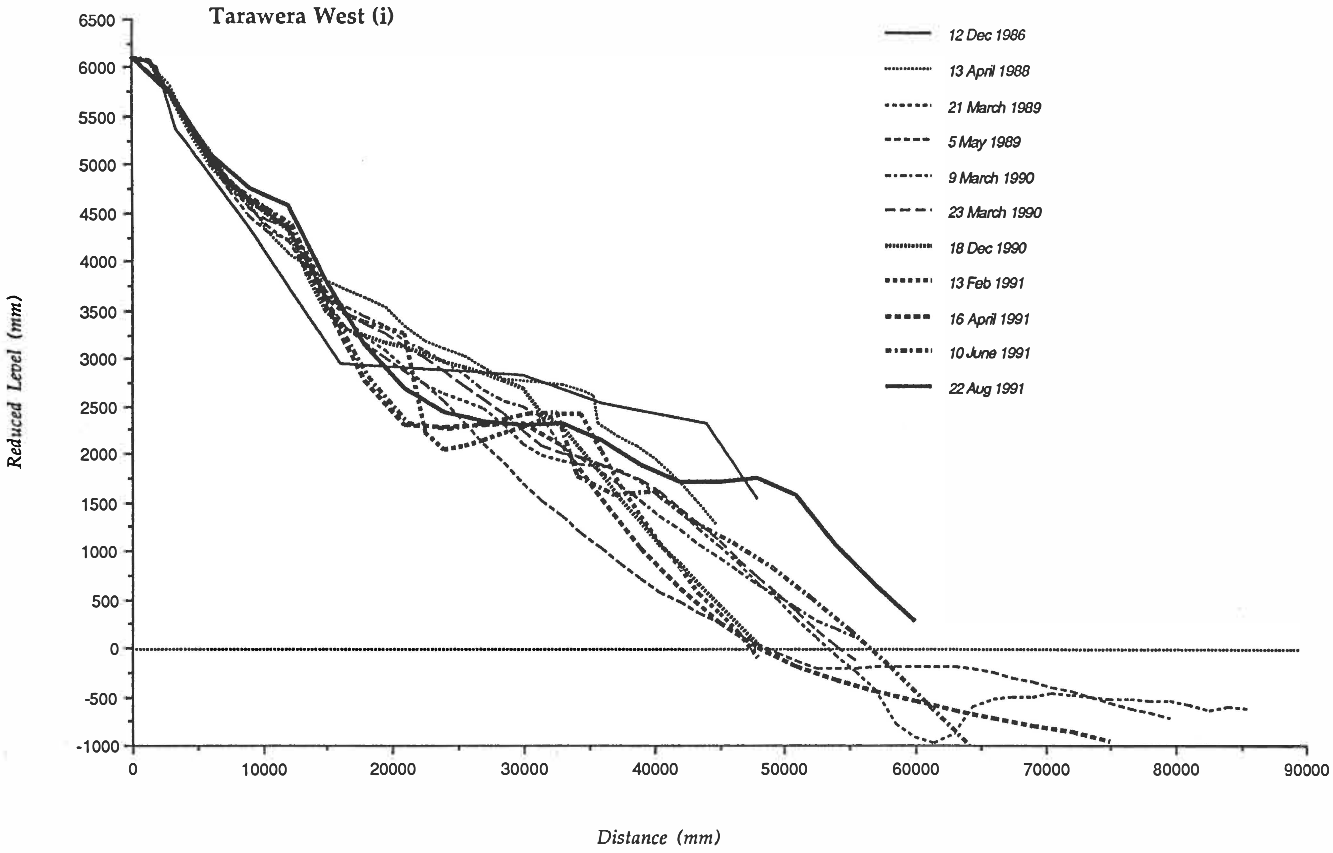
This appendix contains all beach profiles undertaken by the Bay of Plenty Regional Council for survey sites within the Pukehina-Matata study area, as well as the initial survey site profiles carried out by Healy *et al.* (1977).

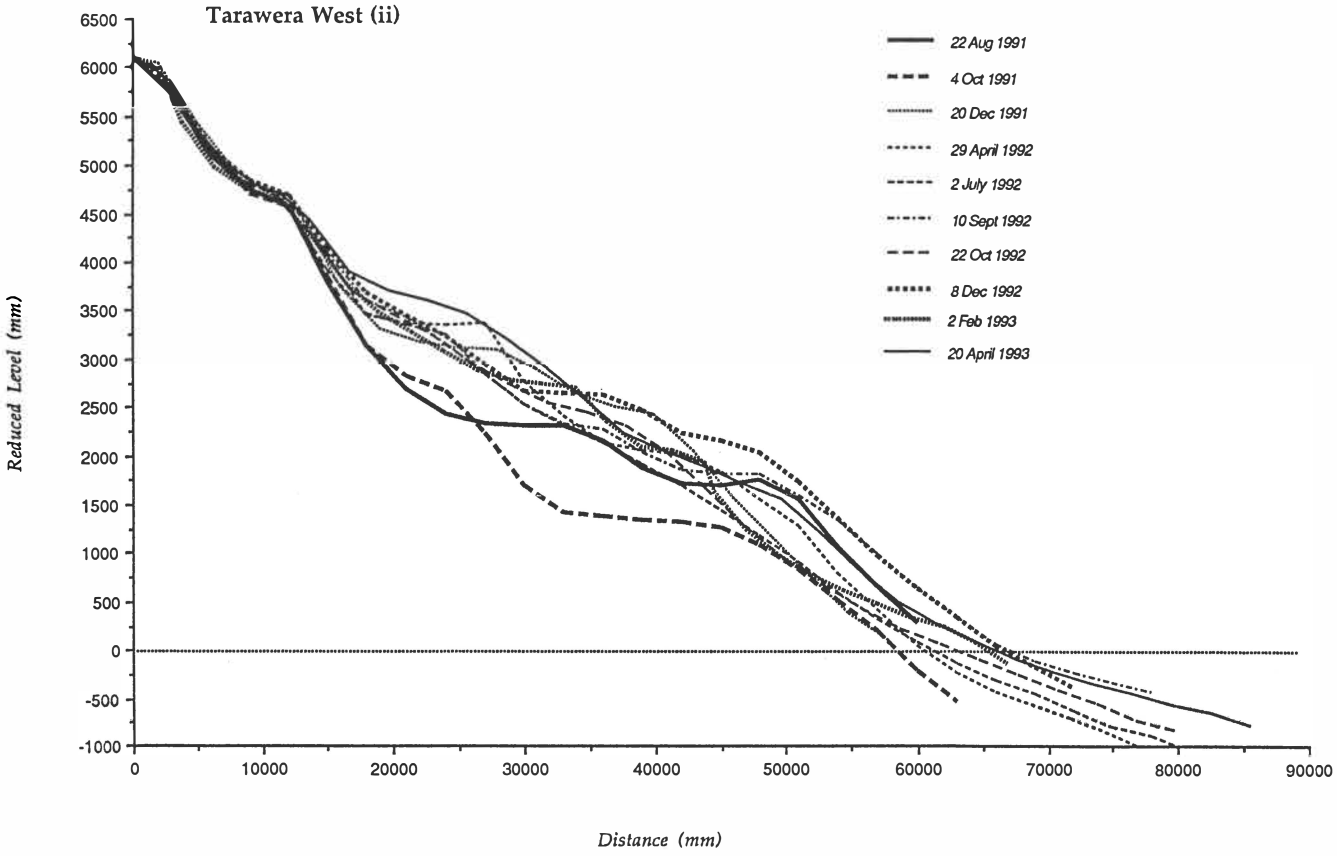
Survey Sites:

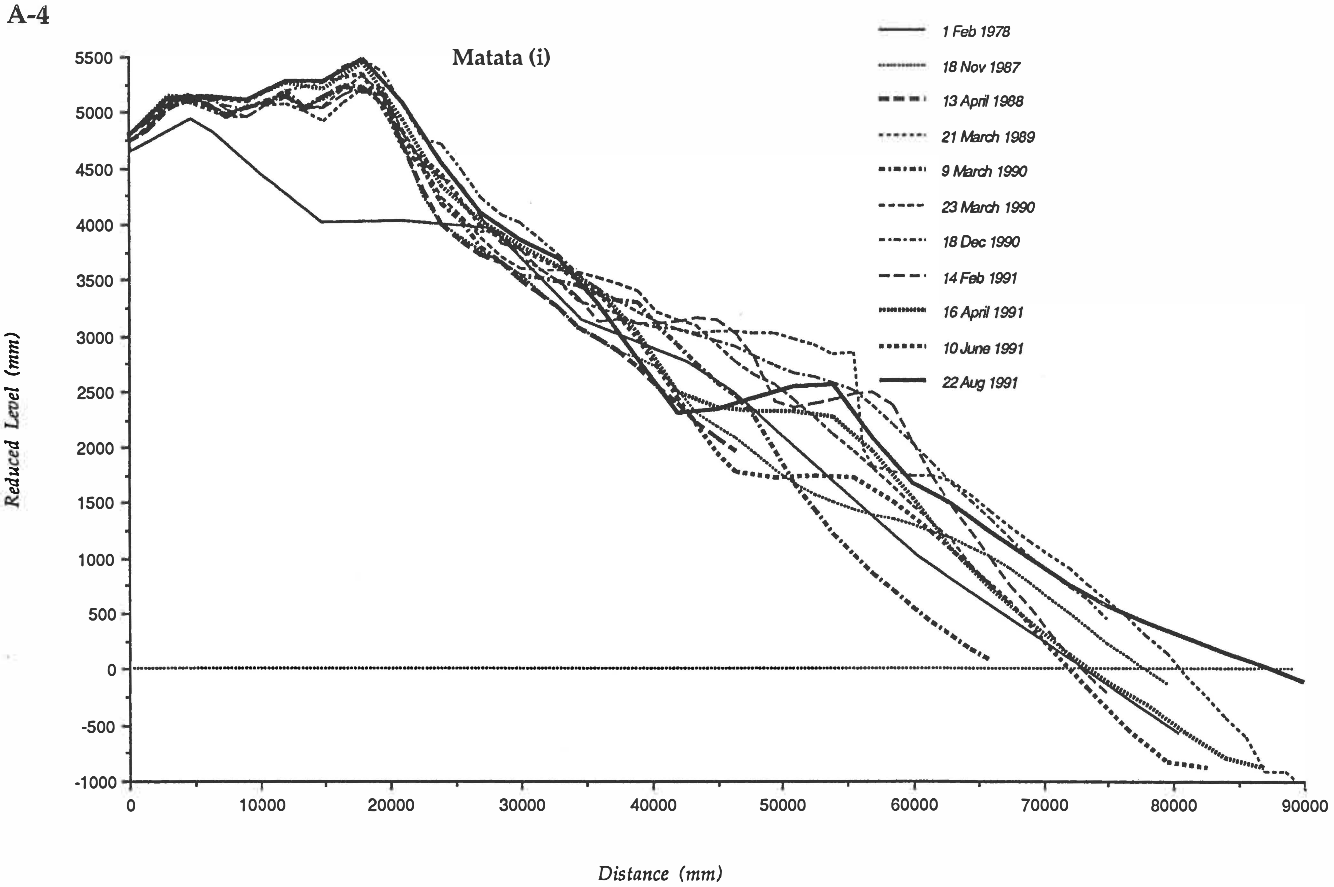
BOPCES site 19 - Tarawera River East
BOPCES site 20 - Tarawera River West
BOPCES site 21 - Matata (old pre-1986 sand mining site)
BOPCES site 22 - Maar's (Murphy's) Motor Camp (north Matata, Kohioawa Beach)
BOPCES site 23 - Pikowai
BOPCES site 24 - Otamarakau
BOPCES site 25 - Rodger's Road Beach
BOPCES site 26 - Pukehina Redoubt
BOPCES site 27 - Pukehina Beach south (basal end)
BOPCES site 28 - Pukehina Beach central
BOPCES site 29 - Pukehina Beach north (spit end)
BOPCES site 30 - Newdick's Beach (south-east Town Point)


Tarawera River east (i)
31 Jan 1978
15 Dec 1986
13 April 1988
21 March 1989
5 May 1989
9 March 1990
22 March 1990
18 Dec 1990
13 Feb 1991
16 April 1991
Reduced Level (mm)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
Distance (mm)
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
110000
120000
130000


Tarawera River east (ii)
16 April 1991
10 June 1991
22 Aug 1991
4 Oct 1991
20 Dec 1991
29 April 1992
10 Sept 1992
22 Oct 1992
2 Feb 1993
20 April 1993
Reduced Level (mm)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
Distance (mm)
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
110000
120000
130000


Tarawera West (i)
12 Dec 1986
13 April 1988
21 March 1989
5 May 1989
9 March 1990
23 March 1990
18 Dec 1990
13 Feb 1991
16 April 1991
10 June 1991
22 Aug 1991
Reduced Level (mm)
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (mm)


Tarawera West (ii)
22 Aug 1991
4 Oct 1991
20 Dec 1991
29 April 1992
2 July 1992
10 Sept 1992
22 Oct 1992
8 Dec 1992
2 Feb 1993
20 April 1993
Reduced Level (mm)
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (mm)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1 Feb 1978
18 Nov 1987
13 April 1988
21 March 1989
9 March 1990
23 March 1990
18 Dec 1990
14 Feb 1991
16 April 1991
10 June 1991
22 Aug 1991
Reduced Level (mm)
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
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0
-500
-1000
0
10000
20000
30000
40000
50000
60000
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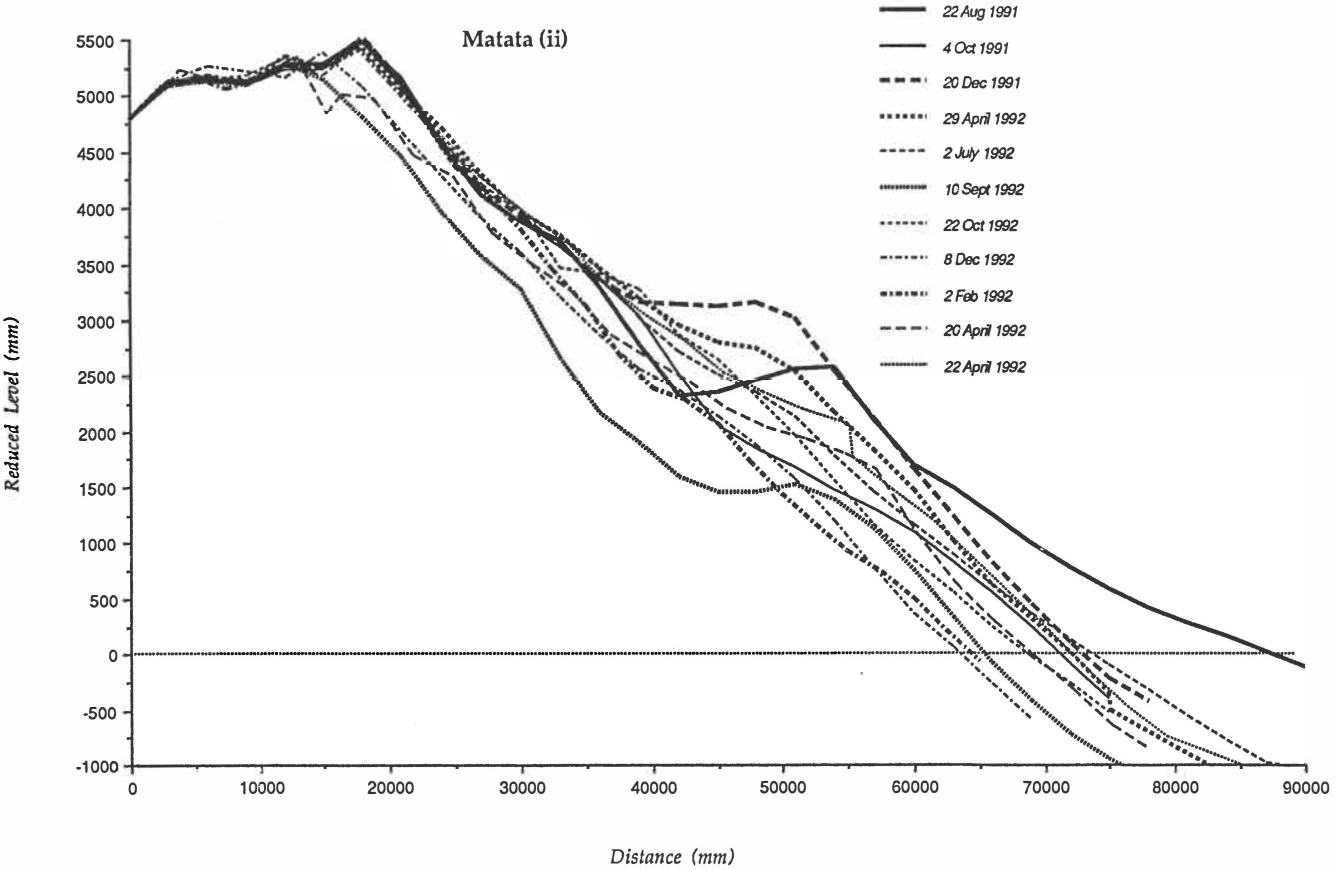
80000
90000
Distance (mm)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22 Aug 1991
4 Oct 1991
20 Dec 1991
29 April 1992
2 July 1992
10 Sept 1992
22 Oct 1992
8 Dec 1992
2 Feb 1992
20 April 1992
22 April 1992
Reduced Level (mm)
5500
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4500
4000
3500
3000
2500
2000
1500
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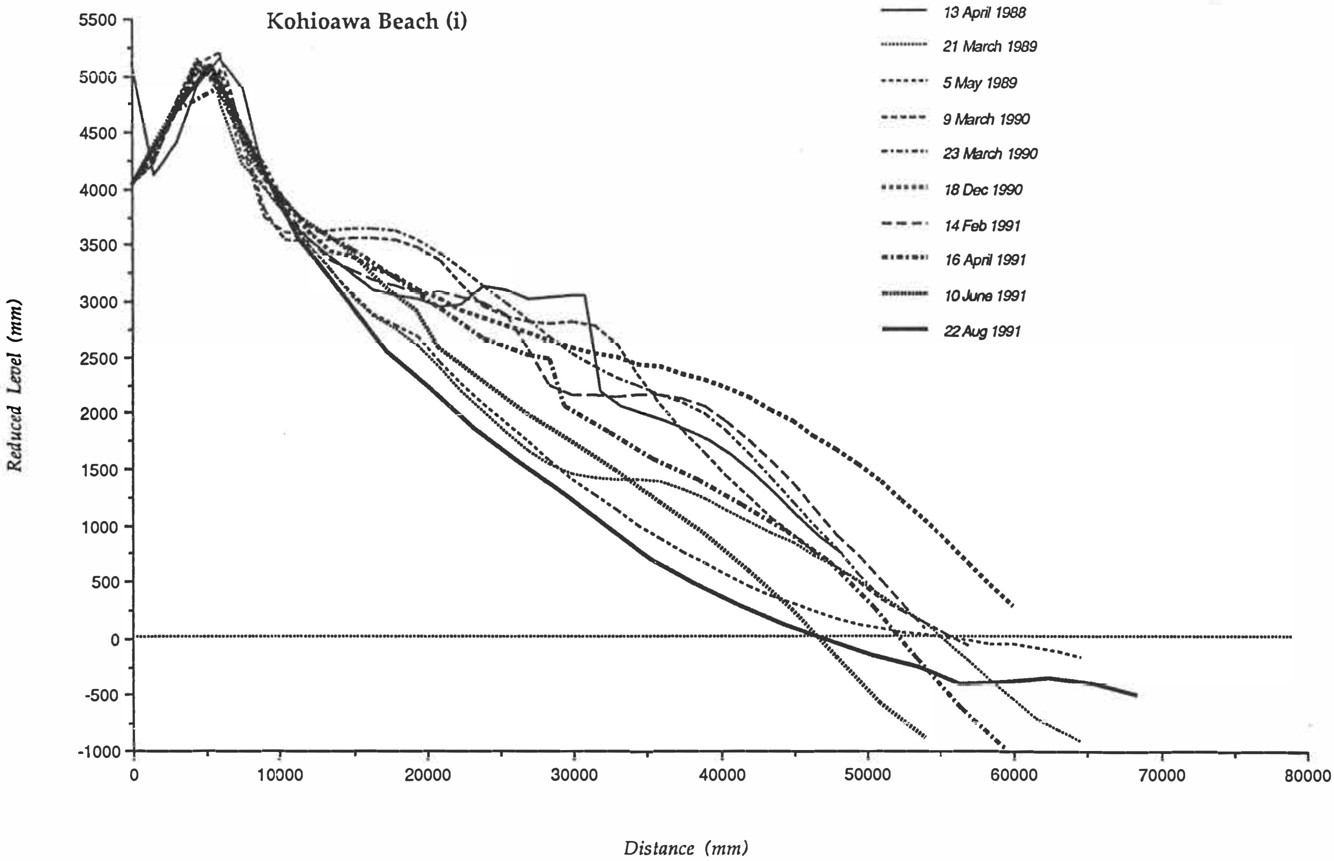
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (mm)


Kohioawa Beach (i)
13 April 1988
21 March 1989
5 May 1989
9 March 1990
23 March 1990
18 Dec 1990
14 Feb 1991
16 April 1991
10 June 1991
22 Aug 1991
Reduced Level (mm)
5500
5000
4500
4000
3500
3000
2500
2000
1500
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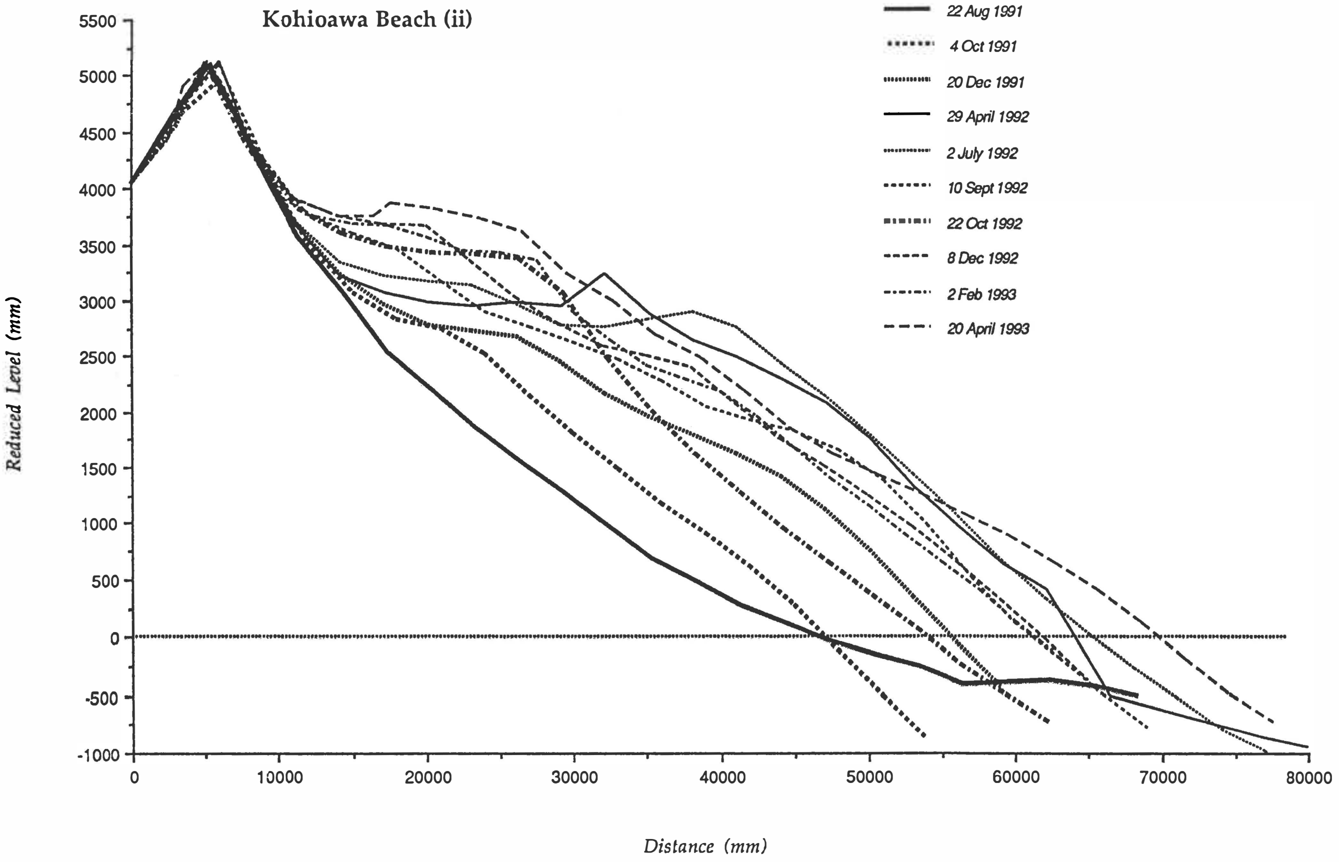
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
Distance (mm)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22 Aug 1991
4 Oct 1991
20 Dec 1991
29 April 1992
2 July 1992
10 Sept 1992
22 Oct 1992
8 Dec 1992
2 Feb 1993
20 April 1993
Reduced Level (mm)
5500
5000
4500
4000
3500
3000
2500
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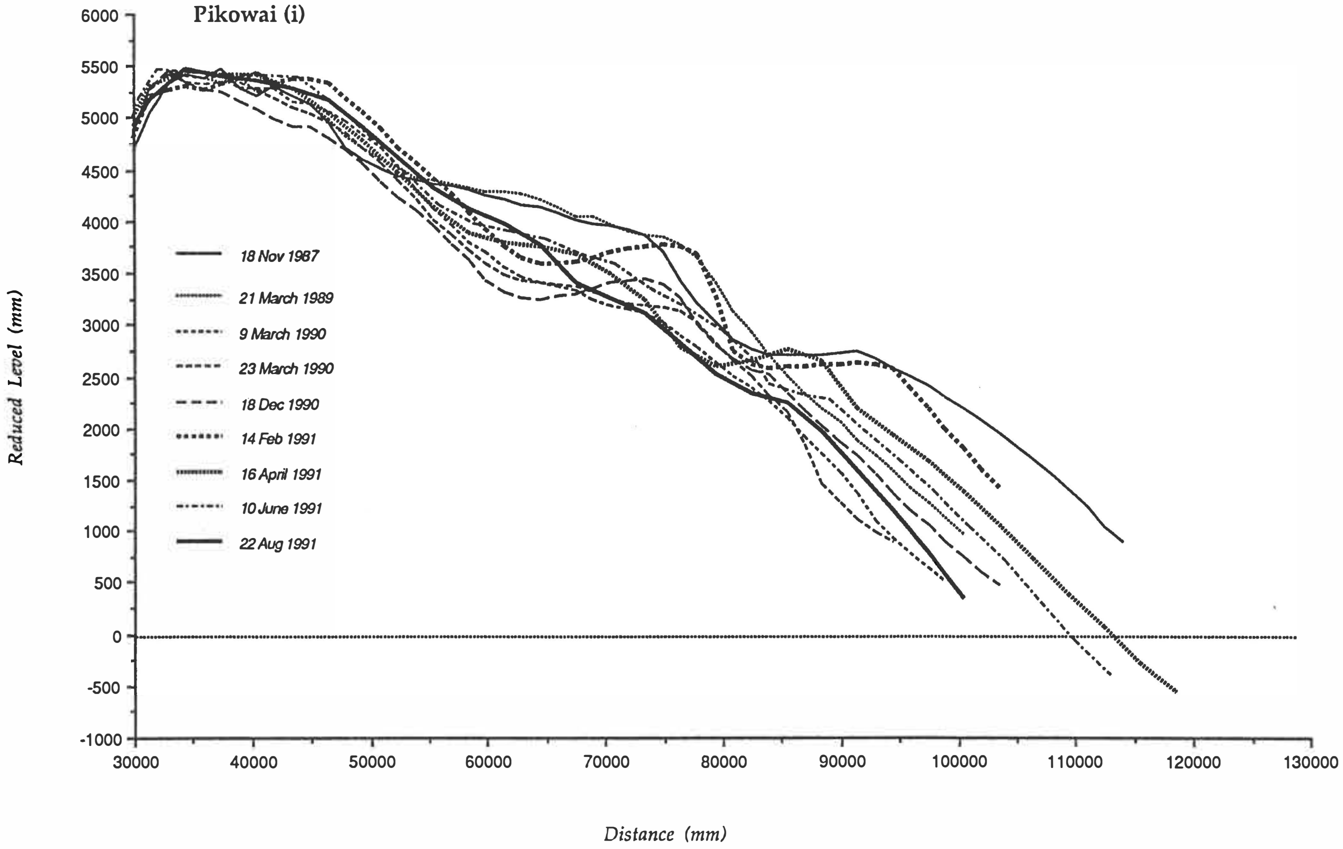
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
Distance (mm)


Pikowai (i)
Reduced Level (mm)
Distance (mm)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
30000
40000
50000
60000
70000
80000
90000
100000
110000
120000
130000
18 Nov 1987
21 March 1989
9 March 1990
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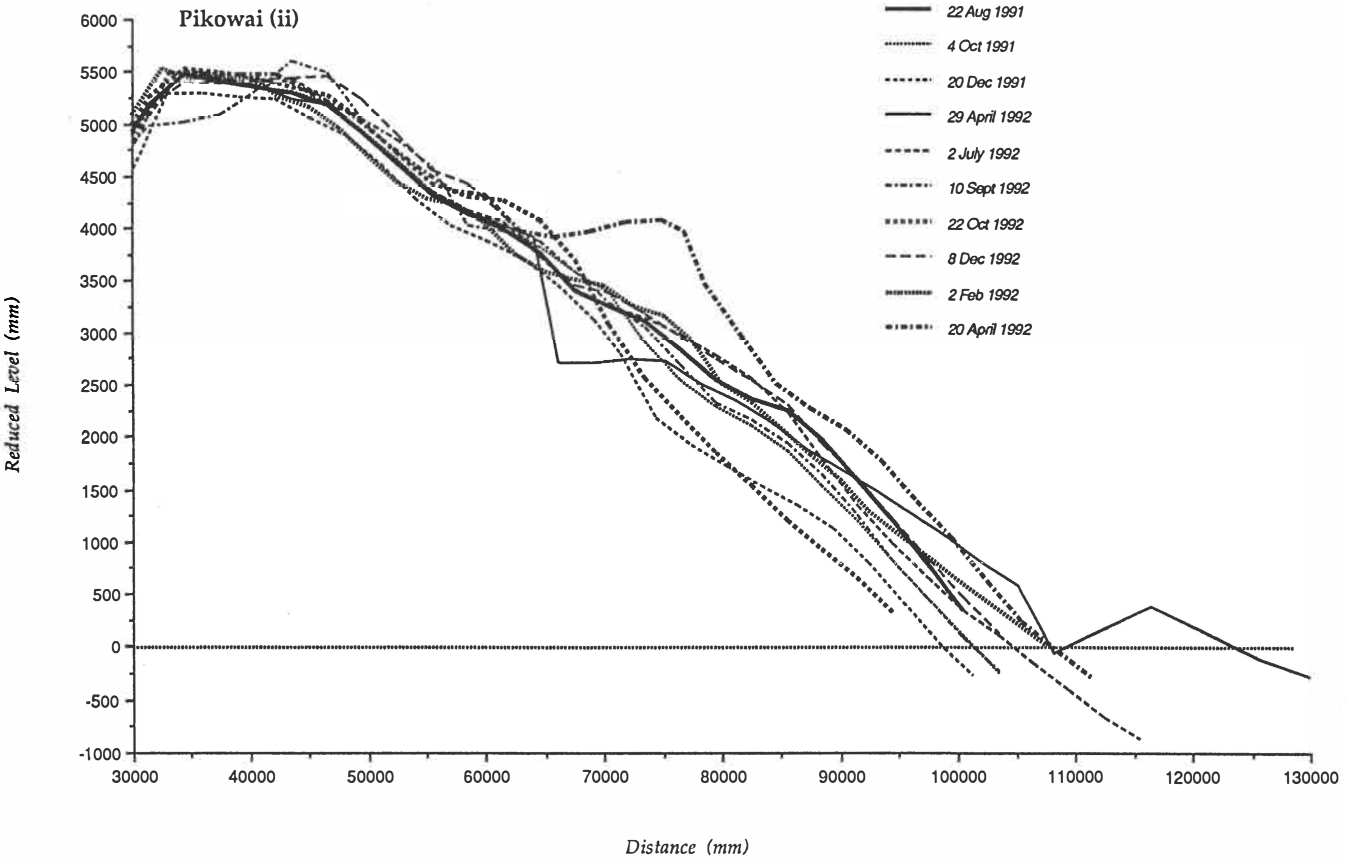
16 April 1991
10 June 1991
22 Aug 1991


Pikowai (ii)
Reduced Level (mm)
Distance (mm)
6000
5500
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4500
4000
3500
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-500
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30000
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60000
70000
80000
90000
100000
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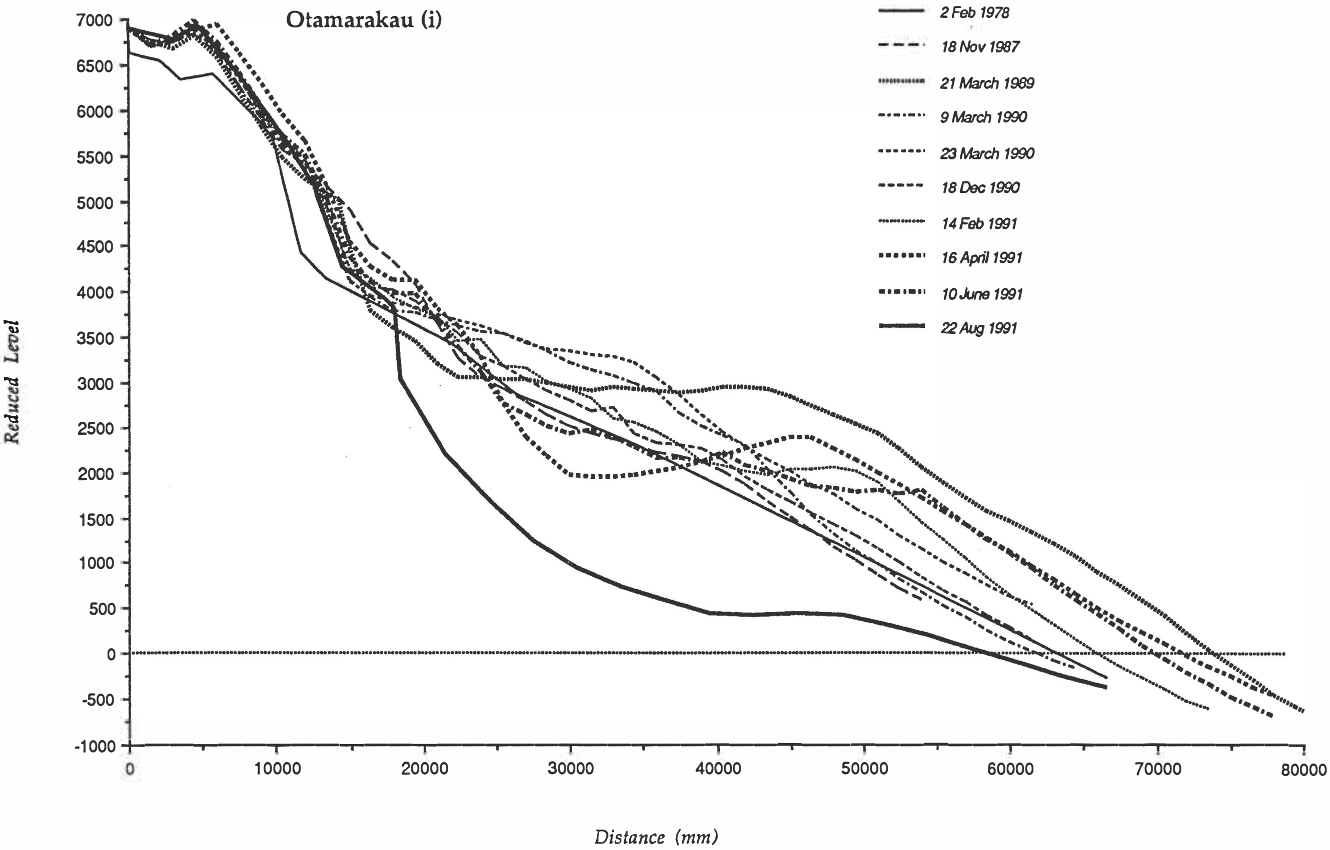
22 Aug 1991
4 Oct 1991
20 Dec 1991
29 April 1992
2 July 1992
10 Sept 1992
22 Oct 1992
8 Dec 1992
2 Feb 1992
20 April 1992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2 Feb 1978
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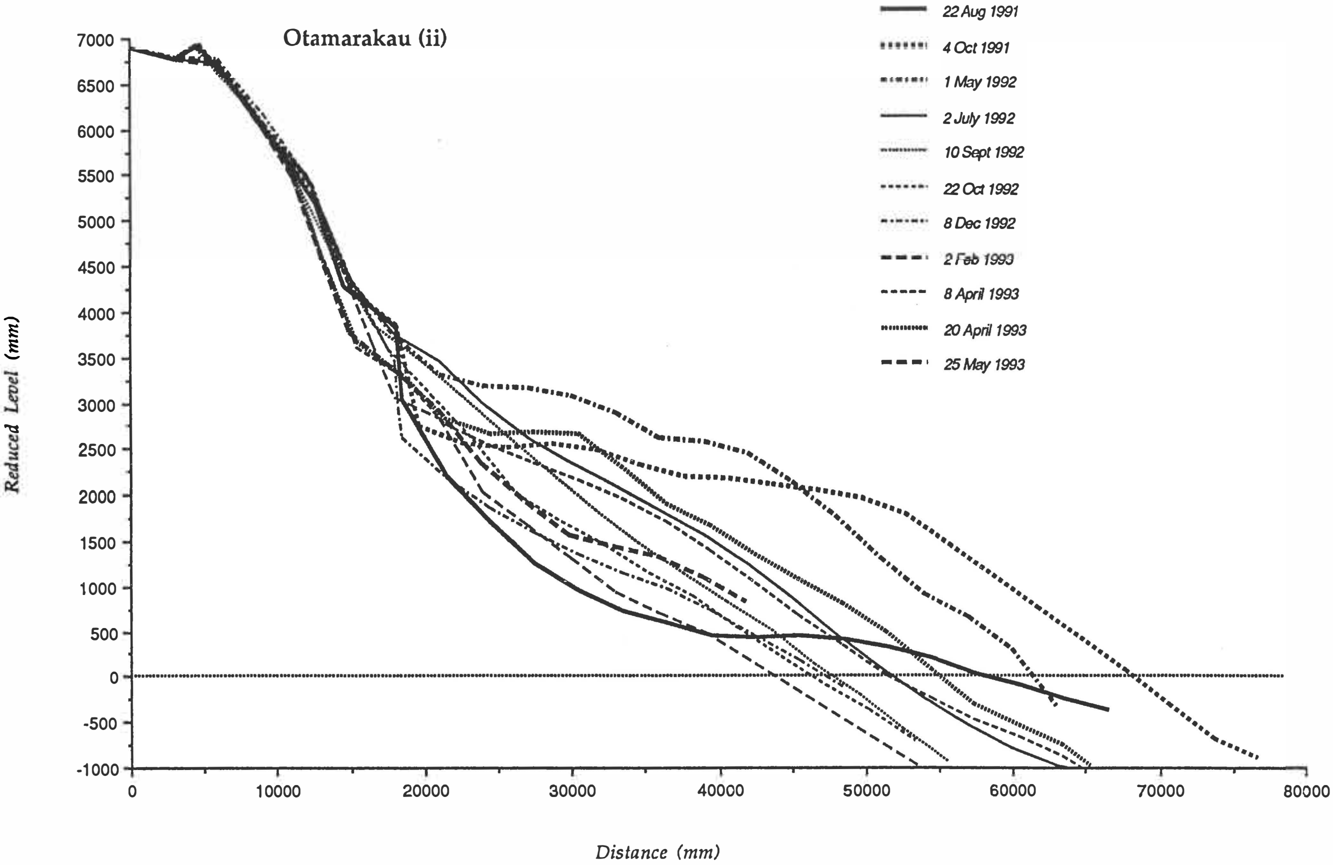
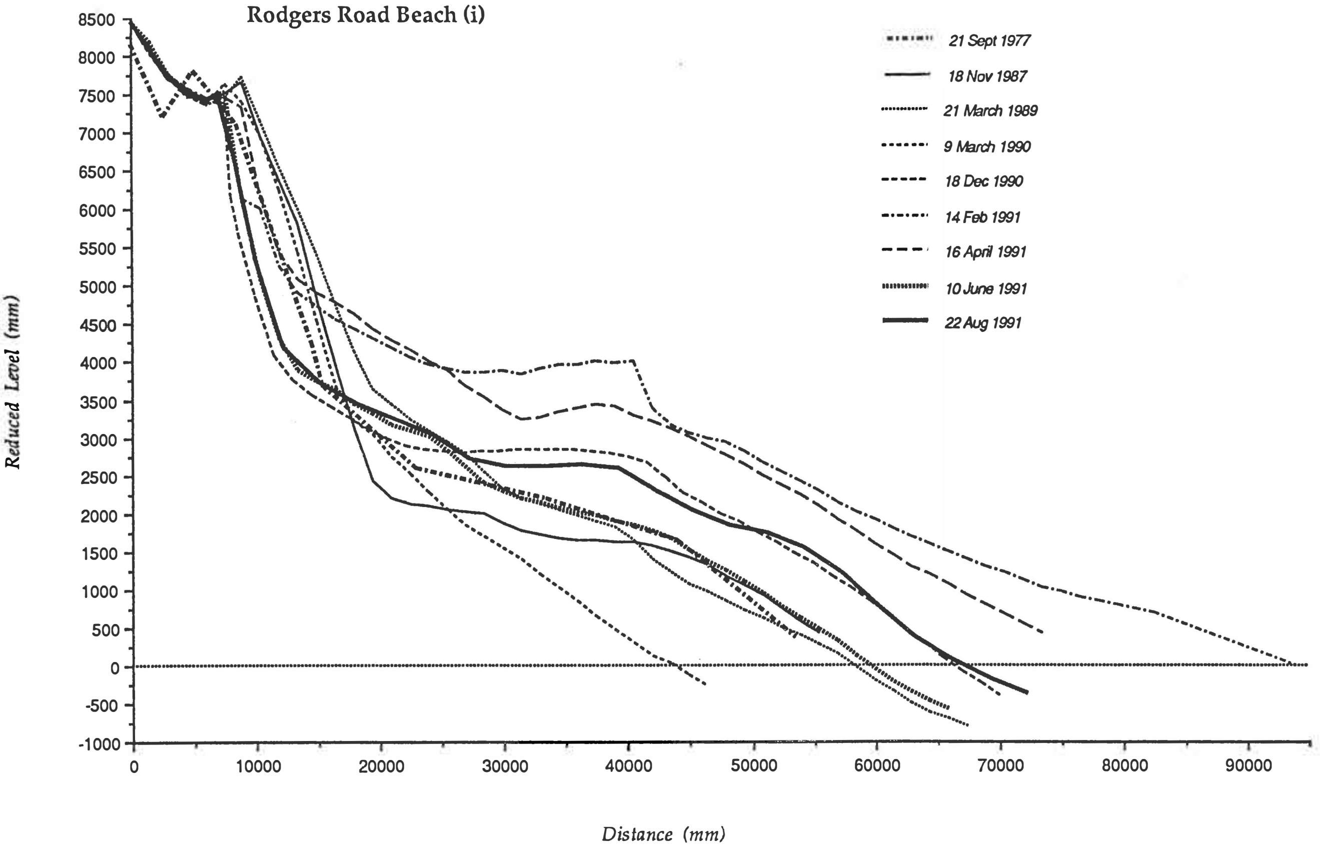
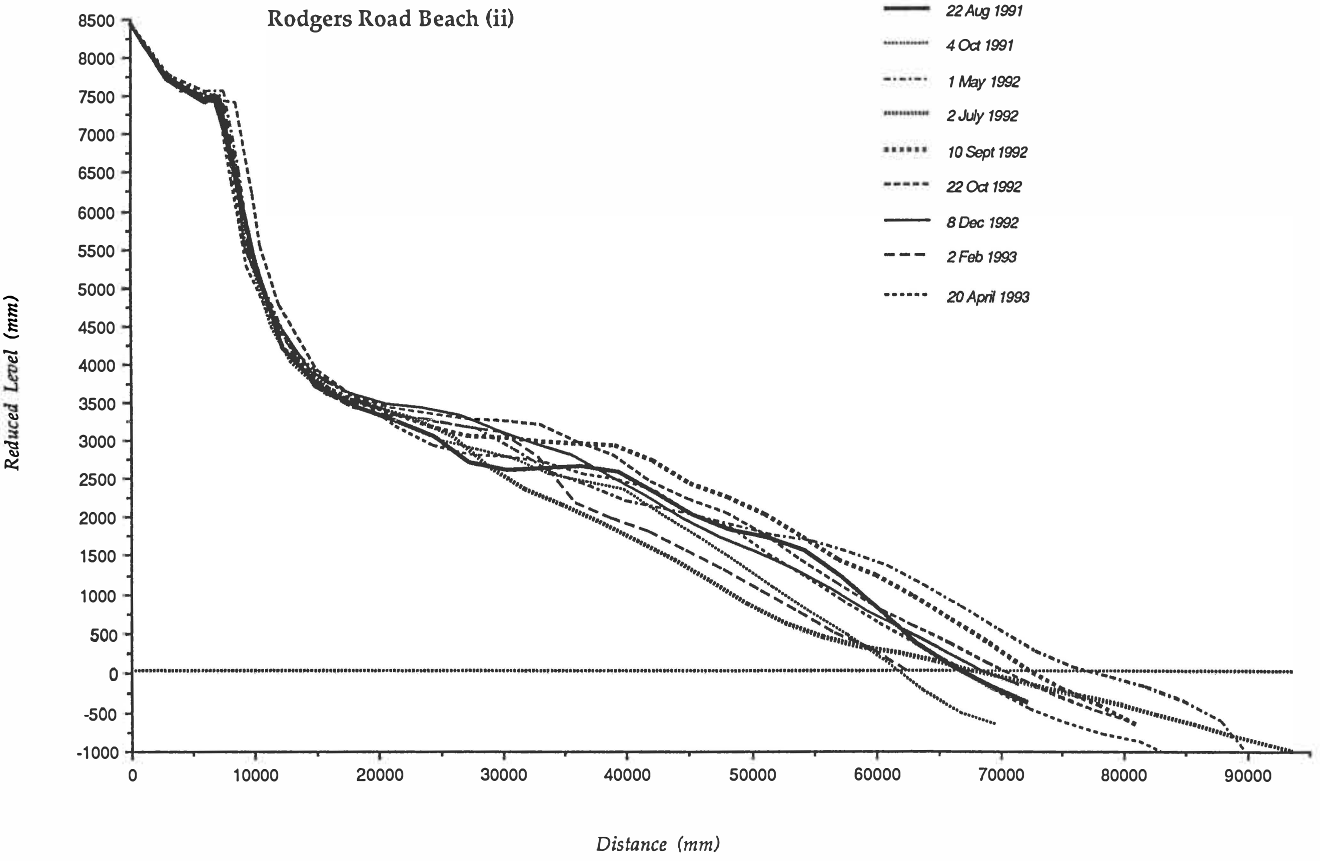
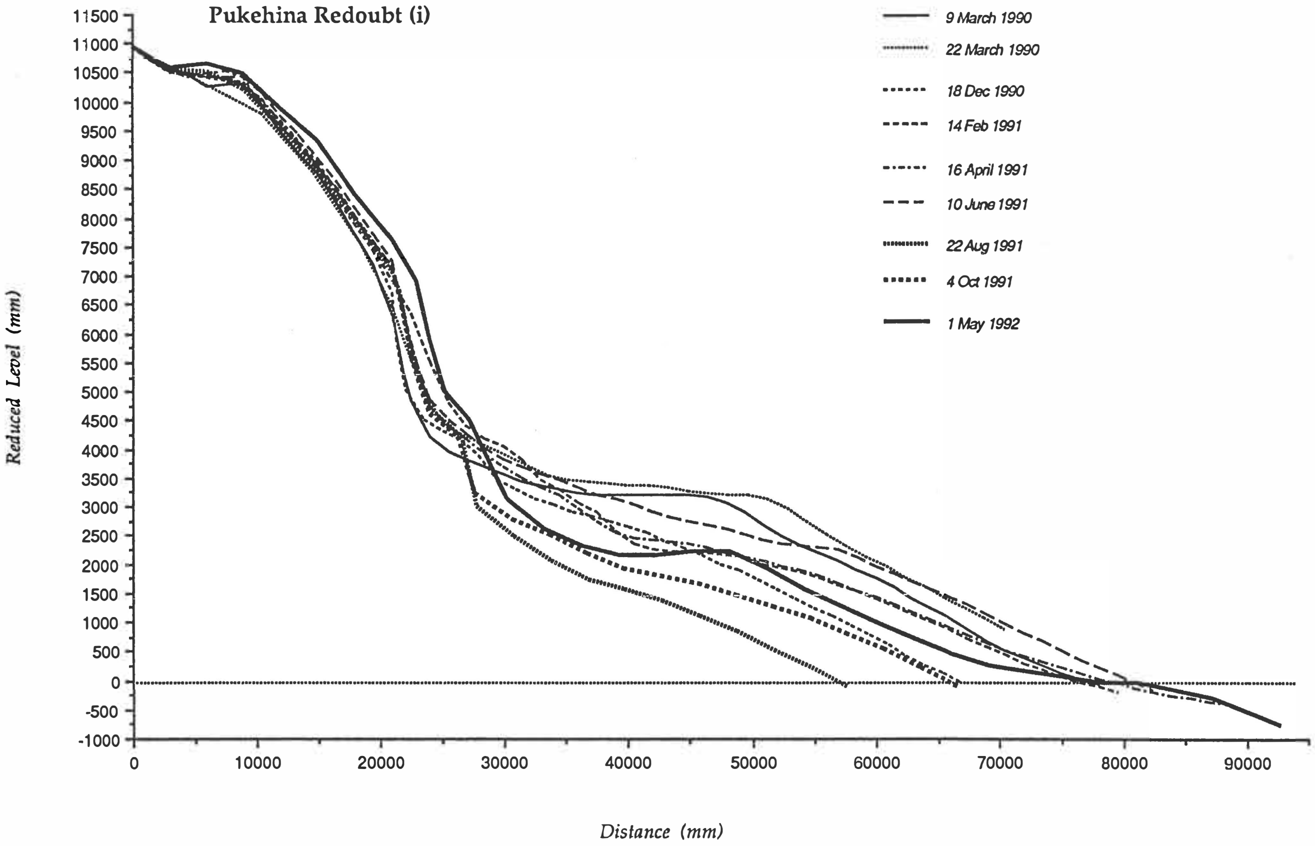
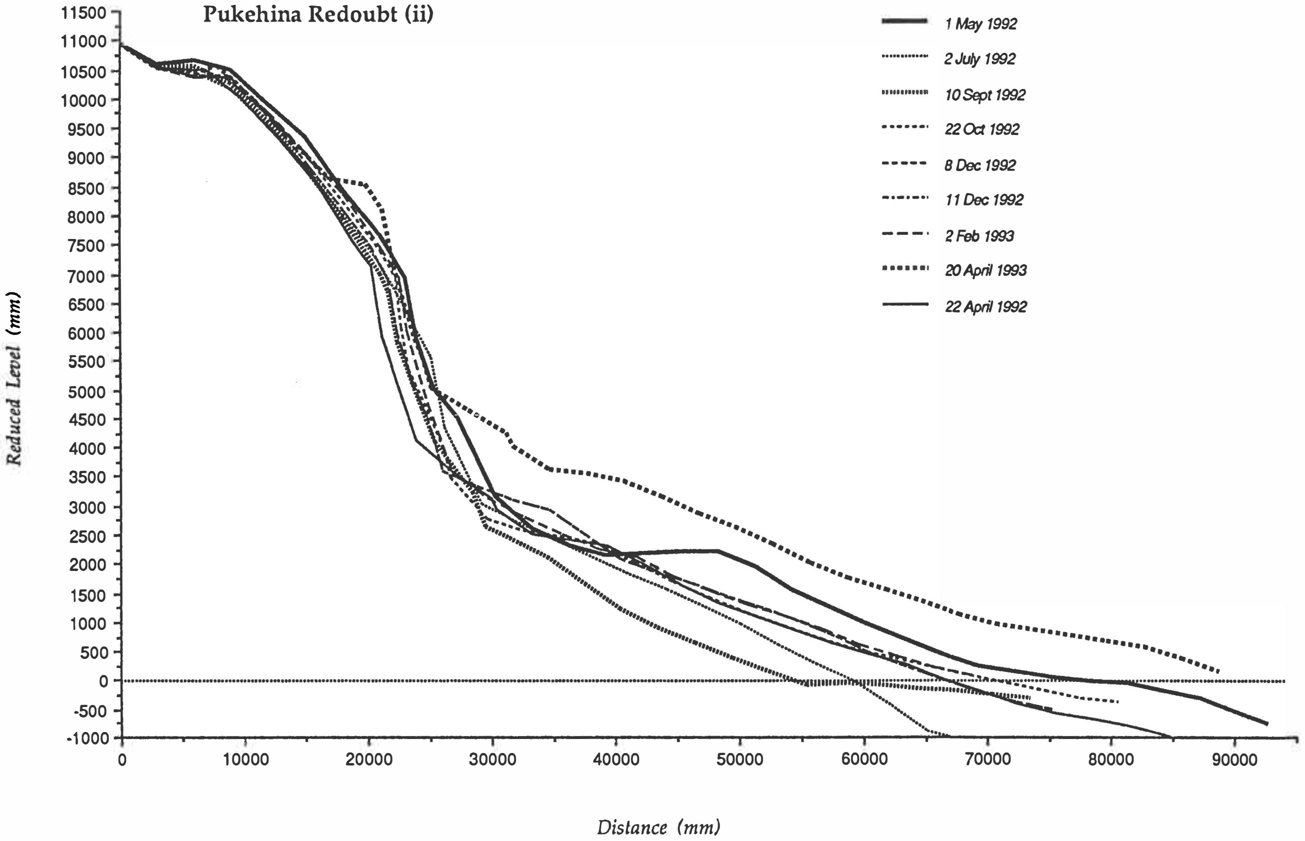
9 March 1990
23 March 1990
18 Dec 1990
14 Feb 1991
16 April 1991
10 June 1991
22 Aug 1991
Reduced Level
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
Distance (mm)

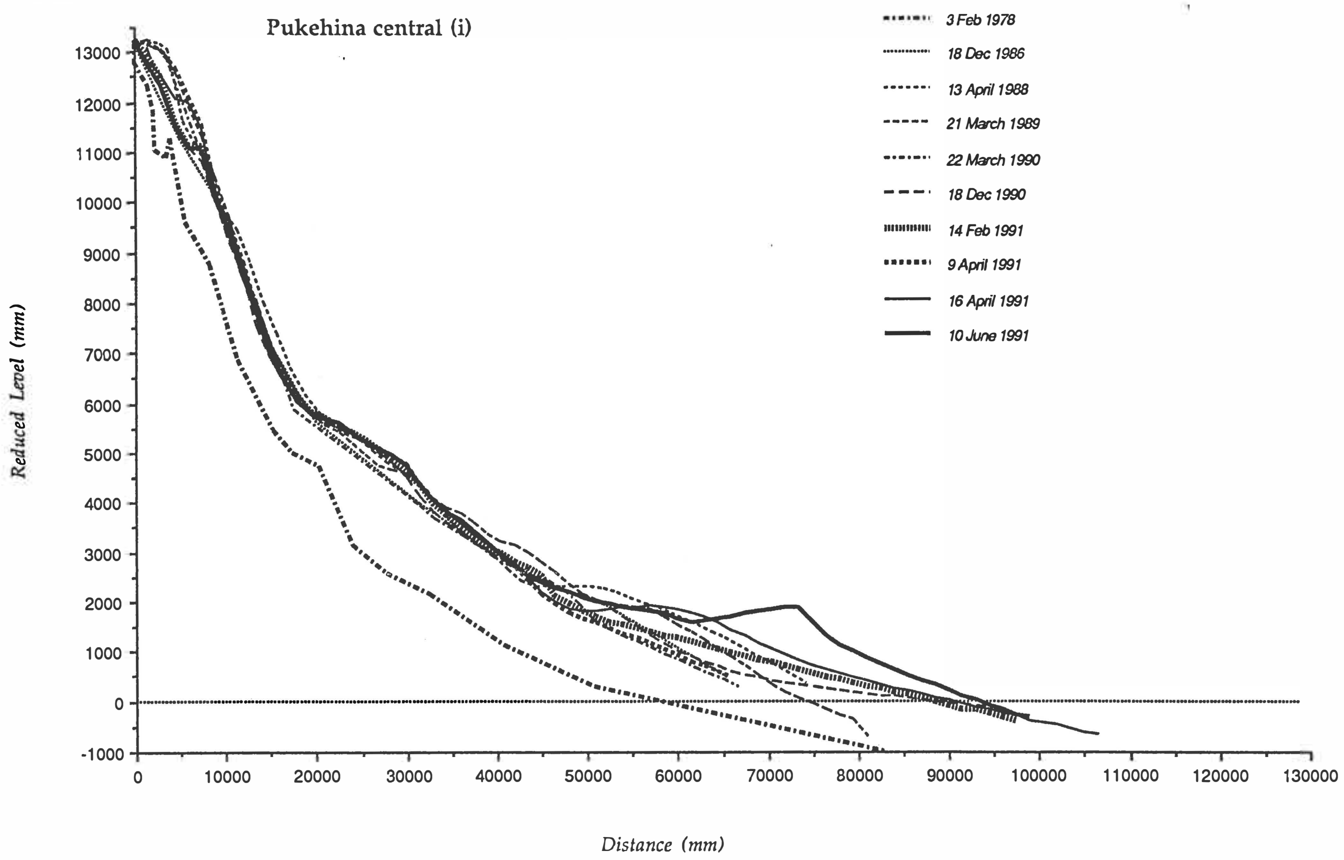

Otamarakau (ii)
22 Aug 1991
4 Oct 1991
1 May 1992
2 July 1992
10 Sept 1992
22 Oct 1992
8 Dec 1992
2 Feb 1993
8 April 1993
20 April 1993
25 May 1993
Reduced Level (mm)
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
Distance (mm)

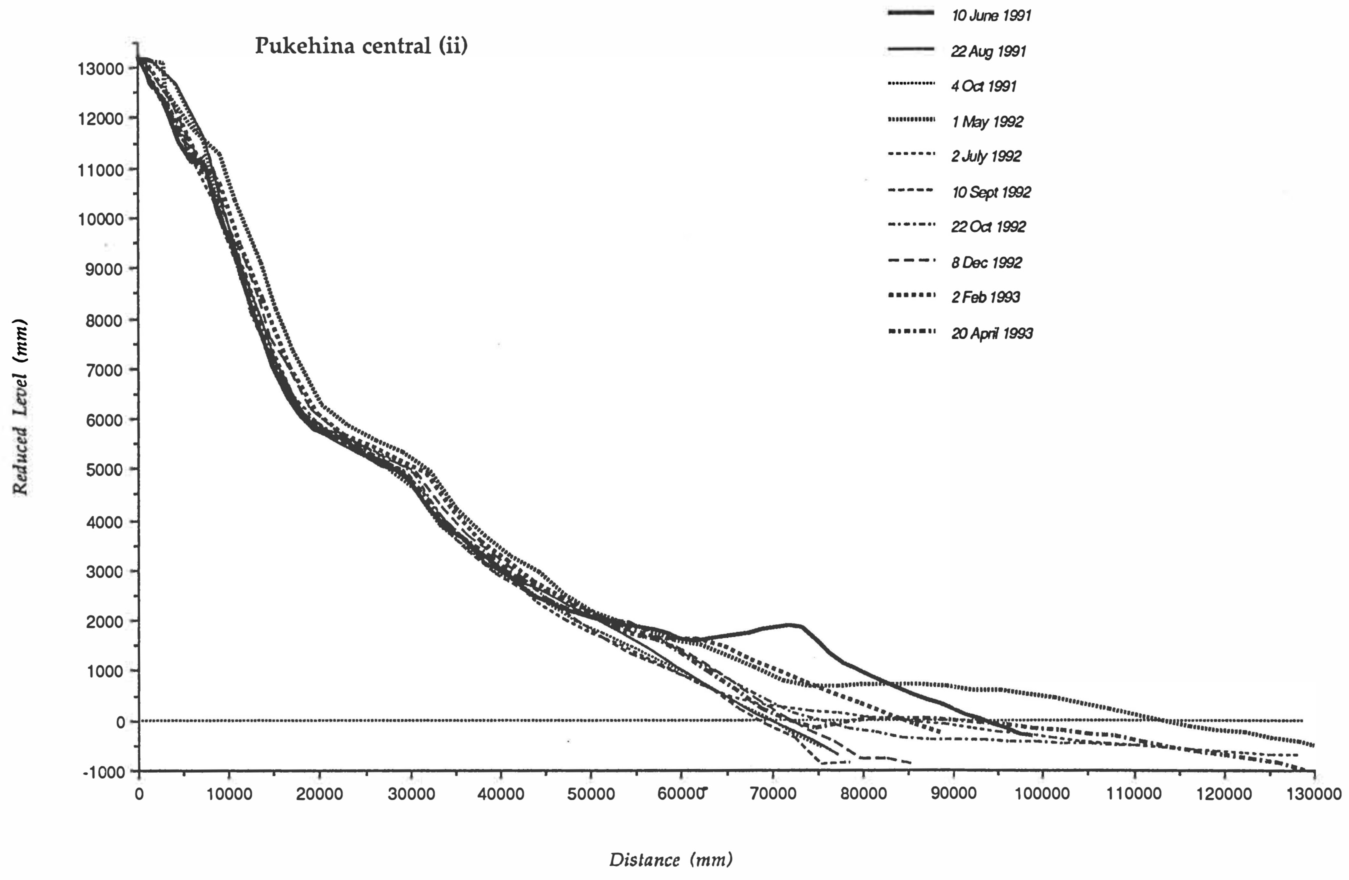

Rodgers Road Beach (i)
21 Sept 1977
18 Nov 1987
21 March 1989
9 March 1990
18 Dec 1990
14 Feb 1991
16 April 1991
10 June 1991
22 Aug 1991
Reduced Level (mm)
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (mm)

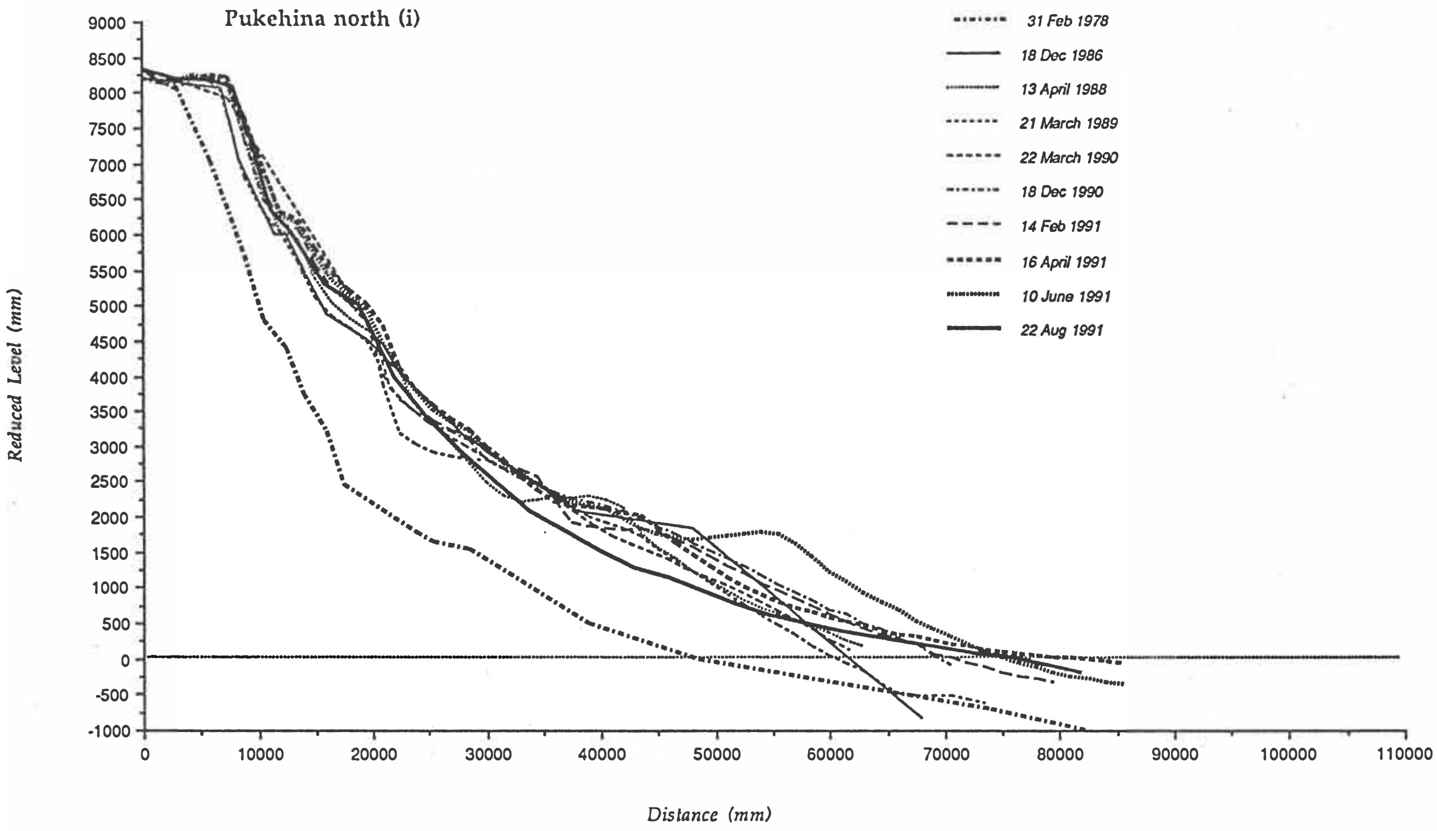

Rodgers Road Beach (ii)
22 Aug 1991
4 Oct 1991
1 May 1992
2 July 1992
10 Sept 1992
22 Oct 1992
8 Dec 1992
2 Feb 1993
20 April 1993
Reduced Level (mm)
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (mm)

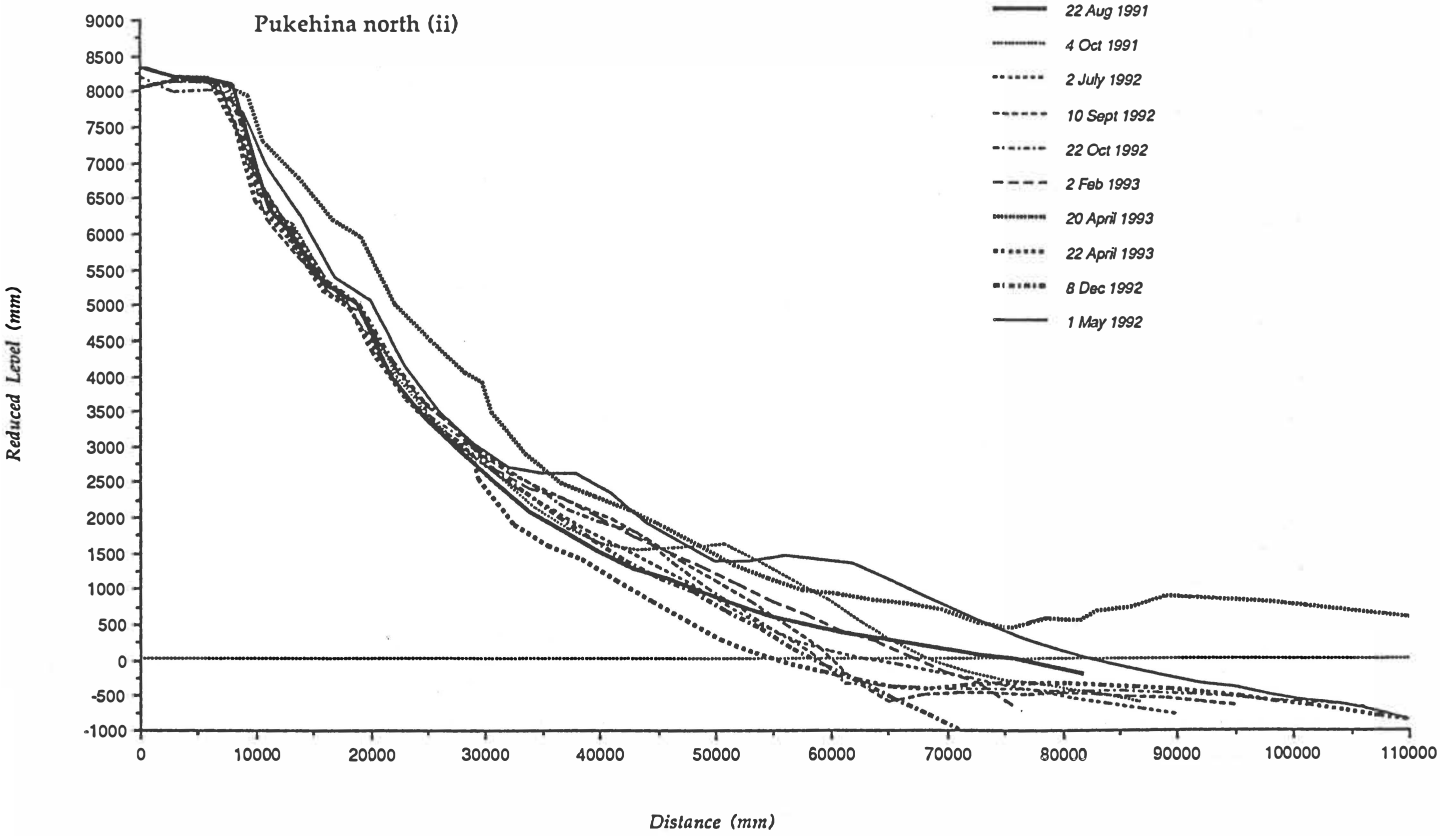

Pukehina Redoubt (i)
Reduced Level (mm)
11500
11000
10500
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (mm)
9 March 1990
22 March 1990
18 Dec 1990
14 Feb 1991
16 April 1991
10 June 1991
22 Aug 1991
4 Oct 1991
1 May 1992


Pukehina Redoubt (ii)
Reduced Level (mm)
11500
11000
10500
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (mm)
1 May 1992
2 July 1992
10 Sept 1992
22 Oct 1992
8 Dec 1992
11 Dec 1992
2 Feb 1993
20 April 1993
22 April 1992

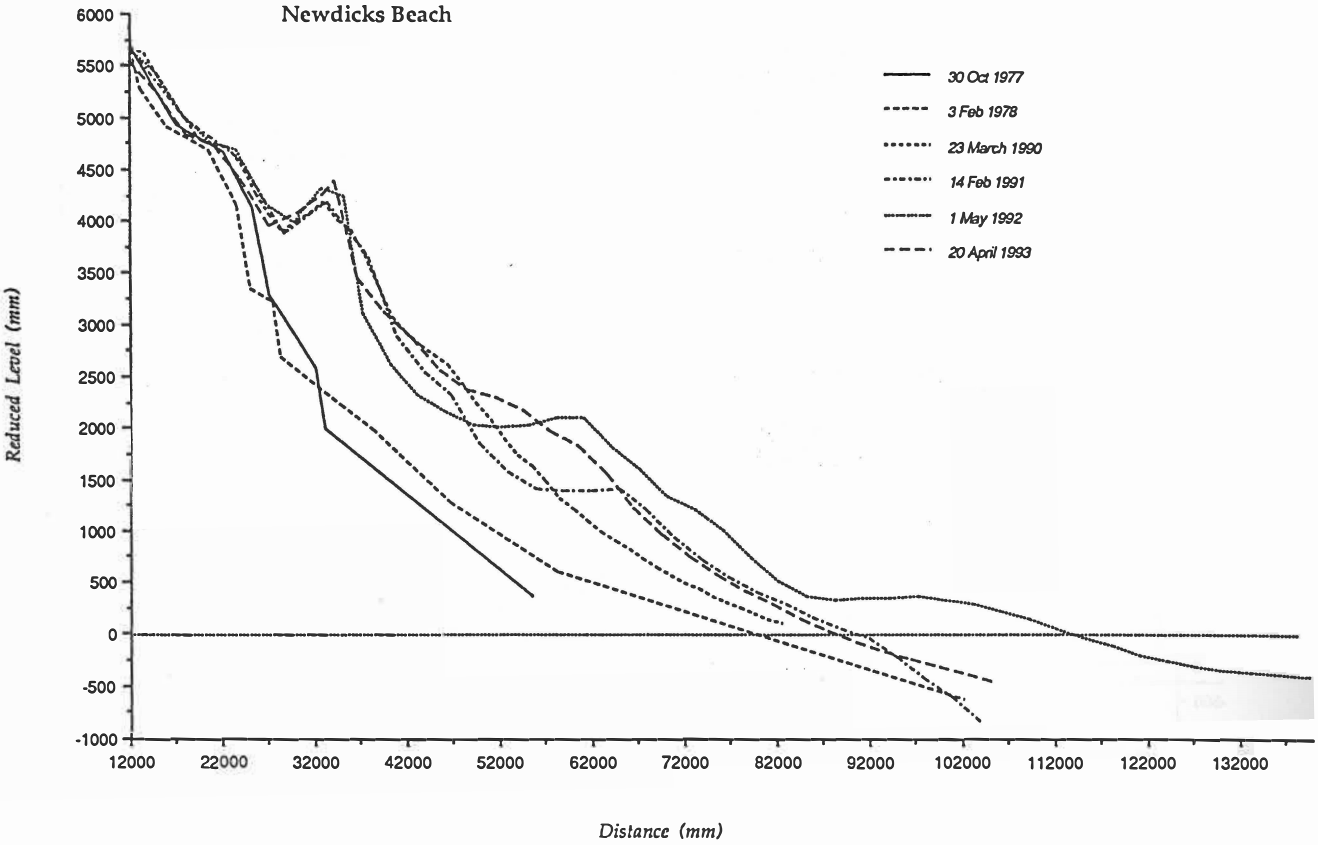

Pukehina central (i)


Pukehina central (ii)


Pukehina north (i)
31 Feb 1978
18 Dec 1986
13 April 1988
21 March 1989
22 March 1990
18 Dec 1990
14 Feb 1991
16 April 1991
10 June 1991
22 Aug 1991
Reduced Level (mm)
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
110000
Distance (mm)


Pukehina north (ii)
22 Aug 1991
4 Oct 1991
2 July 1992
10 Sept 1992
22 Oct 1992
2 Feb 1993
20 April 1993
22 April 1993
8 Dec 1992
1 May 1992
Reduced Level (mm)
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
110000
Distance (mm)

A-12


Newdicks Beach
30 Oct 1977
3 Feb 1978
23 March 1990
14 Feb 1991
1 May 1992
20 April 1993
Reduced Level (mm)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-500
-1000
12000
22000
32000
42000
52000
62000
72000
82000
92000
102000
112000
122000
132000
Distance (mm)

Appendix II: *Beach Profile Volumes*

The following programme calculates beach profile volumes from profile survey data, which is given in two columns of horizontal distance from benchmark and elevation as reduced level to Moturiki datum (msl), with the number of profile points specified at the top of the data file.

```
        Program PROFILE VOLUME

        Character*80 Rawdata,Results
        Real*4 XDIS(100),HM(100)

        Imax = 100

C       Get profile data

        Call GET_DATA (Imax,XDIS,HM,Rawdata)

C       Ask user for and set up output file

        Results = '  '
17      Type 22
22      Format (' Enter output data filename',/,' *',$)
        Read (*,40,ERR=17) Results
40      Format (A80)

        Open (Unit=16,File=Results,Status='New')

        Call PROFILE_VOL (Imax,XDIS,HM,Rawdata)

C       Close output file and end program

        Close (Unit=16)
        Stop

        End

C       Subroutine to input data

        SUBROUTINE GET_DATA (Imax,XDIS,HM,Rawdata)

        Character*1 Tab,Sp,Infocopy(80)
        Character*80 Info,Rawdata
        Integer*2 pos
        Real*4 XDIS(Imax),HM(Imax)
        Equivalence (Info,Infocopy(1))
        Tab = Char(9)
        Sp = ' '

C       Ask user for the input data file

        Rawdata = '  '
17      Type 22
22      Format (' Enter input data filename',/,' *',$)
        Read (*,50,ERR=17) Rawdata
50      Format (A80)
        Open (Unit=15,File=Rawdata,Status='Old',Readonly)

C       Get the beach profile

        Read (15,*) Imax
        Do I=1,Imax
                Read (15,10) Info
                pos=Index(Info,Tab)
                Do While (pos.NE.0)
                        Infocopy(pos)=Sp
                        pos=Index(Info,Tab)
```

```
                    End Do
                    Read (Info,*) x,y
                    XDIS(I) = (x)*0.001
                    HM(I) = (y)*0.001
          End Do

          Return

10        Format (A80)

          End

C         Subroutine to determine the profile volume

          SUBROUTINE PROFILE_VOL (Imax,XDIS,HM)

          Real*4 XDIS(Imax),HM(Imax)

          VOLM = 0.0
          HMprev = HM(1)

          Do J=2,Imax
                    HMcur = HM(J)
                    XDISdif = XDIS(J)-XDIS(J-1)
                    VOLM = VOLM + 0.5*(HMprev+HMcur)*XDISdif
                    HMprev = HMcur
          End Do

          Write (16,10) VOLM

          Return

10        Format ('AREA BELOW PROFILE : ',F9.2,' (metres squared)')

          End
```

BEACH SAMPLES

SAMPLE	Grid Reference	Location	Mean Grair Size (phi)	Sorting	Skewness	Mode	Kurtosis	Gravel %	Entropy Class	WT Number
TP1	V14 165774	Beachface	1.90	0.53	-0.92	2.25	5.76	0.00		W93 707
	V14 161781	Beachface (N)	1.96	0.38	0.56	2.25	3.19	0.00		W93 708
TP2	V14 159784	Beachface (N)	0.93	0.94	0.20	0.50	1.77	0.00		W93 709
P1	V14 167771	Back berm	1.27	0.63	0.94	0.75	3.31	0.00		W93 710
		Beachface	1.69	0.52	0.25	1.50	2.74	0.00	1	W93 711
		Swash	0.61	1.34	-0.83	0.75	3.13	14.35	7	W93 712
P2	V14 169768	Backberm	0.96	0.57	1.18	1.00	4.54	0.00		W93 713
		Beachface	1.97	0.44	1.00	2.00	8.63	0.08	4	W93 714
		Beachface (N)	1.20	0.42	0.55	1.00	5.29	0.09		W93 715
		Swash	1.42	0.94	-1.24	2.25	4.29	2.58	1	W93 716
P3	V14 172765	Backberm	1.41	0.49	1.23	1.25	4.99	0.00		W93 717
		Beachface	1.84	0.50	-1.47	2.00	15.16	1.09	4	W93 718
		Beachface (N)	1.55	0.38	0.56	1.50	3.62	0.00		W93 719
		Swash	1.39	1.02	-1.38	2.00	5.09	4.72	1	W93 720
P4	V14 174763	Backberm	1.37	0.46	1.19	1.25	5.73	0.00		W93 721
		Beachface	1.83	0.62	-2.31	2.00	13.73	1.74	4	W93 722
		Swash	0.43	1.30	-0.19	1.25	1.93	17.05	7	W93 723
P5	V14 179758	Backberm	1.57	0.73	1.04	1.50	6.98	0.58		W93 724
		Beachface	2.11	0.44	0.63	2.00	3.97	0.00	4	W93 725
		Swash	-0.66	1.19	-0.09	0.25	2.27	40.17		W93 726
P6	V14 183754	Backberm	1.50	0.56	1.47	1.50	5.24	0.00		W93 727
		Beachface	2.23	0.35	0.76	2.50	4.75	0.00	4	W93 728
		Beachface (N)	1.73	0.37	1.32	1.75	5.26	0.00		W93 729
		Swash	1.12	1.29	-0.93	2.25	3.04	9.86	7	W93 730
P7	V14 190748	Backberm	1.59	0.40	1.32	1.50	4.21	0.00		W93 731
		Beachface	1.67	0.65	0.00	1.75	4.25	0.20	1	W93 732
		Swash	-0.16	1.67	0.26	-1.00	1.77	41.05	7	W93 733
P8	V14 197742	Backberm	1.42	0.63	0.35	1.50	5.11	0.43		W93 734
		Beachface	1.81	0.74	-2.82	2.00	16.48	1.89	1	W93 735
		Swash	0.18	1.48	-0.29	1.50	1.72	29.40	7	W93 736
P9	V14 201738	Backberm	1.30	0.59	1.06	1.00	3.37	0.00		W93 737
		Beachface	1.89	0.54	0.86	2.25	4.42	0.00	1	W93 738
		Beachface (N)	1.53	0.34	2.29	1.50	8.01	0.00		W93 739
		Swash	0.43	1.25	-0.40	1.75, -1.50	2.07	17.60	7	W93 740
P10	V14 206734	Backberm	1.54	0.65	1.10	1.00	3.62	0.00		W93 741
		Beachface	1.91	0.51	0.80	2.00	4.41	0.00	4	W93 742
		Swash	0.91	1.23	-0.98	1.25	3.15	12.33	7	W93 743
P11	V14 211731	Backberm	1.05	0.84	0.21	1.00	4.40	1.47		W93 744
		Beachface	1.83	0.39	0.50	2.00	2.24	0.00	1	W93 745
		Beachface (N)	0.57	0.97	-0.03	-0.75	2.05	2.35		W93 746
		Swash	1.41	0.76	-1.10	2.00	4.85	1.18	1	W93 747
P12	V14 216727	Backberm	1.52	0.89	-1.68	1.75	8.84	4.91		W93 748
		Beachface	1.55	0.56	0.19	1.75	3.27	0.00	1	W93 749
		Beachface (N)	1.35	0.46	0.64	1.25	5.10	0.13		W93 750
P13	V14 221723	Backberm	1.31	0.90	-1.22	1.25	7.05	5.43		W93 751
		Beachface	1.67	0.44	0.92	2.00	4.01	0.00	1	W93 752
		Swash	0.70	1.45	-0.40	0.75	1.94	18.90	7	W93 753
P14	V14 225720	Backberm	1.76	0.59	2.03	1.50	7.01	0.00		W93 754
		Beachface	1.74	0.54	-0.85	2.25	5.86	0.45	1	W93 755
		Swash	1.22	1.18	-1.13	2.25	3.48	6.47	1	W93 756
P15	V14 233713	Backberm	1.40	0.55	-0.47	1.25	8.12	0.69		W93 757
P16	V14 238709	Backberm	1.17	0.86	-1.65	1.25	7.21	5.74		W93 758
		Beachface	1.38	0.69	-0.76	1.75	4.97	0.71	1	W93 759

SAMPLE	Grid Reference	Location	Mean Grain Size (phi)	Sorting	Skewness	Mode	Kurtosis	Gravel %	Entropy Class	WT Number
		Swash	1.27	0.86	-1.51	1.75	5.50	3.46	1	W93 760
P17	V14 240708	Backberm	1.27	0.65	-0.08	1.25	4.60	0.35		W93 761
		Beachface	1.81	0.45	0.27	1.75	4.34	0.00	1	W93 762
		Swash	0.71	1.19	-0.41	1.25	1.93	10.14	7	W93 763
P18	V14 246703	Backberm	1.47	0.47	-0.07	1.50	4.92	0.00		W93 764
		Beachface	1.71	0.51	0.17	2.25	2.45	0.00	1	W93 765
		Beachface (N)	0.70	1.03	0.03	0.75	1.85	2.38		W93 766
		Swash	1.08	0.94	-0.83	1.75	2.90	2.41	7	W93 767
M1	V15 432611	Backberm	1.18	0.47	1.44	1.25	6.52	0.00		W93 768
M2	V15 428612	Backberm	1.66	0.47	0.70	1.75	4.37	0.00		W93 769
		Beachface	1.45	0.52	-1.52	1.50	12.59	0.91	1	W93 770
		Beachface (N)	1.29	0.53	0.84	1.00	3.47	0.00		W93 771
		Swash	1.52	0.54	-1.30	1.50	7.45	0.23	1	W93 772
M3	V15 424612	Backberm	1.27	0.47	1.12	1.50	5.86	0.00		W93 773
M4	V15 422613	Backberm	0.85	0.55	1.21	0.50	4.88	0.00		W93 774
M5	V15 419613	Backberm	1.18	0.48	2.35	1.00	9.67	0.00		W93 775
M6	V15 416614	Backberm	0.84	0.68	0.90	0.50	6.37	0.95		W93 776
M7	V15 413615	Backberm	1.04	0.80	-0.15	1.25	7.20	3.18		W93 777
M8	V15 410616	Backberm	1.27	0.56	1.42	1.00	5.26	0.00		W93 778
		Beachface	1.32	0.45	0.99	1.25	4.43	0.00	2	W93 779
		Beachface (N)	1.37	0.41	0.73	1.25	3.33	0.02		W93 780
		Swash	0.08	1.34	-0.12	1.50, -0.50	1.98	24.34	7	W93 781
M9	V15 406617	Backberm	1.26	0.56	0.79	1.00	3.00	0.03		W93 782
		Beachface	1.46	0.61	-0.57	1.00	3.20	0.16	1	W93 783
		Beachface (N)	1.34	0.37	0.30	1.50	6.23	0.08		W93 784
		Swash	1.28	0.93	-1.99	2.00	6.70	5.00	1	W93 785
M10	V15 402619	Backberm	1.06	0.58	2.32	0.75	8.91	0.00		W93 786
M11	V15 398620	Backberm	1.16	0.60	1.01	1.50	7.12	0.19		W93 787
		Beachface	1.30	0.55	-0.73	1.75	5.38	0.40	2	W93 788
		Beachface (N)	1.30	0.37	1.33	1.25	3.61	0.00		W93 789
		Swash	0.35	1.44	-0.46	1.75	1.94	22.82	7	W93 790
M12	V15 394622	Backberm	1.20	0.52	1.76	1.50	7.80	0.00		W93 791
		Beachface	0.99	0.68	-1.83	0.75	9.26	3.97	2	W93 792
		Beachface (N)	1.20	0.50	0.22	1.00	4.52	0.18		W93 793
		Swash	0.33	1.02	-0.17	1.00	2.27	9.84	8	W93 794
M13	V15 389623	Backberm	1.33	0.57	0.78	1.50	5.72	0.00		W93 795
		Beachface (N)	1.22	0.45	0.21	1.25	4.62	0.07		W93 796
M14	V15 385626	Backberm	1.12	0.58	-0.65	1.25	5.63	0.73		W93 797
		Beachface	1.25	0.41	0.80	1.25	3.40	0.00	2	W93 798
		Beachface (N)	1.32	0.36	0.98	1.25	3.81	0.00		W93 799
		Swash	-0.12	1.27	0.04	-1.50	2.24	24.98	7	W93 800
M15	V15 382627	Backberm	1.01	0.44	1.12	0.75	4.12	0.00		W93 801
		Beachface	1.21	0.55	0.90	0.75	4.44	0.00	2	W93 802
		Beachface (N)	1.27	0.35	0.35	1.25	2.17	0.00		W93 803
		Swash	0.49	1.13	-0.48	0.75, 1.75	2.26	11.23	8	W93 804
M16	V15 378629	Backberm	1.32	0.60	-0.07	1.25	5.75	0.80		W93 805
		Beachface	0.87	0.74	-0.90	1.25	5.52	3.57	2	W93 806
		Beachface (N)	1.26	0.36	0.71	1.25	6.00	0.04		W93 807
		Swash	0.41	0.91	-0.10	0.50	2.12	5.73	8	W93 808
K1	V15 373631	Backberm	1.07	0.75	0.27	1.50	5.05	1.28		W93 809
		Beachface	0.94	0.67	-1.80	1.25	9.31	4.18	2	W93 810
		Beachface (N)	1.08	0.33	0.90	1.00	2.80	0.00		W93 811
		Swash	0.30	1.00	-0.14	0.50	2.19	10.21	8	W93 812
K2	V15 370632	Backberm	1.07	0.75	-0.80	1.00	6.97	3.05		W93 813
		Beachface	1.03	0.61	0.24	0.75	7.23	0.97	2	W93 814

SAMPLE	Grid Reference	Location	Mean Grair Size (phi)	Sorting	Skewness	Mode	Kurtosis	Gravel %	Entropy Class	WT Number
		Beachface (N)	1.40	0.66	0.77	0.75	2.58	0.00		W93 815
		Swash	0.31	0.99	-0.14	0.75	2.11	10.53	8	W93 816
K3	V15 367634	Backberm	1.23	0.61	0.90	0.75	3.12	0.00		W93 817
K4	V15 364635	Backberm	1.00	0.53	1.36	1.25	7.64	0.00		W93 818
		Beachface	1.25	0.46	0.49	1.25	2.59	0.00	2	W93 819
		Swash	0.37	1.03	-0.48	1.00	2.50	12.65	8	W93 820
K5	V15 360637	Backberm	1.39	0.47	1.28	1.50	4.42	0.00		W93 821
		Beachface	1.33	0.55	0.86	1.50	4.99	0.00	2	W93 822
		Swash	-0.04	0.98	0.01	-0.50	2.33	17.21	8	W93 823
K6	V15 357638	Backberm	1.21	0.68	2.34	1.00	9.09	0.00		W93 824
		Beachface	0.98	0.51	0.00	1.00	4.50	0.83	2	W93 825
		Swash	0.65	0.79	-0.44	0.50	2.86	2.21	8	W93 826
K7	V15 354640	Backberm	1.12	0.51	1.52	1.00	9.66	0.24		W93 827
		Beachface	1.19	0.50	0.33	1.25	2.91	0.00	2	W93 828
		Beachface (N)	1.01	0.41	1.04	1.25	3.81	0.00		W93 829
		Swash	0.88	1.11	-0.83	1.25	2.42	8.61	7	W93 830
K8	V15 346643	Backberm	1.24	0.51	1.23	1.00	7.94	0.16		W93 831
		Beachface	1.15	0.59	0.39	1.00	4.42	0.00	2	W93 832
		Beachface (N)	0.67	0.63	0.24	0.50	3.12	0.09		W93 833
		Swash	0.59	0.98	-0.19	1.25	2.06	4.88	8	W93 834
K9	V15 342645	Backberm	1.10	0.75	0.94	0.75	6.68	0.95		W93 835
		Beachface (N)	1.39	0.39	0.78	1.50	3.01	0.00		W93 836
		Swash	0.53	0.98	-0.33	1.00	2.81	7.18	8	W93 837
K10	V15 336648	Backberm	1.12	0.73	0.30	1.00	9.22	2.18		W93 838
		Beachface	0.96	0.53	0.01	1.00	4.29	0.44	2	W93 839
		Swash	0.45	0.86	-0.66	0.50	3.28	6.57	8	W93 840
K11	V15 332650	Backberm	1.23	0.60	1.84	1.50	7.12	0.00		W93 841
		Beachface	1.27	0.46	0.31	1.50	3.60	0.00	2	W93 842
		Swash	0.57	0.88	-0.65	1.00	3.30	6.20	8	W93 843
K12	V15 329652	Backberm	1.30	0.51	2.11	1.25	9.73	0.06		W93 844
		Beachface	1.24	0.57	-1.27	1.00	11.23	1.52	2	W93 845
		Beachface (N)	1.01	0.40	0.63	1.00	4.25	0.03		W93 846
		Swash	0.52	0.96	-0.31	1.25	2.52	5.76	8	W93 847
K13	V15 325654	Backberm	1.07	0.68	-0.29	1.25	5.80	1.30		W93 848
		Beachface (N)	1.48	0.54	0.98	1.25	3.42	0.00		W93 849
K14	V15 321656	Backberm	1.18	0.65	1.40	0.75	5.14	0.00		W93 850
		Beachface	0.98	0.67	-1.13	1.25	6.92	2.14	2	W93 851
		Swash	0.08	1.13	-0.30	0.50	2.36	18.84	8	W93 852
K15	V15 317658	Backberm	1.19	0.47	2.45	1.25	13.17	0.00		W93 853
		Beachface	0.94	0.61	-0.33	1.00	5.39	0.61	2	W93 854
		Beachface (N)	1.15	0.44	1.35	1.50	5.60	0.00		W93 855
		Swash	0.39	1.11	-1.18	0.75	4.03	12.87	8	W93 856
O1	V15 311661	Backberm	1.02	0.64	0.22	0.50	4.65	1.56		W93 857
O2	V15 304666	Backberm	1.25	0.57	1.40	1.50	5.76	0.00		W93 858
		Beachface (N)	1.07	0.51	0.64	1.00	3.52	0.00		W93 859
O3	V15 299668	Backberm	1.32	0.50	2.34	1.25	9.60	0.00		W93 860
		Beachface	1.38	0.48	0.30	1.25	2.75	0.00	2	W93 861
		Beachface (N)	1.07	0.67	0.73	1.25	2.92	0.00		W93 862
		Swash	0.52	1.01	-0.65	0.50	2.86	9.65	8	W93 863
O4	V15 295671	Backberm	1.04	0.62	-0.48	1.25	8.86	1.64		W93 864
O5	V15 290673	Backberm	1.24	0.60	1.83	1.25	7.77	0.00		W93 865
O6	V15 286676	Backberm	1.19	0.46	1.30	1.00	4.40	0.00		W93 866
		Beachface	1.12	0.58	-0.67	1.00	8.43	1.17	2	W93 867
		Swash	-0.08	1.23	-0.46	0.75	2.75	22.25	8	W93 868
O7	V15 280680	Backberm	0.87	0.55	0.47	1.00	4.79	0.00		W93 869

SAMPLE	Grid Reference	Location	Mean Grair Size (phi)	Sorting	Skewness	Mode	Kurtosis	Gravel %	Entropy Class	WT Number
		Beachface	1.33	0.63	0.98	1.50	5.92	0.00	2	W93 870
		Beachface (N)	1.04	0.71	0.59	1.50	3.52	0.69		W93 871
		Swash	0.22	1.18	-0.37	0.75	2.06	20.31	7	W93 872
O8	V15 273684	Backberm	1.01	0.50	1.76	0.75	6.51	0.00		W93 873
		Beachface	1.40	0.54	0.38	1.25	2.86	0.00	2	W93 874
		Beachface (N)	0.87	0.54	-0.29	1.00	3.98	0.16		W93 875
		Swash	0.18	1.48	-0.29	1.50	1.72	29.40	7	W93 876
O9	V15 269687	Backberm	1.36	0.47	1.22	1.50	8.96	0.16		W93 877
O10	V15 267689	Backberm	1.37	0.71	-1.12	1.25	8.32	2.19		W93 878
		Beachface	1.51	0.62	0.43	1.50	5.04	0.08	1	W93 879
		Swash	-0.97	1.12	0.85	-1.25	4.13	62.28	7	W93 880
O11	V15 261692	Backberm	1.38	0.43	1.89	1.25	7.97	6.53		W93 881
		Beachface	1.59	0.47	0.16	1.50	2.68	0.00	1	W93 882
		Beachface (N)	1.30	0.48	1.21	1.00	5.43	0.06		W93 883
		Swash	0.28	1.28	-0.08	1.50	1.67	21.82	7	W93 884
O12	V15 257695	Backberm	1.06	0.60	0.29	1.00	7.14	0.68		W93 885
		Beachface	1.43	0.43	0.40	1.50	4.32	0.00	1	W93 886
		Beachface (N)	1.35	0.46	0.06	1.50	4.63	0.07		W93 887
		Swash	-0.90	1.58	0.71	-1.75	2.32	65.83	7	W93 888
O13	V15 252699	Backberm	1.79	0.47	1.29	1.50	3.59	0.00		W93 889
O14	V15 249701	Backberm	1.32	0.48	0.69	1.50	4.09	0.00		W93 890

Note: beachface samples are from April unless denoted by an N for November.

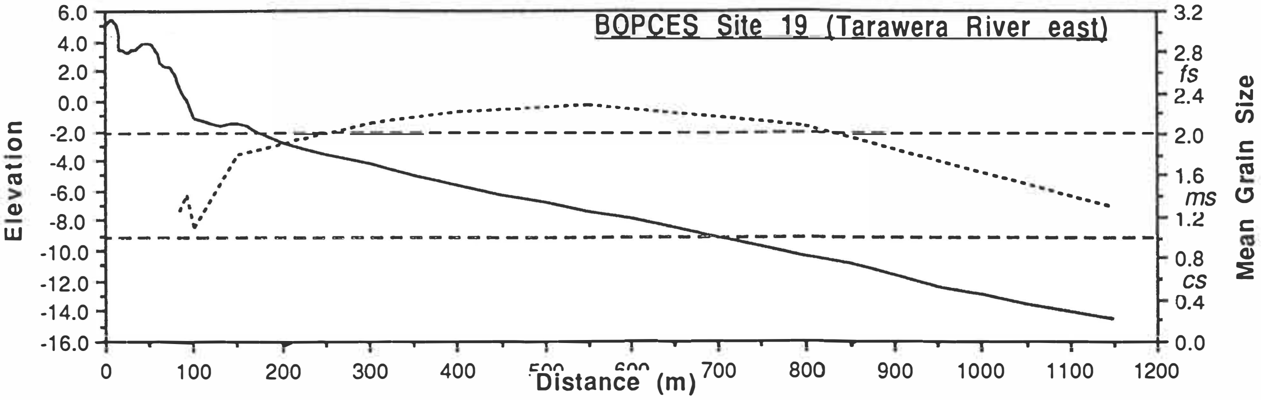
RIVER SAMPLES

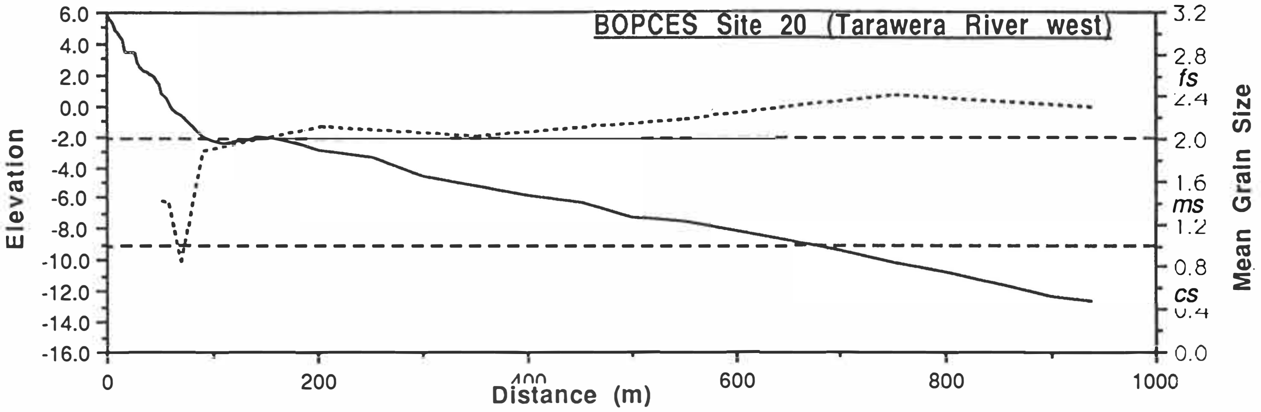
SAMPLE	Grid Reference	Location	Mean Grair Size (phi)	Sorting	Skewness	Mode	Kurtosis	Gravel %	WT Number
TARA 1	V15 431604	River (dredge)	-0.68	1.64	-0.31	0.75	2.02	47.99	W93 891
TARA 2	V15 412557	River (dredge)	-0.37	1.83	-0.43	1.25	1.82	43.80	W93 892
AWAK 1	V15 394573	River (hand)	-0.30	1.68	-0.40	0.75	1.95	37.64	W93 893
OHIN 1	V15 375624	River (hand)	0.80	0.98	-1.00	1.00	4.88	8.38	W93 894
MIMI 1	V15 350623	River (hand)	0.52	1.08	-1.34	1.00	4.90	12.63	W93 895
MIMI 2	V15 352639	River (hand)	0.81	0.90	-1.20	1.25	4.96	8.56	W93 896
HERE 1	V15 343642	River (hand)	0.92	1.28	-0.99	1.25	3.84	14.51	W93 897
PIKO 1	V15 324651	River (hand)	-1.91	2.39	0.36	-4.25	1.44	62.58	W93 898
PIKO 2	V15 297587	River (hand)	-2.54	2.13	1.11	-4.00	2.98	80.74	W93 899
HAUO 1	V15 299666	River (hand)	0.17	1.72	-1.03	1.25	3.08	26.15	W93 900
WAIT 1	V15 266679	River (dredge)	1.09	0.87	-2.40	1.50	9.96	6.52	W93 901
WAIT 2	V15 240650	River (dredge)	-0.49	1.67	-0.98	0.50	2.96	29.00	W93 902
PONG 1	V14 194702	River (dredge)	0.67	0.66	1.61	0.75	8.64	4.38	W93 903
KAIK 1	V14 142708	River (dredge)	0.30	1.85	-0.87	1.00	2.37	26.78	W93 904

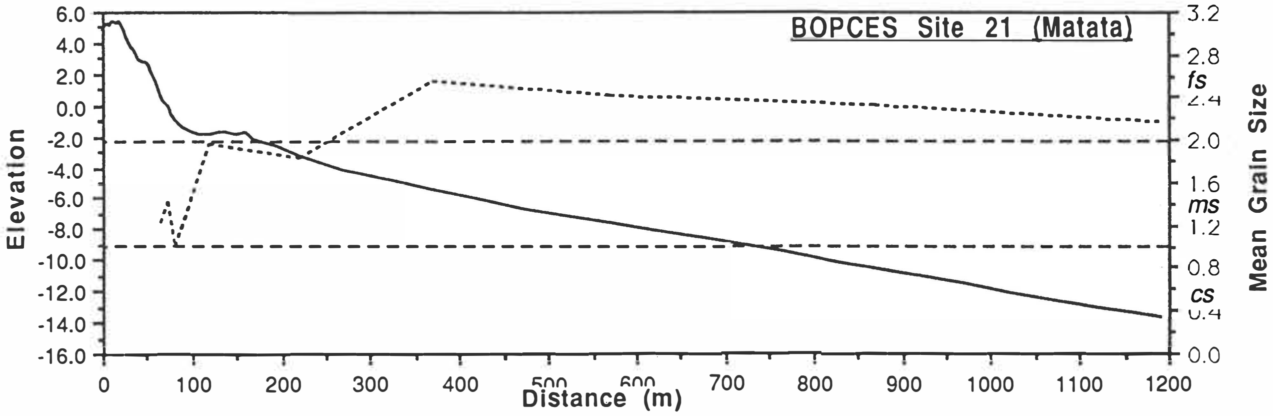
Entropy Class	Mean Grain Siz	Sorting	Skewness	dal Grain Size
1	1.56	0.62	-0.26	1.52
2	1.16	0.60	0.01	1.06
3	2.41	0.59	-0.40	0.01
4	2.02	0.55	-0.31	0.56
5	2.11	0.73	-0.09	-0.02
6	0.51	0.65	0.74	0.18
7	0.32	1.31	-0.29	0.63
8	0.38	1.00	-0.39	0.66

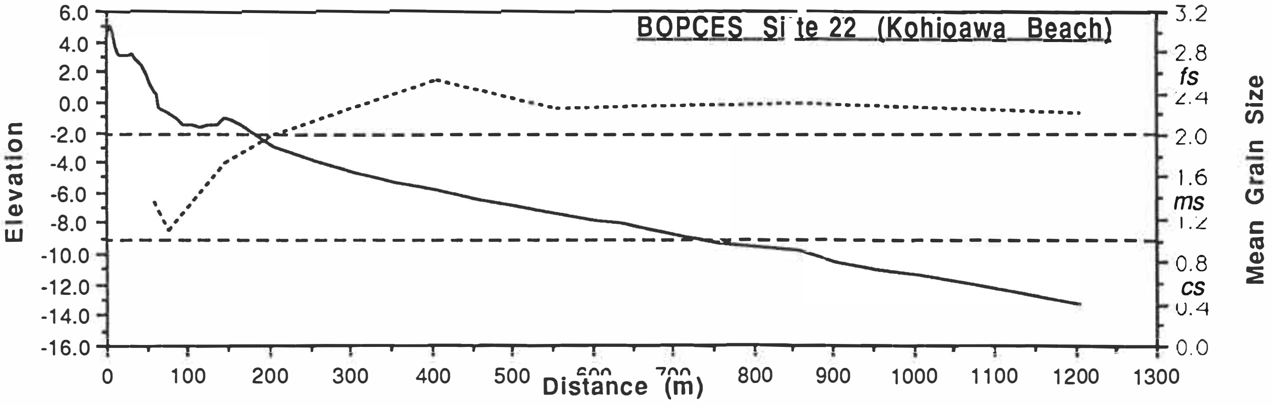
NEARSHORE SAMPLES										
SAMPLE	Grid Reference	Archive Numbe	ean Grain S	Mode	Sorting	Skewness	ewness(F&	Kurtosis	Gravel %	Entropy Class
e 19 HWM	V15 440609	W92 1644	1.24	1.25	0.50	-0.15	0.11	4.62	0.11	
MWM		W92 1645	1.40	1.50	0.56	-0.32	0.04	4.38	0.10	
LWM		W92 1646	1.09	1.75	0.70	-0.12	0.05	3.03	0.11	
2		W92 1647	1.80	1.50	0.52	0.60	0.19	2.59	0.00	1
3		W92 1648	2.10	2.25	0.59	-0.44	-0.05	3.62	0.00	4
4		W92 1649	2.22	2.50	0.67	-0.48	0.02	5.55	0.25	3
5		W92 1650	2.28	2.25	0.62	0.27	0.11	2.76	0.00	3
6		W92 1651	2.08	1.75	0.63	0.38	0.09	2.54	0.00	5
7		W92 1652	1.30	1.50	0.46	0.22	0.05	4.45	0.00	2
e 20 HWM	V15 418613	W92 1653	1.41	1.25, 2.00	0.54	-0.15	0.03	3.57	0.04	
MWM		W92 1654	1.39	1.50	0.57	-0.03	0.01	3.09	0.00	
LWM		W92 1655	0.84	0.75	0.87	0.05	0.01	2.40	0.85	
2		W92 1656	1.89	2.00	0.50	-0.03	0.06	3.44	0.00	4
3		W92 1657	2.11	2.25	0.61	-0.20	0.01	3.63	0.04	4
4		W92 1658	2.02	2.25	0.64	-0.30	0.03	4.42	0.18	4
5		W92 1659	2.19	2.25	0.59	0.02	0.05	3.24	0.00	3
6		W92 1660	2.42	2.75	0.63	-0.43	-0.04	4.26	0.05	3
7		W92 1661	2.30	2.75	0.69	-0.60	-0.05	5.31	0.27	3
e 21 HWM	V15 400619	W92 1662	1.21	1.50	0.61	-1.06	-0.15	6.09	0.81	
MWM		W92 1663	1.43	1.25, 2.00	0.53	-0.55	-0.11	3.63	0.00	
LWM		W92 1664	0.99	1.25	0.79	-0.42	-0.23	2.78	0.82	
2		W92 1665	1.96	2.25	0.53	0.01	0.04	4.10	0.06	4
3		W92 1666	1.82	1.50, 2.00	0.68	0.04	0.02	2.76	0.05	5
4		W92 1667	2.54	2.75	0.57	-0.41	0.01	6.00	0.13	3
5		W92 1668	2.41	2.50	0.59	-0.25	0.04	3.81	0.00	3
6		W92 1669	2.32	2.25, 2.75	0.58	-0.38	0.03	5.73	0.13	3
7		W92 1670	2.16	1.75, 2.75	0.49	0.10	0.01	3.38	0.00	4
e 22 HWM	V15 384626	W92 1671	1.36	1.50	0.50	-0.54	-0.06	4.62	0.03	
MWM		W92 1672	1.26	1.75	0.63	-0.90	-0.19	4.27	0.47	
LWM		W92 1673	1.08	0.5, 1.25	0.82	-0.32	-0.22	2.56	0.26	
2		W92 1674	1.72	1.75	0.48	0.55	0.20	3.85	0.00	1
3		W92 1675	2.01	1.75	0.60	-0.07	0.22	4.38	0.08	4
4		W92 1676	2.54	2.75	0.57	-0.19	-0.01	4.07	0.04	3
5		W92 1677	2.25	1.75	0.67	0.10	-0.02	2.25	0.00	5
6		W92 1678	2.31	3.00	0.58	0.01	-0.07	2.75	0.00	3
7		W92 1679	2.21	2.25	0.59	-0.79	0.02	7.66	0.27	3
e 23 HWM	V15 329651	W92 1680	1.25	1.50	0.47	-0.29	0.01	5.06	0.11	
MWM		W92 1681	1.36	1.00	0.41	0.63	0.24	3.81	0.02	
LWM		W92 1682	0.68	0.75	0.63	0.34	0.12	3.45	0.25	
2		W92 1683	1.68	1.75	0.50	0.00	0.15	4.09	0.02	1
3		W92 1684	1.15	0.50, 1.00	0.76	0.37	0.12	2.77	0.19	2
4		W92 1685	2.49	3.00	0.58	-0.98	0.02	9.10	0.24	3
5		W92 1686	2.44	2.25	0.54	-0.48	0.06	7.53	0.15	3
6		W92 1687	2.47	3.00	0.57	-0.47	-0.06	4.03	0.00	3
7		W92 1688	2.49	2.75	0.52	-0.50	0.02	6.53	0.06	3
e 24 HWM	V15 280680	W92 1689	1.46	1.75	0.48	-0.18	0.00	3.92	0.00	
MWM		W92 1690	1.41	1.50	0.51	-0.81	-0.03	5.98	0.19	
LWM		W92 1691	0.97	_0.25, 1.50	0.96	-0.44	-0.30	2.35	2.84	
2		W92 1692	1.52	1.50	0.60	-0.03	0.11	3.86	0.11	1
3		W92 1693	2.02	2.00	0.61	-0.10	0.05	3.71	0.03	4
4		W92 1694	2.20	2.00, 3.00	0.83	-0.47	-0.12	3.09	0.03	5
5		W92 1695	2.45	2.50, 3.00	0.57	-0.35	0.02	5.53	0.09	3
6		W92 1696	2.32	2.00	0.60	-0.23	0.00	4.27	0.08	3
7		W92 1697	0.75	0.75	0.59	0.82	0.22	5.06	0.23	6
e 25 HWM	V14 247703	W92 1698	1.52	0.25, 1.75	0.62	-1.01	-0.17	4.93	0.13	

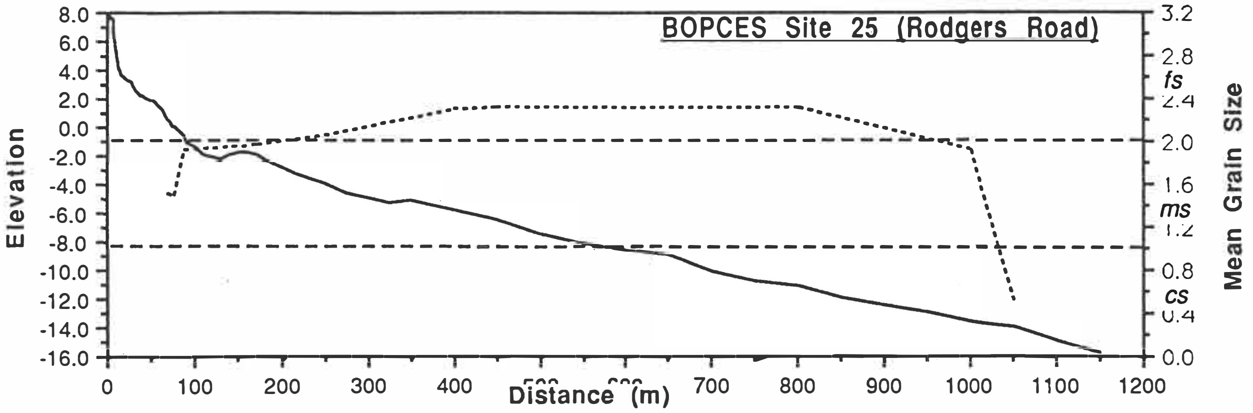
MWM		W92 1699	1.48	0.25, 1.50	0.66	-0.83	-0.08	4.52	0.41	
LWM		W92 1700	1.92	2.00	0.44	-0.61	0.08	8.36	0.10	
2		W92 1701	1.95	1.75	0.53	-0.39	0.10	5.32	0.08	4
3		W92 1702	2.05	2.50	0.71	-0.38	-0.06	4.03	0.19	5
4		W92 1703	2.28	2.75	0.66	-0.15	-0.05	3.09	0.00	3
5		W92 1704	2.30	2.50	0.66	-0.50	0.03	5.72	0.23	3
6		W92 1705	2.31	2.00, 2.75	0.64	-0.02	-0.01	2.86	0.04	5
7		W92 1706	0.52	0.25	0.54	1.07	0.18	5.65	0.20	6
e 26 HWM	V14 214728	W92 1707	1.40	1.75	0.77	-0.51	-0.21	3.01	0.31	
MWM		W92 1708	1.60	0.25, 2.25	0.80	-0.95	-0.42	3.28	0.01	
LWM		W92 1709	1.96	1.75	0.52	-1.20	0.02	8.84	0.15	
2		W92 1710	2.08	2.25	0.52	-0.68	0.08	7.36	0.13	4
3		W92 1711	2.21	2.00, 2.50	0.74	-0.25	-0.01	3.44	0.15	5
4		W92 1712	2.50	2.50, 3.00	0.54	-0.91	0.05	10.80	0.26	3
5		W92 1713	2.60	3.00	0.54	-0.64	-0.10	6.46	0.08	3
6		W92 1714	2.49	3.00	0.61	-0.36	-0.18	3.02	0.00	3
7		W92 1715	0.57	0.25	0.61	0.63	0.21	4.24	0.16	6
e 27 HWM	V14 204736	W92 1716	1.82	1.75	0.44	-0.79	0.07	7.16	0.05	
MWM		W92 1717	1.80	1.75	0.45	0.30	0.10	3.45	0.00	
LWM		W92 1718	1.25	0.75, 1.75	0.90	-0.24	-0.16	2.38	0.31	
2		W92 1719	2.00	2.25	0.56	-1.16	0.00	7.70	0.09	4
3		W92 1720	2.36	2.75	0.57	-0.01	0.06	3.77	0.00	3
4		W92 1721	2.57	3.00	0.60	-0.37	0.01	5.17	0.11	3
5		W92 1722	2.49	3.00	0.61	-0.71	0.00	5.79	0.10	3
6		W92 1723	2.40	3.00	0.63	-0.26	-0.06	3.18	0.00	3
7		W92 1724	0.56	0.25	0.59	0.67	0.18	4.28	0.11	6
8		W93 905	0.51	0.50	0.62	0.63	0.24	3.45	0.26	6
e 28 HWM	V14 183754	W92 1725	1.93	2.25	0.39	-0.23	0.04	7.35	0.05	
MWM		W92 1726	2.01	2.50	0.43	-0.99	0.02	13.65	0.22	
LWM		W92 1727	1.98	2.00	0.40	-1.38	0.11	17.37	0.23	
2		W92 1728	2.03	2.50	0.52	-0.39	-0.03	4.28	0.00	4
3		W92 1729	2.17	2.00	0.61	-0.32	0.07	5.11	0.13	4
4		W92 1730	2.40	2.75	0.61	-0.51	0.02	6.06	0.17	3
5		W92 1731	2.32	3.00	0.72	-0.30	-0.13	2.69	0.00	5
6		W92 1732	2.39	2.25	0.59	-0.38	0.06	5.25	0.11	3
7		W92 1733	1.13	1.00	0.48	1.14	0.33	4.44	0.00	2
e 29 HWM	V14 174762	W92 1734	1.67	1.75	0.57	-0.61	0.01	4.82	0.14	
MWM		W92 1735	1.80	2.25	0.48	-0.76	-0.08	7.31	0.17	
LWM		W92 1736	1.10	0.50	0.88	-0.12	0.05	2.01	0.13	
2		W92 1737	1.86	2.00	0.63	-1.16	-0.07	6.34	0.22	4
3		W92 1738	2.19	2.00	0.54	0.09	0.05	3.24	0.00	4
4		W92 1739	2.35	2.25	0.58	-0.11	0.11	5.13	0.09	3
5		W92 1740	2.49	2.75	0.55	-0.46	0.06	6.22	0.11	3
6		W92 1741	2.64	3.00	0.50	-0.70	0.04	10.35	0.16	3
7		W92 1742	1.53	1.50	0.41	1.05	0.30	4.20	0.00	1
8		W93 906	1.78	1.25, 2.25	0.94	0.06	0.06	2.17	0.00	5
e 30 HWM	V14 165774	W92 1743	2.00	2.00	0.34	0.26	0.13	4.39	0.00	
MWM		W92 1744	1.89	2.25	0.53	-0.92	-0.08	5.76	0.00	
LWM		W92 1745	1.94	2.00	0.46	-0.68	-0.06	5.97	0.05	
2		W92 1746	1.77	2.25	0.68	-0.97	-0.21	4.68	0.12	4
3		W92 1747	2.17	2.50	0.57	-0.58	-0.08	4.44	0.00	4
4		W92 1748	0.44	0.25	0.70	1.13	0.27	5.47	0.61	6
5		W92 1749	0.78	1.00	0.80	0.36	0.09	3.23	0.84	6
6		W92 1750	0.06	0.25	0.69	1.03	0.12	5.53	2.26	6
7		W92 1751	0.42	0.25	0.68	0.31	0.12	3.10	0.73	6
Archive numbers for nearshore samples are as given in Dommerholt (in prep. 1993)										

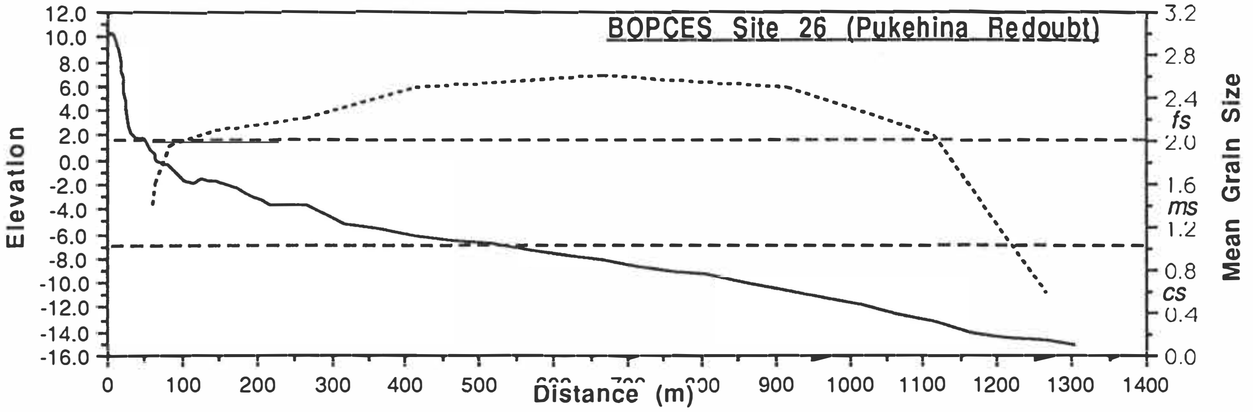

BOPCES Site 19 (Tarawera River east)
Elevation
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Distance (m)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Mean Grain Size
3.2
2.8
fs
2.4
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0

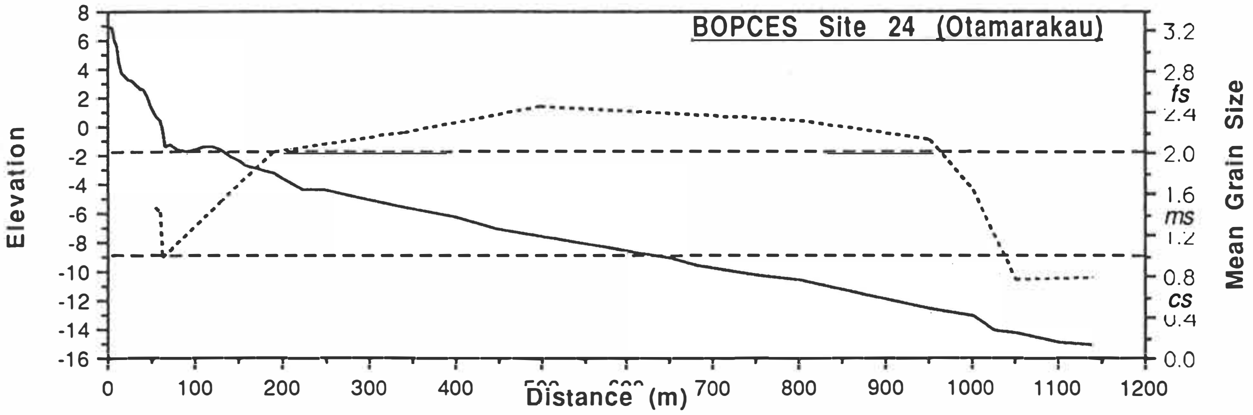

BOPCES Site 20 (Tarawera River west)
Elevation
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Distance (m)
0
200
400
600
800
1000
Mean Grain Size
3.2
2.8
fs
2.4
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0

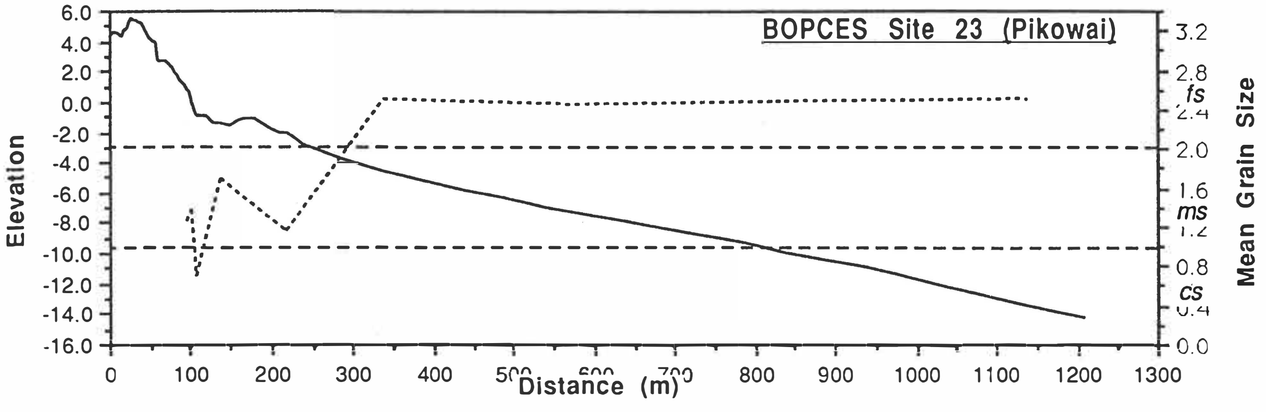

BOPCES Site 21 (Matata)
Elevation
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Distance (m)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Mean Grain Size
3.2
2.8
fs
2.4
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0


BOPCES Site 22 (Kohioawa Beach)
Elevation
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Distance (m)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
Mean Grain Size
3.2
2.8
fs
2.4
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0


BOPCES Site 25 (Rodgers Road)
Elevation
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Distance (m)
0
100
200
300
400
700
800
900
1000
1100
1200
Mean Grain Size
3.2
2.8
fs
2.4
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0


BOPCES Site 26 (Pukehina Redoubt)
Elevation
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Distance (m)
0
100
200
300
400
500
900
1000
1100
1200
1300
1400
Mean Grain Size
3.2
2.8
2.4
fs
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0


BOPCES Site 24 (Otamarakau)
Elevation
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
Distance (m)
0
100
200
300
400
700
800
900
1000
1100
1200
Mean Grain Size
3.2
2.8
fs
2.4
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0


BOPCES Site 23 (Pikowai)
Elevation
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Distance (m)
0
100
200
300
400
800
900
1000
1100
1200
1300
Mean Grain Size
3.2
2.8
fs
2.4
2.0
1.6
ms
1.2
0.8
cs
0.4
0.0

Appendix V: Entropy Program

The *Entropy* program used on the University of Waikato's VAX system and contained in the Earth Sciences Research library of programmes requires a data set of sediment textural data, mineralogical information or combinations that may include carbonate %'s, angularity of grains, FeO staining etc. Such a data set for textural information for example, should be entered sequentially row by row from -3.0 ϕ or -2.0 ϕ depending on the size range of samples to 4.0 ϕ for normal sandy type sediments. The first column is used for the sample number although no alphabetical values can be used. This column is disregarded later when running the programme. An example of the use of the programme is given below.

```
*** ENTROPY PROGRAM VER.2     COWELL 30/8/87

NB:1        Data file must -
           (1) contain numerical data only
           (2) contain values for ALL elements
NB:2        Data can be FREEFIELD: 1 row of variables per observation (case). Rows end
with a carriage return and each row must have the same number of variables. The MAXIMUM
No. of variables permitted is 250.

Enter FILENAME for INPUT of your DATA:
Sediment.dat
Enter FILENAME for OUTPUT of RESULTS:
Sediment.out
Enter RUN IDENTIFIER:
1
Enter No. of OBSERVATIONS to analyse:
238         (the maximum being 250)
Enter TOTAL No. of VARIABLES in data set:
30
Enter No. of variables to analyse:
29          (discounting the first column)
Are these variables consecutive (Y/N)?
Y           (although not in the case of mineralogical data)
Enter COLUMN No. for 1st variable
2           (as the first column is sample numbers)
NB: ENTROPY cannot handle data values of zero!
Enter VALUE to SUBSTITUTE for ZEROS:
0.001       (this creates one of the major problems, since a value of zero (0 or 0.0 etc...)
            cannot be logged by the ENTROPY equation and hence it is necessary to enter a
            very small value, which has negligible effect)
NORMALISE variables for each case (Y/N)?
Y
MAXIMUM No. of GROUPS to be extracted:
10          (an optimum number from other studies is 7 to 10 depending on the size and
nature               of the data set)
MINIMUM No. of GROUPS to be extracted:
2
OUTPUT results for INTERMEDIATE GROUPS (Y/N)?
N
```

The *Entropy* program then outputs all data observations from the data file, followed by all data observations for the variables being analysed. This helps in checking that the number of variables for each observation is the same. Then follows output of the means for all data and separation of data observations into groups or classes.

Appendix 6A: LIGHT MINERALOGY

Sample No.	Environment	Quartz	Plag. Feld.	K-Feld.	Glass	Lithics (P)	Lithics (RF)	Heavy Mins.
TP1	Beach	6.4	19.7	0.4	45.6	21.6	3.3	2.6
P2	Beach	6.6	28.6	0	49	13.3	1.1	1.4
P6	Beach	3.8	28.5	0.6	39.9	20.4	4.5	2.2
P9	Beach	4.7	32.4	0.4	36.9	12.6	11.4	1.6
P11	Beach	14.6	42.6	1.3	22.8	4	10.7	4
P14	Beach	11.9	34.5	0.6	25.4	12.3	14.1	1.2
P18	Beach	5.8	36.6	0.6	26.3	10.1	14.2	6.4
O10	Beach	12.8	44.5	0.3	21	8.5	9.5	3.4
O7	Beach	20.9	42.2	0	14.6	7.2	6.5	8.6
O2	Beach	23.9	23.5	1.4	21.9	7.5	10.2	11.6
K12	Beach	22.2	42.5	0.4	11.5	7.2	9.6	6.6
K8	Beach	11.2	48.3	0.6	16.7	8.1	10.8	4.3
K7	Beach	13.6	28.2	0.8	37.2	9.8	7.1	3.2
K2	Beach	22.6	32.8	0.7	21.9	14	7.7	0.3
M12	Beach	17	37.8	1.6	15.3	14.7	6	7.6
M8	Beach	24.7	44	2.3	12.5	12	3.5	1
M2	Beach	17	43.1	2	16	13.3	3	5.6
PONG	Stream	10.8	43.8	0.3	17.8	14.6	11.5	1.2
WAIT	Stream	17.6	42.9	0	14.9	5.3	12.3	7
PIKO	Stream	15.8	29.2	0.6	21.4	10.7	11.7	10.6
HERE	Stream	6.4	11.9	0	17.1	55	9.6	0
MIMI	Stream	7.1	29.8	0.3	14.6	25.9	19.8	2.5
OHIN	Stream	12.1	37.9	1	20.9	15.3	8.2	4.6
TARA	River	4.9	19.6	1.6	17.3	41.3	13.3	2
30/7	Offshore	21.1	24.5	1.2	5.3	10.7	36.5	1.3
28/7	Offshore	18.4	46.4	2.4	8.8	3.2	3.2	17.6
26/7	Offshore	21.3	38.9	2.2	12.3	8.3	12.4	4.5
24/7	Offshore	19.9	43.9	0.8	6.6	8.2	13.2	7.4
23/7	Offshore	5.4	34.3	1.3	34.3	6.8	15.2	2.7
22/7	Offshore	11.1	27.3	2.6	21.6	7.5	15	14.9
20/7	Offshore	5	26.4	0.6	36.5	8.9	9.7	13

Note: all values are expressed as percentages

Appendix 6B: HEAVY MINERALOGY

Sample No.	Environment	Hyp	Aug	Cgt	Aeg	G. Hbl	B Hbl	Bio	Olv	Apt	Zir	Opaques
TP1	*Beach*	18	2.6	23.3	0	18.6	0.6	15	1.3	0.3	1.6	18.6
P2	*Beach*	18.3	5.6	32	0	20	1	12.3	0	0	0	10.6
P6	*Beach*	26	7.3	19.6	0	17	0.6	9.6	0	0	0.3	19.3
P9	*Beach*	31.3	4.6	20.3	0	16.3	0.6	8	0	0.3	1.3	17
P11	*Beach*	47	10.3	13	0	17.6	0	4	0	0	0.6	7.3
P14	*Beach*	32	4	28.6	0	16	1.6	9	0	0	0	8.6
P18	*Beach*	23.3	5.3	16.6	0	19.3	1.3	9.3	0	0	0	24.6
O2	*Beach*	30.6	6.6	10	0	13	0	1	0.6	0	1.6	36.3
O7	*Beach*	60.6	7.6	6	0	8.6	0	2	0	0	0	15
O10	*Beach*	44.3	8.3	12.3	0	18	0.3	1	0	0	0	15.6
K2	*Beach*	61.6	6	9	0	15	0.3	0	0	0	0	8
K7	*Beach*	26	3.6	22	0	16.6	0.3	0.6	0	0	0	30.6
K8	*Beach*	51	13.6	11.6	0	13	0	0.6	0.6	0	1	8.3
K12	*Beach*	36	10.3	6.3	0	13	0	1	0	0	0	33.3
M2	*Beach*	37	5	6	0	12.3	3.6	0	0	0	0.6	35.3
M8	*Beach*	50.3	3	10.6	0	22.3	0	3.8	0	0	0	10
M12	*Beach*	22.6	9.6	12	0	20.3	0	3	0	0	0	32.3
Site 30/7	*Offshore*	59.6	12.3	2.6	3.3	4	0	0.3	0	0	0	17.6
Site 28/3	*Nearshore*	22.3	4	18.3	0.3	13	0.3	3.3	0	0	0	38.3
Site 28/7	*Offshore*	52	19.3	7.3	0	9.6	1	2	0	0	0	8.6
Site 26/7	*Offshore*	70.6	1	2	0.3	13.6	0	0	0	0	0	12.6
Site 24/7	*Offshore*	58.3	6	11.3	0.6	8	0	1	0	0	0	14.6
Site 23/7	*Offshore*	20.3	10.6	13.6	0.3	18	1	0	0	0	2.3	33.6
Site 22/7	*Offshore*	23.6	6.6	4.6	0	24	0.3	0	0	0	1.3	39.3
Site 20/7	*Offshore*	28.9	6.6	13.6	0	18	0.6	0	0	0	1	31
KAIT 2	*River*	16.6	3	6.9	0	2.3	0	3	0	0	0.6	67.6
KAIK 1	*Stream*	34	4.6	21.6	0.3	5.3	0.6	8	0	0	0	25.6
PONG 1	*Stream*	43	10	17	0	9	0	0.6	0	0	0	20.3
WAIT 2	*Stream*	63.6	3	6	0	4	0	2	0.3	0	0	21
HAUO 1	*Stream*	36	7	14.3	0	10.6	0	4.3	0.3	0	0.6	27
PIKO 2	*Stream*	30	1.6	3	0	3.3	0.3	1	0	0	0	60.6
HERE 2	*Stream*	23.6	6	27	0	18.6	0.6	2.3	0	0	0	21.6
MIMI 1	*Stream*	43	15	18.6	0	7.3	0	0	0	0	0	16
OHIN 1	*Stream*	49.6	5.6	14.6	0	10.6	0.6	0	0	0	0	19
TARA 2	*River*	71.3	2	8	0	2.6	0	1	0	0	0	15

Hyp= hypersthene, Aug= augite, Cgt= cummingtonite, Aeg= aegerine, G Hbl= green hornblende

B Hbl= brown hornblende, Bio= biotite, Olv= olivine, Apt= apatite, Zir= zircon.

SEDIMENT COMPOSITION

Sample No.	% CaCO3	% Light	% Heavy
TP1	3.17	96.37	0.46
P2	3.45	96.25	0.30
P6	3.57	96.10	0.33
P9	3.84	95.66	0.50
P11	3.16	95.90	0.94
P14	3.58	95.94	0.48
P18	4.01	93.81	2.18
O2	2.30	92.11	5.59
O7	2.56	94.35	3.09
O10	5.12	93.17	1.71
K2	1.32	98.51	0.17
K7	1.30	95.87	2.83
K8	1.72	96.28	2.00
K12	1.42	94.80	3.78
M12	1.99	96.41	1.60
M8	1.59	97.71	0.70
M2	1.73	92.93	5.34
Site 30/7	8.27	90.52	1.21
Site 28/3	5.53	93.06	1.41
Site 28/7	2.10	91.78	6.12
Site 26/7	9.43	87.08	3.49
Site 24/7	2.83	95.20	1.97
Site 23/7	5.47	91.93	2.60
Site 22/7	6.96	87.09	5.95
Site 20/7	8.77	85.45	5.78
KAIT	0	90.19	9.81
KAIK	0	97.67	2.33
PONG	0	98.49	1.51
WAIT	0	95.08	4.92
HAUO	0	95.48	4.52
PIKO	0	89.36	10.64
HERE	0	99.98	0.02
MIMI	0	98.25	1.75
OHIN	0	96.46	3.54
TARA	0	98.35	1.65

Beaufort Number	Descriptive Term	Specifications		Equivalent Mean Velocity Ranges*	
		Land	Sea	Knots	Metres/sec
0	Calm	Calm; smoke rises vertically.	Sea like a mirror.	<1	0 - 0.2
1	Light air	Direction of wind shown by smoke drift but not by windvanes.	Ripples with the appearance of scales are formed, but without foam crests.	1- 3	0.3- 1.5
2	Light breeze	Wind felt on face; leaves rustle; ordinary vanes moved by wind.	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break.	4- 6	1.6- 3.3
3	Gentle breeze	Leaves and small twigs in constant motion; wind extends light flag.	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses.	7-10	3.4- 5.4
4	Moderate breeze	Raises dust and loose paper; small branches are moved.	Small waves, becoming longer; fairly frequent white horses.	11-16	5.5- 7.9
5	Fresh breeze	Small trees in leaf begin to sway; crested wavelets form on inland waters.	Moderate waves, taking a more pronounced long form; many white horses are formed (change of some spray).	17-21	8.0-10.7
6	Strong breeze	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray).	22-27	10.8-13.8
7	Near gale	Whole trees in motion; inconvenience felt when walking against wind.	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.	28-33	13.9-17.1
8	Gale	Breaks twigs off trees; generally impedes progress.	Moderately high waves of greater length; edges of crests begin to break into the spindrift; the foam is blown in well-marked streaks along the direction of the wind.	34-40	17.2-20.7
9	Strong gale	Slight structural damage occurs (chimney pots and slates removed).	High waves; dense streaks of foam along the direction the wind; crests of waves begin to topple, tumble and roll over; spray may affect visibility.	41-47	20.8-24.4
10	Storm	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; on the whole, the surface of the sea takes a white appearance; the tumbling of the sea becomes heavy and shock-like; visibility affected.	48-55	24.5-28.4
11	Violent storm	Very rarely experienced; accompanied by widespread damage.	Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind the waves); the sea is completely covered with long white patches of foam lying along the direction of the wind; everywhere the edges of the wave crests are blown into froth; visibility affected.	56-63	28.5-32.6
12	Hurricane		The air is filled with foam and spray; sea completely white with driving spray; visibility very seriously affected.	64 & over	32.7 & over

Appendix VIII: Tidal Reduction of Current Data

A. Tidal constituent results in order of amplitude

```
=========================================================================
Latitude: 37  0.00S       Longitude: 176  0.00E          depth
Covering period : 15/ 7/1993 to 23/ 8/1993  nzst
=========================================================================

Constituent     Period          Frequency       Amplitude       phase
name            hours           cycles/h        metres          degrees
=========================================================================
       Z0       0.0000          0.0000          16.7725         0.00
       M2       12.4206         0.0805          0.7457          133.03
       N2       12.6583         0.0790          0.1349          100.50
       S2       12.0000         0.0833          0.1158          242.36
       K1       23.9345         0.0418          0.0668          174.76
       MSF      354.3671        0.0028          0.0309          233.00
       MM       661.3093        0.0015          0.0304          306.82
       L2       12.1916         0.0820          0.0208          185.50
       MU2      12.8718         0.0777          0.0186          347.75
       M3       8.2804          0.1208          0.0159          96.69
       EPS2     13.1273         0.0762          0.0143          37.15
       Q1       26.8684         0.0372          0.0132          345.33
       O1       25.8193         0.0387          0.0131          119.61
       UPS1     21.5782         0.0463          0.0127          86.44
       MK3      8.1771          0.1223          0.0125          37.50
       OO1      22.3061         0.0448          0.0112          246.41
       ETA2     11.7545         0.0851          0.0081          135.49
       3MK7     3.5296          0.2833          0.0075          353.80
       MO3      8.3863          0.1192          0.0071          116.77
       MS4      6.1033          0.1638          0.0067          221.56
       ALP1     29.0727         0.0344          0.0066          204.45
       2SM6     4.0457          0.2472          0.0064          91.86
       M8       3.1052          0.3220          0.0063          287.80
       SK3      7.9927          0.1251          0.0059          258.48
       MN4      6.2692          0.1595          0.0053          104.45
       M6       4.1402          0.2415          0.0049          68.07
       2SK5     4.7974          0.2084          0.0048          174.44
       2MS6     4.0924          0.2444          0.0042          259.32
       M4       6.2103          0.1610          0.0040          333.65
       2Q1      28.0062         0.0357          0.0040          122.45
       J1       23.0985         0.0433          0.0033          69.67
       NO1      24.8332         0.0403          0.0030          291.10
       SN4      6.1602          0.1623          0.0026          0.60
       2MN6     4.1663          0.2400          0.0022          213.98
       2MK5     4.9309          0.2028          0.0014          112.18
       S4       6.0000          0.1667          0.0005          77.01
=========================================================================
```

B. Tidal constituent results in order of amplitude

Latitude: 37 0.00S Longitude: 176 0.00E
Covering period : 15/ 7/1993 to 23/ 8/1993 nzst

U-velocity

Constituent name	Period hours	Frequency cycles/h	Amplitude metres	phase degrees
Z0	0.0000	0.0000	27.2716	0.00
MM	661.3093	0.0015	1.0627	109.09
O1	25.8193	0.0387	0.9465	341.29
K1	23.9345	0.0418	0.7404	106.83
MSF	354.3671	0.0028	0.3873	21.86
Q1	26.8684	0.0372	0.2698	345.57
2Q1	28.0062	0.0357	0.2396	216.98
M2	12.4206	0.0805	0.2322	297.90
UPS1	21.5782	0.0463	0.1956	83.95
M4	6.2103	0.1610	0.1840	157.24
MK3	8.1771	0.1223	0.1786	10.73
ALP1	29.0727	0.0344	0.1733	148.71
NO1	24.8332	0.0403	0.1704	291.93
M3	8.2804	0.1208	0.1438	106.73
J1	23.0985	0.0433	0.1350	98.06
OO1	22.3061	0.0448	0.1122	174.04
S4	6.0000	0.1667	0.1065	119.16
SN4	6.1602	0.1623	0.1023	17.43
MN4	6.2692	0.1595	0.1020	22.10
ETA2	11.7545	0.0851	0.1013	121.35
MU2	12.8718	0.0777	0.0935	206.31
MO3	8.3863	0.1192	0.0918	239.99
L2	12.1916	0.0820	0.0881	184.42
S2	12.0000	0.0833	0.0863	27.92
EPS2	13.1273	0.0762	0.0846	81.26
2MK5	4.9309	0.2028	0.0640	237.18
2MN6	4.1663	0.2400	0.0621	287.72
MS4	6.1033	0.1638	0.0588	189.13
3MK7	3.5296	0.2833	0.0532	338.42
N2	12.6583	0.0790	0.0426	240.20
M6	4.1402	0.2415	0.0360	322.96
2SM6	4.0457	0.2472	0.0311	347.72
2SK5	4.7974	0.2084	0.0308	36.78
M8	3.1052	0.3220	0.0294	180.66
SK3	7.9927	0.1251	0.0212	283.38
2MS6	4.0924	0.2444	0.0166	133.26

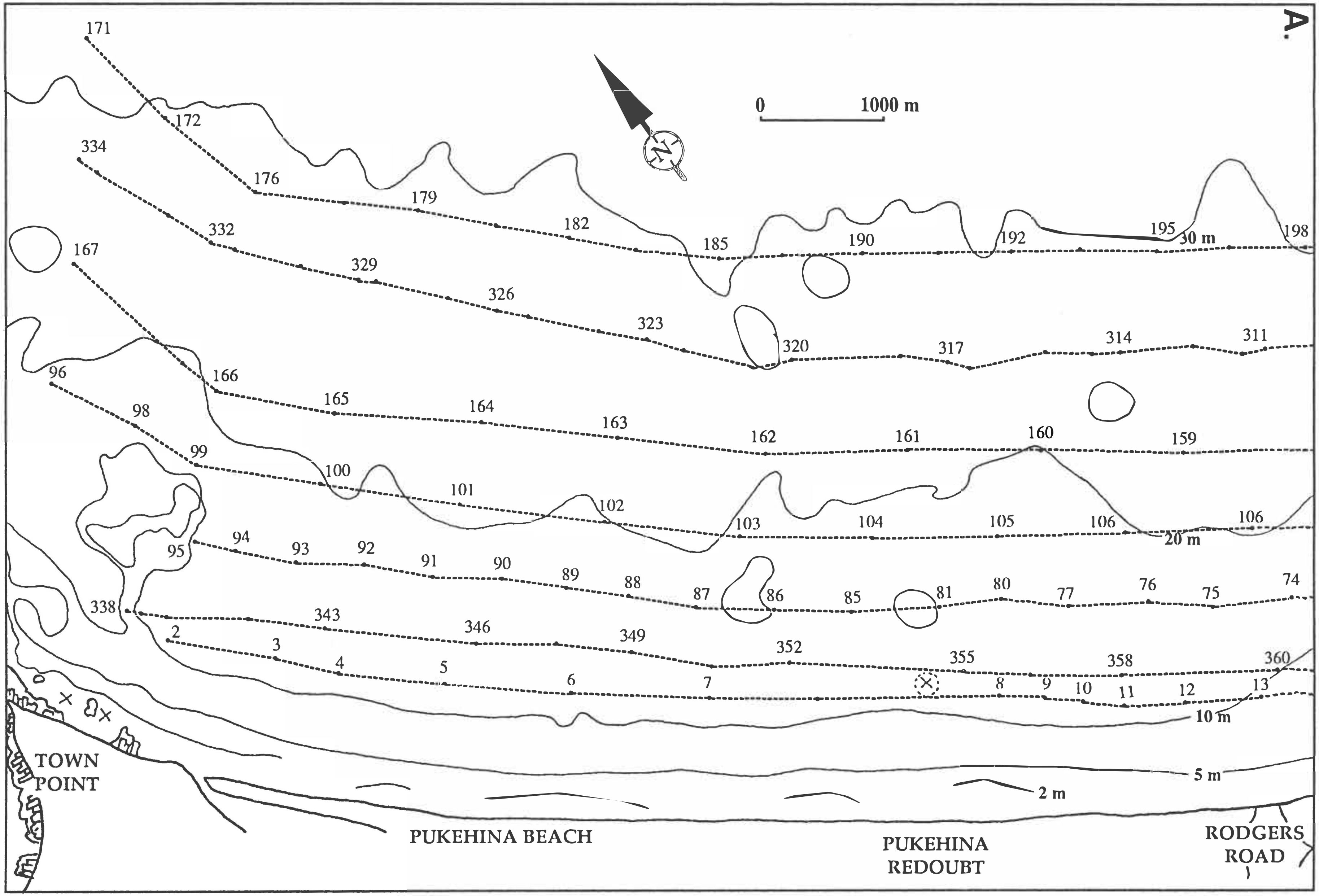
C. Tidal constituent results in order of amplitude

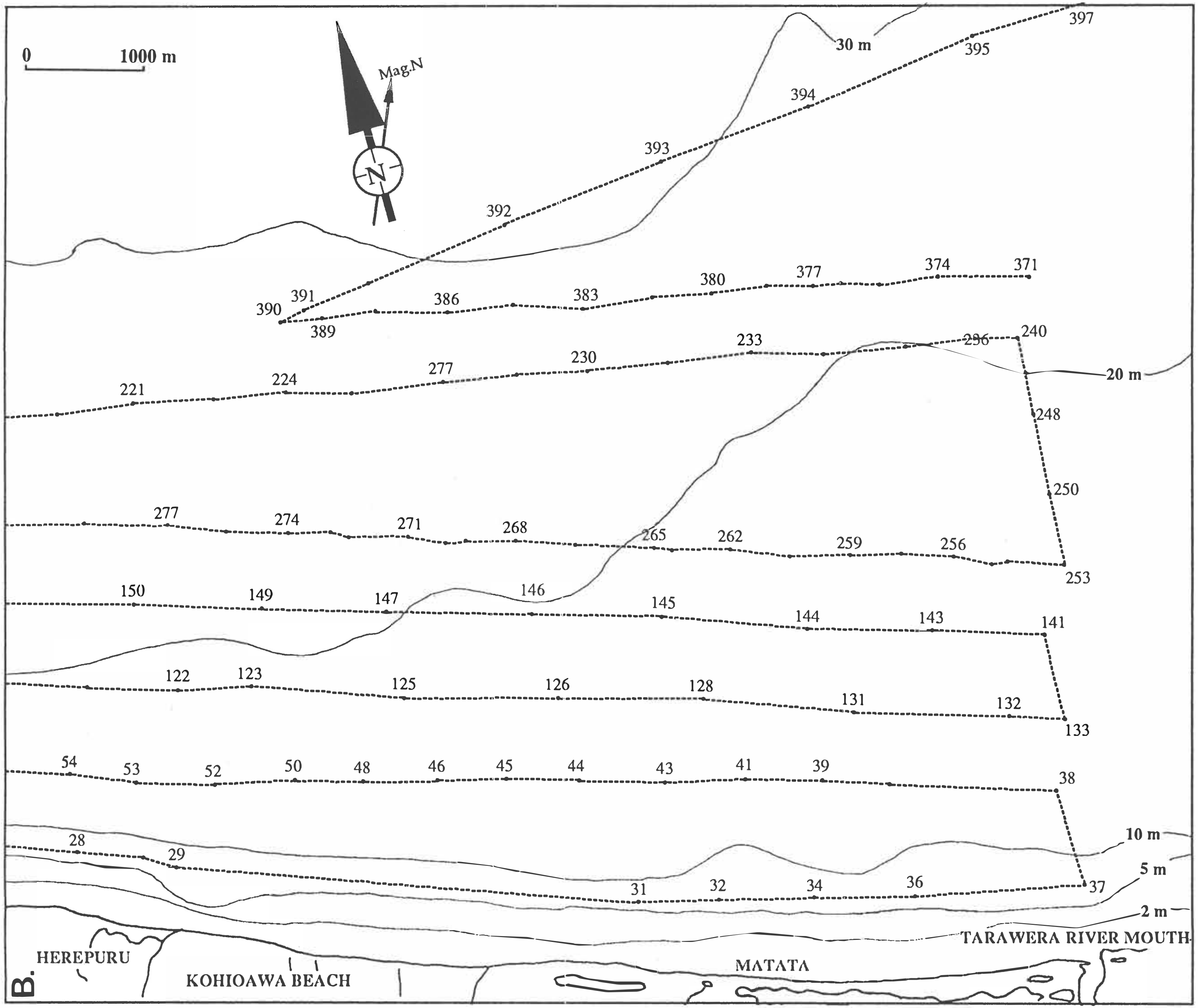
Latitude: 37 0.00S Longitude: 176 0.00E
Covering period : 15/ 7/ 1993 to 23/ 8/ 1993 nzst

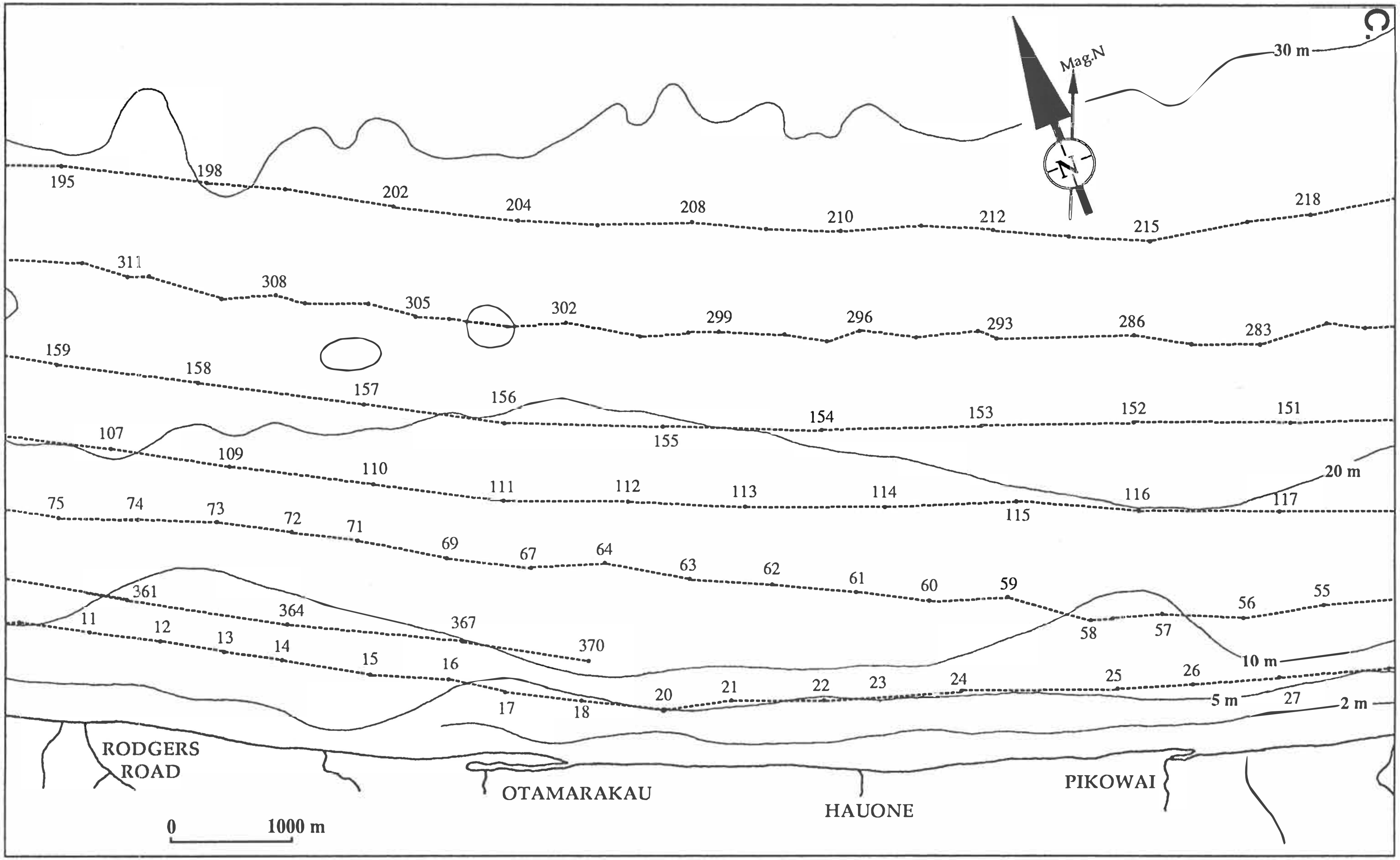
V-velocity

Constituent name	Period hours	Frequency cycles/ h	Amplitude metres	phase degrees
Z0	0.0000	0.0000	29.7735	0.00
K1	23.9345	0.0418	1.4841	300.17
O1	25.8193	0.0387	1.4008	186.10
MM	661.3093	0.0015	0.7813	237.69
J1	23.0985	0.0433	0.5906	286.84
MSF	354.3671	0.0028	0.5008	222.07
M2	12.4206	0.0805	0.4201	228.14
ALP1	29.0727	0.0344	0.3722	337.69
Q1	26.8684	0.0372	0.3196	151.13
OO1	22.3061	0.0448	0.2667	352.09
UPS1	21.5782	0.0463	0.2559	196.12
N2	12.6583	0.0790	0.1788	227.48
L2	12.1916	0.0820	0.1741	82.65
SK3	7.9927	0.1251	0.1559	115.05
MS4	6.1033	0.1638	0.1365	298.87
ETA2	11.7545	0.0851	0.1259	319.52
NO1	24.8332	0.0403	0.1150	223.89
MO3	8.3863	0.1192	0.1137	47.29
MK3	8.1771	0.1223	0.0949	259.64
S4	6.0000	0.1667	0.0945	319.99
M6	4.1402	0.2415	0.0808	330.88
2Q1	28.0062	0.0357	0.0800	149.95
MU2	12.8718	0.0777	0.0795	219.32
M4	6.2103	0.1610	0.0620	41.88
M3	8.2804	0.1208	0.0431	225.69
2SK5	4.7974	0.2084	0.0428	3.34
2MK5	4.9309	0.2028	0.0393	38.16
MN4	6.2692	0.1595	0.0375	181.70
2MN6	4.1663	0.2400	0.0359	128.77
M8	3.1052	0.3220	0.0343	135.56
2MS6	4.0924	0.2444	0.0324	246.99
SN4	6.1602	0.1623	0.0324	229.03
2SM6	4.0457	0.2472	0.0245	299.02
S2	12.0000	0.0833	0.0243	275.14
EPS2	13.1273	0.0762	0.0240	36.09
3MK7	3.5296	0.2833	0.0228	74.27

Appendix IX: Side-scan Sonar Tracklines and Fix Positions




0
1000 m
Mag.N
N
30 m
397
395
394
393
392
391
390
389
386
383
380
377
374
371
240
236
233
230
277
224
221
20 m
248
250
277
274
271
268
265
262
259
256
253
150
149
147
146
145
144
143
141
122
123
125
126
128
131
132
133
54
53
52
50
48
46
45
44
43
41
39
38
10 m
28
29
31
32
34
36
37
5 m
2 m
TARAWERA RIVER MOUTH
HEREPURU
KOHIOAWA BEACH
MATATA
B.


C.
30 m
Mag.N
N
195
198
202
204
208
210
212
215
218
311
308
305
302
299
296
293
286
283
159
158
157
156
155
154
153
152
151
107
109
110
111
112
113
114
115
116
117
20 m
75
74
73
72
71
69
67
64
63
62
61
60
59
58
57
56
55
361
364
367
370
11
12
13
14
15
16
17
18
20
21
22
23
24
25
26
27
10 m
5 m
2 m
RODGERS
ROAD
OTAMARAKAU
HAUONE
PIKOWAI
0
1000 m

Calculated Littoral Drift Rates:-

*(a)...i) Deepwater (S4 wave data) method**

Wave Direction (° TN)	*Wave angle (°)#*	*Hs (m)*	*Hrms (m)*	*Pls (W/m2)*	*Q (m3/s)*	*Q m3/day*
235.6		0.36	0.255			
188.5		0.43	0.304			
170.9		0.34	0.240			
238.7		0.33	0.233			
228.5		0.27	0.191			
217.9		0.29	0.205			
195.3		0.19	0.134			
145.9		0.21	0.149			
150.2		0.2	0.141			
157		0.32	0.226			
126.4	-36.4	0.19	0.134	1.845149	0.000153	3.310358
136.6		0.29	0.205			
166.7		0.28	0.198			
202.2		0.41	0.290			
152.6		0.53	0.375			
164.8		0.87	0.615			
246.3		0.92	0.651			
240.6		0.88	0.622			
231.1		0.6	0.424			
178.7		0.77	0.545			
123.7	-33.7	1.09	0.771	220.8059	0.01834	396.1451
169.5		0.7	0.495			
102.4	61	0.7	0.495	220.0836	0.01828	394.8492
112.7	-22.7	0.58	0.410	103.1784	0.00857	185.1111
152.6		0.32	0.226			
186		0.24	0.170			
180.8		0.26	0.184			
125	-35	0.18	0.127	2.047237	0.00017	3.672923
195.2		0.31	0.219			
148.5		0.56	0.396			
147.1		0.61	0.431			
147.2		0.42	0.297			
154.7		0.34	0.240			
160.7		0.25	0.177			
145.9		0.2	0.141			
185		0.24	0.170			
116.3	-26.3	0.2	0.141	5.982211	0.000497	10.73261
308		0.24	0.170			
181.8		0.23	0.163			
185.2		0.29	0.205			
250.4		0.18	0.127			
148.3		0.15	0.106			
120.9	-30.9	0.17	0.120	2.850932	0.000237	5.114822
205.7		0.18	0.127			
231		0.15	0.106			
173.7		0.18	0.127			
206.8		0.26	0.184			
180.5		0.26	0.184			
225.1		0.23	0.163			
216.7		0.34	0.240			
212.4		0.44	0.311			
272.8		0.33	0.233			
229.2		0.33	0.233			
226.5		0.65	0.460			
215.1		0.48	0.339			
193.1		0.46	0.325			
261.6		0.68	0.481			
258.5		0.62	0.438			
204.2		0.81	0.573			
162.7		1.07	0.757			
259.3		1.49	1.054			
288.1		1.33	0.941			
267.6		1.02	0.721			
263.4		1.24	0.877			
261.2		1.88	1.330			
257.6		2.12	1.499			
240.8		2.4	1.697			
259.7		2.74	1.938			
279.4		2.6	1.839			
308.7		0.95	0.672			
124.6	-34.6	0.67	0.474	58.02469	0.00482	104.1014

*(a)...ii) Modified deepwater (S4) method***

Wave Direction (° TN)	*Wave angle (°)#*	*Pls (W/m2)*	*Q (m3/s)*	*Q m3/day*
10	31.5	45.4343	0.003774	81.51312
320	81.5	20.83467	0.001731	37.37923
335	66.5	30.82779	0.002561	55.30775
270				
325	76.5	10.4002	0.000864	18.65887
338	63.5	22.77786	0.001892	40.86548
210				
70	28.5	11.13543	0.000925	19.97795
30	11.5	4.623559	0.000384	8.29507
170				
100	-58.5	-8.91701	-0.00074	-15.9979
45	-4.5	-4.69156	-0.00039	-8.41707
200				
270				
40	0.5	2.363839	0.000196	4.240934
315	86.5	47.84881	0.003974	85.84496
10	31.5	474.3481	0.039399	851.0221
305				
5	36.5	174.2296	0.014471	312.5832
55	-13.5	-156.166	-0.01297	-280.176
90	-48.5	-794.73	-0.06601	-1425.82
70	-28.5	-225.894	-0.01876	-405.273
50	-8.5	-79.3331	-0.00659	-142.331
120	78.5	59.94463	0.004979	107.5459
120	78.5	13.55362	0.001126	24.31638
10	31.5	16.48753	0.001369	29.58008
50	-8.5	-6.67026	-0.00055	-11.967
150				
170				
50	-8.5	-45.4129	-0.00377	-81.4748
50	-8.5	-56.2385	-0.00467	-100.897
40	1.5	3.96267	0.000329	7.109378
25	16.5	24.25149	0.002014	43.5093
70	-28.5	-17.219	-0.00143	-30.8925
5	36.5	11.17683	0.000928	20.05222
40	1.5	0.978122	8.12E-05	1.754836
345	56.5	10.50856	0.000873	18.85327
45	-3.5	-2.27743	-0.00019	-4.08592
225				
25	16.5	16.29432	0.001353	29.23343
70	-28.5	-7.57426	-0.00063	-13.5889
130	-88.5	-0.24056	-2E-05	-0.43158
135				
90	-48.5	-8.80714	-0.00073	-15.8008
35	6.5	1.297822	0.000108	2.328406
80	-38.5	-8.73626	-0.00073	-15.6736
95	-53.5	-21.135	-0.00176	-37.9181
100	-58.5	-19.533	-0.00162	-35.0439
90	-48.5	-16.2545	-0.00135	-29.162
45	-3.5	-5.4402	-0.00045	-9.7602
185				
100	-58.5	-35.4503	-0.00294	-63.6009
290				
355	46.5	220.1025	0.018282	394.8831
265				
275				
320	81.5	65.52211	0.005442	117.5524
345	56.5	177.8063	0.014769	319.0002
360	41.5	381.2331	0.031665	683.9656
300				
310				
65	-23.5	-982.834	-0.08163	-1763.29
345	56.5	617.2605	0.051269	1107.419
290				
290				
355	46.5	4228.45	0.351213	7586.21
315	86.5	604.7852	0.050233	1085.038
270				
245				
305				
325	76.5	100.8833	0.008379	180.9935

Wave Direction (° TN)	Wave angle (°)#	Hs (m)	Hrms (m)	Pls (W/m2)	Q (m3/s)	Q m3/day
113.9	-23.9	0.71	0.502	161.6839	0.013429	290.0751
156.9		0.8	0.566			
164.6		0.72	0.509			
158.3		1.3	0.919			
228.5		0.56	0.396			
199		0.44	0.311			
184.4		0.46	0.325			
191.8		0.33	0.233			
193.3		0.33	0.233			
208.6		0.35	0.248			
177.1		0.25	0.177			
182.2		0.23	0.163			
190.9		0.32	0.226			
231.2		0.21	0.149			
222.6		0.27	0.191			
228		0.53	0.375			
209.8		2.22	1.570			
274.1		2.13	1.506			
263.4		1.41	0.997			
244		1.91	1.351			
269.5		2.23	1.577			
290.2		1.88	1.330			
270.4		2.3	1.627			
289.7		1.87	1.322			
273.8		2.4	1.697			
303		1.34	0.948			
270.1		1.27	0.898			
46.9	43.1	0.78	0.552	57.52921	0.004778	103.2124
241.8		0.88	0.622			
14	-62.5	0.7	0.495	-211.938	-0.0176	-380.235
3.8	-52.3	0.44	0.311	-79.8181	-0.00663	-143.201
299.4		0.51	0.361			
201.5		0.53	0.375			
177.1		0.35	0.248			
265.6		0.47	0.332			
213.6		0.47	0.332			
219.2		0.54	0.382			
234		0.41	0.290			
230.1		0.36	0.255			
208.6		0.33	0.233			
211.5		0.23	0.163			
193.8		0.49	0.347			
202.3		0.3	0.212			
208.6		0.31	0.219			
116.4	-26.4	0.37	0.262	27.68277	0.002299	49.66533
140.1		0.25	0.177			
140		1.15	0.813			
124.5	83	1.41	0.997	331.6387	0.027546	594.9889
117.9	-27.9	0.73	0.516	137.6	0.011429	246.8664
212.4		0.43	0.304			
132.3		0.26	0.184			
263.4		0.31	0.219			
202.3		0.25	0.177			
172.7		0.12	0.085			
174		0.16	0.113			
305.4		0.11	0.078			
70.5	19.5	0.13	0.092	3.271153	0.000272	5.868736
207.8		0.23	0.163			
200.2		1.49	1.054			
90.2	-0.2	0.73	0.516	293.7553	0.024399	527.0228
101.5	60	0.64	0.453	179.9865	0.01495	322.9116
141		0.79	0.559			
146.2		0.64	0.453			
145		0.47	0.332			
148.7		0.31	0.219			
178.4		0.27	0.191			
209.3		0.12	0.085			
233.9		0.23	0.163			
89.5	0.5	0.2	0.141	11.56659	0.000961	20.75147
145		0.24	0.170			
213.1		0.44	0.311			
64.9	25.1	0.39	0.276	43.28912	0.003596	77.66447
118.2	-28.2	0.31	0.219	15.84107	0.001316	28.42027
141.8		0.48	0.339			

Wave Direction (° TN)	Wave angle (°)#	Pls (W/m2)	Q (m3/s)	Q m3/day
45	-3.5	-34.2818	-0.00285	-61.5045
35	6.5	85.25342	0.007081	152.9521
145				
210				
205				
70	-28.5	-70.7605	-0.00588	-126.95
15	26.5	75.38831	0.006262	135.2532
15	26.5	32.86202	0.00273	58.95735
355	46.5	40.4228	0.003358	72.52204
180				
45	-3.5	-2.52213	-0.00021	-4.52492
355	46.5	16.3931	0.001362	29.41066
285				
125	83.5	2.627703	0.000218	4.71433
225				
30	11.5	52.85561	0.00439	94.8276
355	46.5	4744.866	0.394107	8512.706
180				
45	-3.5	-190.531	-0.01583	-341.829
305				
355	46.5	4798.48	0.39856	8608.894
320	81.5	832.7415	0.069167	1494.011
310				
300				
320	81.5	1533.358	0.12736	2750.979
320	81.5	357.1721	0.029667	640.7981
330	71.5	674.3548	0.056012	1209.852
360	41.5	346.9082	0.028814	622.3837
5	36.5	453.8899	0.0377	814.3183
330	71.5	152.0983	0.012633	272.8776
345	56.5	75.43966	0.006266	135.3454
360	41.5	119.9233	0.009961	215.1529
320	81.5	35.14028	0.002919	63.04475
235				
355	46.5	97.85571	0.008128	175.5617
10	31.5	88.48553	0.00735	158.7508
300				
110	-68.5	-45.6637	-0.00379	-81.9248
5	36.5	48.58476	0.004035	87.16533
120	-78.5	-14.6374	-0.00122	-26.2609
290				
180				
195				
135				
135				
120	-78.5	-7.3119	-0.00061	-13.1182
100	-58.5	-803.674	-0.06675	-1441.86
190				
75	-33.5	-274.458	-0.0228	-492.402
315	86.5	8.217584	0.000683	14.74307
220				
230				
345	56.5	18.35769	0.001525	32.93531
220				
40	1.5	0.354948	2.95E-05	0.636808
210				
95	-53.5	-3.73618	-0.00031	-6.70303
205				
200				
235				
100	-58.5	-185.688	-0.01542	-333.141
90	-48.5	-355.403	-0.02952	-637.624
100	-58.5	-185.688	-0.01542	-333.141
60	-18.5	-60.1646	-0.005	-107.941
75	-33.5	-32.2532	-0.00268	-57.8651
65	-23.5	-18.2499	-0.00152	-32.7419
185				
105	-63.5	-12.7596	-0.00106	-22.8919
325	76.5	4.911421	0.000408	8.81152
75	-33.5	-17.0097	-0.00141	-30.5169
120	-88.5	-3.54508	-0.00029	-6.36018
140				
215				
140				

Wave Direction (° TN)	*Wave angle (°)#*	*Hs (m)*	*Hrms (m)*	*Pls (W/m2)*	*Q (m3/s)*	*Q m3/day*
158.7		0.43	0.304			
126.6	-36.6	1.05	0.743	127.3302	0.010576	228.4416
139.8		0.58	0.410			
175.9		1.27	0.898			
126	-36	1.6	1.132	409.1169	0.033981	733.9916
83.7	6.3	0.79	0.559	356.6672	0.029625	639.8923
332.5	-21	0.53	0.375	-90.242	-0.0075	-161.902
207.7		0.33	0.233			
219.9		0.3	0.212			
71.5	18.5	0.34	0.240	37.02435	0.003075	66.42492
224.6		0.23	0.163			
337.4	-25.9	0.19	0.134	-8.13632	-0.00068	-14.5973
210		0.24	0.170			
Average (m3/6hrs) ***(a)...i)***					0.007269	160.7148
Total Gross to SE (m3/41 days)			5039.24			
Total Gross to NW (m3/41 days)			-699.94			
Net Drift (41 days)			4339.30 m3 to south-east			
Annual Littoral Drift			*38630 m3 to south-east*			

Wave Direction (° TN)	*Wave angle (°)#*	*Pls (W/m2)*	*Q (m3/s)*	*Q m3/day*
25	16.5	43.62268	0.003623	78.26291
210				
55	-13.5	-76.9007	-0.00639	-137.967
85	-43.5	-1178.35	-0.09787	-2114.06
150				
215				
30	11.5	52.85561	0.00439	94.8276
190				
180				
220				
345	56.5	14.90348	0.001238	26.73815
250				
185				
Average (m3/6hrs) ***(a)...ii)***			0.013	289.3954
Total Gross to SE (m3/41 days)			39842.5	
Total Gross to NW (m3/41 days)			-10821.0	
Net Drift (41 days)		29021.47 m3 to south-east		
Annual Littoral Drift		*258361 m3 to south-east*		

** based on the average 6 hourly wave data bursts* *** as for a)...i) except wave direction determined from the swell component*

 # deepwater onshore wave angle to Pukehina Beach

NOTE: positive values indicate a south-east longshore direction, negative values a north-west heading direction.

Appendix X(b): Calculation Diabathic Transport

Burst ***Number***	**Direction** *(onsh./offsh.)*	**Wave height** *(m)*	**Period** *(s)*	**Bedload** *(m2/s)*	**Suspended** *(m2/s)*	**Rate (m3/m/6 hrs)**	
						Bedload	**Suspended load**
66	onshore	1.88	6	1.95E-06	5.77E-10	0.04212	1.24632E-05
67	onshore	2.12	5.8	2.19E-05	8.809E-08	0.47304	0.001902744
68	onshore	2.4	5.8	1.58E-05	3.201E-08	0.340632	0.000691416
69	onshore	2.74	6.6	2.32E-05	4.337E-08	0.501336	0.000936792
70	offshore	2.6	6.3	-2.08E-05	-4.153E-08	-0.449496	-0.000897048
90	onshore	2.13	5.9	1.74E-05	5.521E-08	0.376272	0.001192536
92	onshore	1.91	6.3	1.55E-05	6.101E-08	0.33372	0.001317816
93	onshore	2.23	6	1.55E-05	3.815E-08	0.334152	0.00082404
94	onshore	1.88	6.9	1.57E-05	6.916E-08	0.338904	0.001493856
95	onshore	2.3	7.1	2.13E-05	6.718E-08	0.460512	0.001451088
96	offshore	1.87	6.9	-1.56E-05	-6.929E-08	-0.336312	-0.001496664
97	offshore	2.4	6	-1.64E-05	-3.391E-08	-0.35316	-0.000732456
98	offshore	1.34	7	-1.52E-06	-8.257E-08	-0.0329184	-0.001783512
150	onshore	1.27	8.8	1.26E-05	2.117E-07	0.27216	0.00457272

Total:	***Bedload***	***Suspended***
	2.30	0.01
per year/m	20.48	0.08
per year/km	20484	84
per/year/sector	662970	2733

Calculated Littoral Drift Rates:-

*(b)... Breaking wave (Beach observational data) method**

Date	Breaker angle (°)#	Hb av. (m)	Hb rms (m)	hb (m)	C	E (J/m)	Pls (W/m2)	Q (m3/s)	Q m3/day
20/4		0.4	0.451	0.579	2.383	256.186			
21/4	10	0.8	0.903	1.158	3.370	1024.744	590.5442	0.04905	4237.952567
22/4		0.3	0.339	0.434	2.064	144.1046			
23/4		0.25	0.282	0.362	1.884	100.0727			
24/4		0.1	0.113	0.145	1.191	16.01163			
25/4		0.3	0.339	0.434	2.064	144.1046			
26/4		0.1	0.113	0.145	1.191	16.01163			
27/4	-7	0.6	0.677	0.868	2.918	576.4185	-203.483	-0.0169	-1460.268585
28/4	-7	1.05	1.185	1.519	3.861	1765.282	-824.374	-0.06847	-5915.995895
29/4	-2	0.5	0.564	0.724	2.664	400.2907	-37.1951	-0.00309	-266.9248263
30/4	-1	0.5	0.564	0.724	2.664	400.2907	-18.6089	-0.00155	-133.5437644
1/5	-5	0.5	0.564	0.724	2.664	400.2907	-92.5915	-0.00769	-664.4689328
1/5		0.3	0.339	0.434	2.064	144.1046			
3/5	4	0.3	0.339	0.434	2.064	144.1046	20.69351	0.001719	148.5039072
4/5		0.25	0.282	0.362	1.884	100.0727			
5/5	5	0.25	0.282	0.362	1.884	100.0727	16.36802	0.00136	117.4626221
6/5	2	0.25	0.282	0.362	1.884	100.0727	6.575221	0.000546	47.18608869
7/5	-5	0.5	0.564	0.724	2.664	400.2907	-92.5915	-0.00769	-664.4689328
8/5	-2	0.65	0.734	0.941	3.038	676.4912	-71.671	-0.00595	-514.3365052
9/5		1.25	1.411	1.809	4.212	2501.817			
10/5	4	1	1.129	1.447	3.768	1601.163	419.789	0.034868	3012.553328
11/5		0.8	0.903	1.158	3.370	1024.744			
12/5	7	0.75	0.847	1.085	3.263	900.654	355.471	0.029525	2550.984235
13/5		1.5	1.693	2.171	4.614	3602.616			
14/5		1	1.129	1.447	3.768	1601.163			
15/5		0.3	0.339	0.434	2.064	144.1046			
16/5	3	1.3	1.467	1.881	4.296	2705.965	607.5314	0.050461	4359.858415
17/5	2	0.6	0.677	0.868	2.918	576.4185	58.67302	0.004873	421.0581558
18/5	2	0.5	0.564	0.724	2.664	400.2907	37.19506	0.003089	266.9248263
19/5		0.3	0.339	0.434	2.064	144.1046			
20/5	5	0.2	0.226	0.289	1.685	64.0465	9.369599	0.000778	67.23952839
21/5		1.5	1.693	2.171	4.614	3602.616			
22/5		0.15	0.169	0.217	1.459	36.02616			
23/5		0.2	0.226	0.289	1.685	64.0465			
24/5		0.3	0.339	0.434	2.064	144.1046			
25/5		0.2	0.226	0.289	1.685	64.0465			
26/5		0.3	0.339	0.434	2.064	144.1046			
27/5	5	0.6	0.677	0.868	2.918	576.4185	146.0576	0.012131	1048.160515
28/5		0.1	0.113	0.145	1.191	16.01163			
29/5		0.1	0.113	0.145	1.191	16.01163			
30/5		0.1	0.113	0.145	1.191	16.01163			
31/5		0.15	0.169	0.217	1.459	36.02616			
1/6		0.2	0.226	0.289	1.685	64.0465			
2/6		0.25	0.282	0.362	1.884	100.0727			
3/6	-2	0.3	0.339	0.434	2.064	144.1046	-10.372	-0.00086	-74.43326931
4/6	2	0.6	0.677	0.868	2.918	576.4185	58.67302	0.004873	421.0581558
5/6		0.9	1.016	1.302	3.574	1296.942			
6/6	1	2.1	2.370	3.039	5.460	7061.127	672.7337	0.055877	4827.772985
7/6	1	2	2.257	2.894	5.328	6404.65	595.4838	0.049461	4273.400461
8/6	1	1.1	1.242	1.592	3.952	1937.407	133.5908	0.011096	958.6946776
9/6	1	0.8	0.903	1.158	3.370	1024.744	60.25872	0.005005	432.437722
10/6		0.5	0.564	0.724	2.664	400.2907			
11/6		0.3	0.339	0.434	2.064	144.1046			
12/6	4	0.3	0.339	0.434	2.064	144.1046	20.69351	0.001719	148.5039072
13/6	1	2.5	2.822	3.618	5.957	10007.27	1040.267	0.086404	7465.32338
14/6	5	1.8	2.032	2.605	5.055	5187.767	2276.813	0.189111	16339.2054
15/6	2	0.6	0.677	0.868	2.918	576.4185	58.67302	0.004873	421.0581558
16/6		0.25	0.282	0.362	1.884	100.0727			
17/6		0.2	0.226	0.289	1.685	64.0465			
18/6		0.25	0.282	0.362	1.884	100.0727			
19/6		0.3	0.339	0.434	2.064	144.1046			
20/6	-1	0.6	0.677	0.868	2.918	576.4185	-29.3544	-0.00244	-210.6574047
21/6		0.8	0.903	1.158	3.370	1024.744			
22/6		0.3	0.339	0.434	2.064	144.1046			
23/6		0.4	0.451	0.579	2.383	256.186			
16/7		0.2	0.226	0.289	1.685	64.0465			
17/7		0.2	0.226	0.289	1.685	64.0465			
18/7		0.15	0.169	0.217	1.459	36.02616			
19/7	10	0.15	0.169	0.217	1.459	36.02616	8.989916	0.000747	64.5147876
20/7		0.2	0.226	0.289	1.685	64.0465			

Date	*Breaker angle (°)#*	*Hb av. (m)*	*Hb rms*	*hb*	*C*	*E*	*Pls (W/m2)*	*Q (m3/s)*	*Q m3/day*
21/7		0.5	0.564	0.724	2.664	400.2907			
22/7	4	0.4	0.451	0.579	2.383	256.186	42.47966	0.003528	304.8489629
23/7	2	0.3	0.339	0.434	2.064	144.1046	10.37202	0.000861	74.43326931
24/7	4	0.25	0.282	0.362	1.884	100.0727	13.11841	0.00109	94.1422915
25/7	-4	0.35	0.395	0.506	2.229	196.1424	-30.4229	-0.00253	-218.3256965
26/7		0.3	0.339	0.434	2.064	144.1046			
27/7		0.2	0.226	0.289	1.685	64.0465			
28/7		0.3	0.339	0.434	2.064	144.1046			
29/7		0.4	0.451	0.579	2.383	256.186			
30/7	-1	0.4	0.451	0.579	2.383	256.186	-10.6523	-0.00088	-76.44491141
31/7	-2	0.5	0.564	0.724	2.664	400.2907	-37.1951	-0.00309	-266.9248263
1/8	-1	0.4	0.451	0.579	2.383	256.186	-10.6523	-0.00088	-76.44491141
2/8	-1	0.8	0.903	1.158	3.370	1024.744	-60.2587	-0.00501	-432.437722
3/8	1	0.8	0.903	1.158	3.370	1024.744	60.25872	0.005005	432.437722
4/8	1	0.6	0.677	0.868	2.918	576.4185	29.35439	0.002438	210.6574047
5/8	1	0.3	0.339	0.434	2.064	144.1046	5.189172	0.000431	37.23931984
6/8	1	0.2	0.226	0.289	1.685	64.0465	1.883085	0.000156	13.51367881
7/8		0.2	0.226	0.289	1.685	64.0465			
8/8	-1	1.5	1.693	2.171	4.614	3602.616	-290.084	-0.02409	-2081.741265
9/8	-6	1.75	1.975	2.532	4.984	4903.561	-2540.68	-0.21103	-18232.80434
10/8	-1	1.25	1.411	1.809	4.212	2501.817	-183.895	-0.01527	-1319.695196
11/8		0.8	0.903	1.158	3.370	1024.744			
12/8	-2	0.6	0.677	0.868	2.918	576.4185	-58.673	-0.00487	-421.0581558
13/8	-2	0.3	0.339	0.434	2.064	144.1046	-10.372	-0.00086	-74.43326931
14/8	-1	0.2	0.226	0.289	1.685	64.0465	-1.88309	-0.00016	-13.51367881
15/8	15	0.4	0.451	0.579	2.383	256.186	152.6145	0.012676	1095.215098
16/8	1	0.3	0.339	0.434	2.064	144.1046	5.189172	0.000431	37.23931984
17/8	4	0.3	0.339	0.434	2.064	144.1046	20.69351	0.001719	148.5039072
18/8	10	0.5	0.564	0.724	2.664	400.2907	182.3696	0.015148	1308.748313
19/8		0.4	0.451	0.579	2.383	256.186			
20/8	1	0.3	0.339	0.434	2.064	144.1046	5.189172	0.000431	37.23931984
21/8	5	0.3	0.339	0.434	2.064	144.1046	25.81958	0.002145	185.290352
22/8	5	0.5	0.564	0.724	2.664	400.2907	92.59148	0.007691	664.4689328
23/8	5	0.5	0.564	0.724	2.664	400.2907	92.59148	0.007691	664.4689328
24/8	5	0.4	0.451	0.579	2.383	256.186	53.00246	0.004402	380.3642119
25/8	1	0.2	0.226	0.289	1.685	64.0465	1.883085	0.000156	13.51367881
Average									
1st Dates								0.007306	631.2157715
2nd Dates								-0.00493	-425.5362066
Total								0.002381	205.6795649

(b)...

	1st data set (66 days)	*2nd data set (42 days)*	***Total (108 days)***
Total Gross to SE (m3/108 days)	51565.34	5766.8395	57332.18
Total Gross to NW (m3/108 days)	-9905.1	-23213.824	-33118.9
Net Drift (108 days)	41660.2 m3 to SE	17447.0 m3 to NW	24213.2 m3 to SE
Annual Littoral Drift	*140796 to the S.E.*	*58964 to the N.W.*	*81831 to the south-east*

 # breaking wave angle to Pukehina Beach
NOTE: positive values indicate a south-east longshore direction, negative values a north-west heading direction.