SAND AND GRAVEL DEPOSITS OF THE COAST AND INNER SHELF EAST COAST, NORTHLAND PENINSULA, NEW ZEALAND

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ABSTRACT

The east coast of Northland has a narrow and steep inner shelf which reaches depths of 50 m within 1-5 km offshore. Mixed sand and gravel sediments occur at 30-50 m depths as thin (1-10 m), discontinuous, sheet deposits underlain by planed, bedrock surfaces. The deposits lie off rocky sections of the coast which form high standing cliffs between drowned embayments. Coastal deposits are predominantly situated in the embayments as localised pockets totalling only 15% of the shoreline length. The hinterland consists of a dissected block of greywackes which are deeply weathered to clay except for unweathered coastal cliff exposures. During the Pleistocene, the coast and inner shelf have evolved under conditions of relative tectonic stability in comparison to much larger sea level fluctuations.

Coastal sand and gravel sediments were derived predominantly from erosion of coastal rock, rather than from hinterland fluvial sources. In addition, a high regional shell sand content of 40% varies from 2-82% between beaches depending upon contributions of sediment from other sources. Beach morpho-dynamics display a quasi-seasonal pattern with a tendency to erosion in winter, accretion in spring-early summer, and a variable response in summer-autumn, although episodes of erosion are possible at any time of the year. Short term beach changes of 20-40 m in two years were greater than <10 m historical changes determined from air photos for the last 30-40 years.

A comparison of inner shelf sediment samples within and between five areas along the coast did not show either marked textural or geographic groupings. The gravel deposits were not interpreted as relict fluvial as has been previously proposed, and are now thought to have been derived directly from the erosion of adjacent coastal exposures during sea level highs 20-40 m below present in the last glaciation and since the post-glacial transgression.

Shell presently forms 36-56% of the inner shelf gravel fraction and is derived from contemporary inner shelf communities. The shell is mixed within the deposits to a depth of at least 1.5 m, and to the base of one of the deposits. Other sediment and core data suggest that the deposits are now at least palimpsest and may be modern. Detailed studies of sediment mobility in the shallowest (20 m deep) deposit indicate that sediment up to 50 mm diameter is actively involved in a seabed transport system within the deposit, and that the deposits are presently evolving in terms of their sediment characteristics and spatial distribution of facies.

The major implication of these findings for a proposal to dredge inner shelf deposits is that coastal erosion is not likely at the five deposits located off cliffed, rocky coasts. This conclusion is less certain for the shallowest deposit which is adjacent to a long, sand beach, but it is thought that dredging would have very little adverse physical effect.

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

This thesis presents the results of a variety of geomorphic and sedimentary investigations carried out on sand and gravel deposits of the coast and inner shelf along the east coast of the Northland Peninsula, New Zealand. The investigations were done in the process of assessing a proposal by Landsea Minerals Ltd. to dredge sand and gravel from inner shelf deposits (Anon, 1974a; 1974b; Gibb, 1974; Landsea Minerals Ltd., 1975).

Offshore sand and gravel dredging of the type proposed by Landsea Minerals Ltd. is new to New Zealand, although it is well established in Europe (Hill, 1971; Archer, 1973) and is developing along the northeast coast of the United States (Schlee, 1968; Manheim, 1972; Cruickshank and Hess, 1975). When the company's proposal was first announced, there was only a limited amount of information about the quantity, quality and location of offshore deposits of sand and gravel in Northland. Therefore, before any dredging could begin, it was necessary to assess the deposit resource. This was

to be done through a prospecting programme. In addition, because of the nature of the proposed dredging operation, the company was required to determine possible environmental impacts on the inner shelf and the adjacent coastline (Mining Act, 1971; Commission for the Environment, 1973). An environmental investigation was necessary because little was known about the origin and evolution of the deposits, how they are related to the stability and possible nourishment of the adjacent beach deposits, and the contemporary processes which are affecting them.

The company's needs for resource and environmental studies resulted in their approach to the author's supervisor, Dr R. M. Kirk. After some discussion, the project was accepted since it would allow for research work in the author's fields of interest. Material in this thesis therefore deals essentially with research topics in coastal and shelf geomorphology and sedimentology. The related matters of resource assessment and environmental impacts are being dealt with in a separate report to the company.

1.2 RESEARCH CONTEXT AND OBJECTIVES

Research for this thesis has been conducted within the context of other existing regional and systematic studies on coastal and shelf sedimentary deposits. Recent overseas reviews on these studies have included those by Davies (1972), King (1972), and Hails (1974) on beaches and coasts, and those by Shepard (1973), Swift et al. (1972), and Stanley and Swift (1976) on shelf areas. Within New Zealand coastal studies have been reviewed by McLean (1976a),

and shelf sedimentation by Carter (1975). The substance of these reviews will be presented in Chapter Two, but it can be stated now that there are at least two current trends in coastal and shelf research fields which are relevant to the present study.

First, it is being recognised increasingly that there is a considerable amount of geographic variation in the nature of sedimentation among coastal and shelf areas. This is due to the different sources of sediment, mechanisms of deposition, and contemporary process environments influencing the coasts and shelves of the world. Thus, it is difficult to generalise from area to area, and local studies and knowledge are considered necessary to understand sedimentation in a specific area.

Second, numerous attempts have recently been made to directly study specific processes of sedimentation, and the formation of sedimentary deposits in coastal and shelf environments. This is in contrast to traditional research which has tended to deal simply with descriptions of morphology and surface sediment distribution, with processes then being inferred from the descriptions. In addition, many of the existing physical models for specific seabed sedimentary processes are largely based on laboratory and theoretical studies, and there are few field studies which have been done to verify these models.

Research objectives for this study have given consideration to these two themes, as well as attempting to meet the requirements of the company. Thus, the broad research objectives of the thesis are:

(i) A description of the coastal and inner shelf deposits, and the geologic, geomorphic, and physical environment factors which have resulted in their formation. This includes the origin and evolution of the deposits, their contemporary dynamics, and the relationship between inner shelf and coastal deposits;

(ii) A detailed study of contemporary processes of sedimentation on inner shelf sand and gravel deposits. This includes processes of seabed wave activity and sediment movement, and is intended to advance knowledge in the field study of the processes, as well as defining their significance in the study area.

Both research objectives are intended to provide information on sand and gravel deposits in the study area, so that the future management and use of these resources will rest on a more knowledgeable foundation.

1.3 THE STUDY AREA

The study area is located along the east coast of the Northland Peninsula which projects from the North Island of New Zealand for about 340 km northwest of the city of Auckland (Fig. 1.1 and 1.2 - map pocket). The portion of this coast on which work has been concentrated lies between Cape Brett and Bream Head.

Because of the company's requirements and other considerations of time and effort, some parts of this coast were studied in more detail than others. The main areas of study were in the vicinity of Home Point and Whangaruru Harbour and along the Pataua and

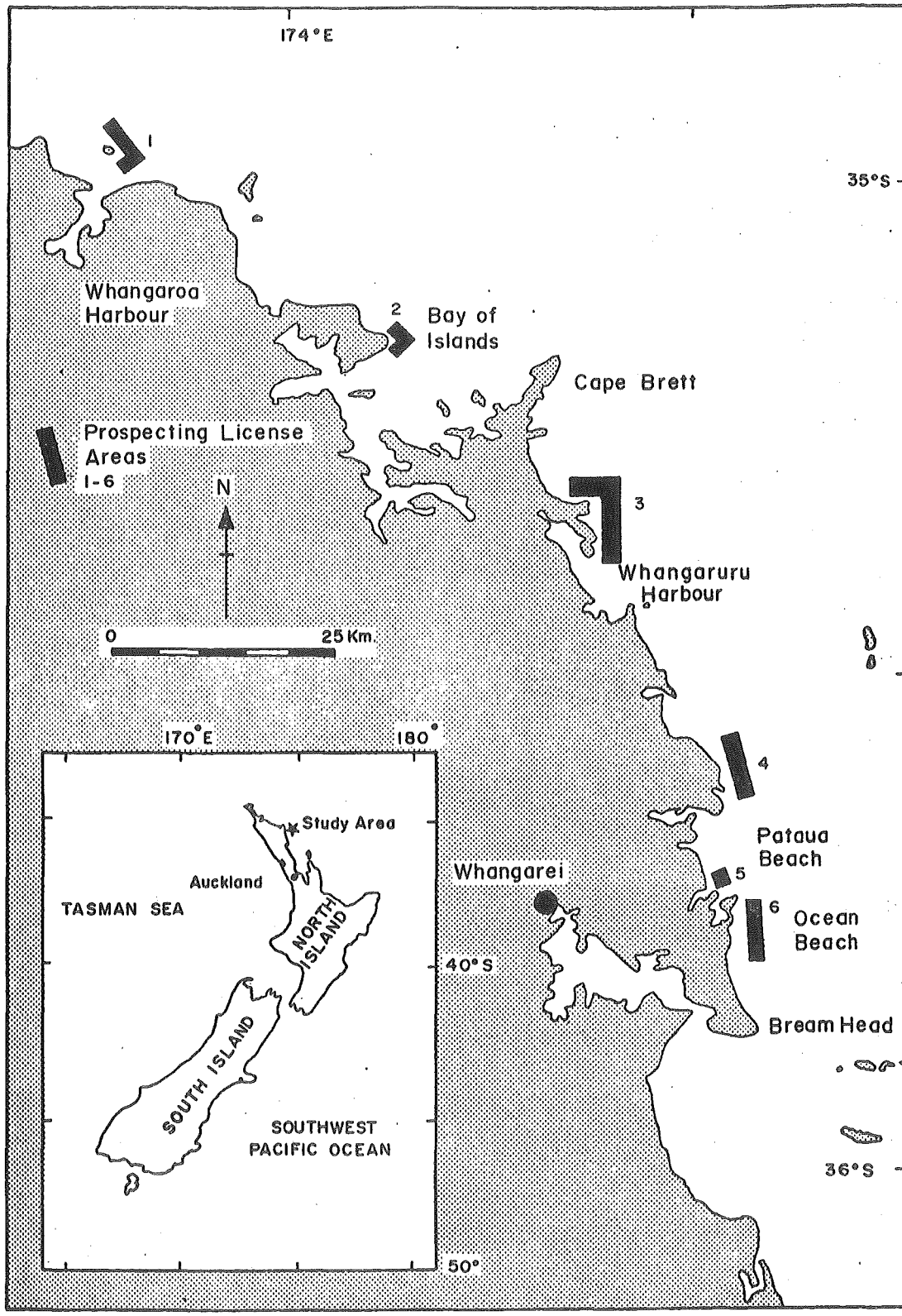


Fig. 1.1 - Study area location map. Sand and gravel prospecting areas: (1) Stephenson Island, (2) Ninepin, (3) Home Point, (4) North Gable, (5) Pataua, (6) Awarua Rock.

Ocean Beach coasts. Some fieldwork was also carried out on the coast immediately north of the Bay of Islands and around the entrance to Whangaroa Harbour. Use has also been made of previous research by others in related areas along the east coast of Northland. These related areas extend from as far north as the North Cape region to as far south as the coastal and inner shelf regions in the northern approaches to the Hauraki Gulf and along the exposed eastern Coromandel and Bay of Plenty coasts (Fig. 1.2 - map pocket).

As can be seen from Fig. 1.1 and 1.2, the east coast of Northland has a highly indented shoreline and displays many coastal features which are typical of a "classical" drowned or submerged coast (Cotton, 1958, p 442). The coast is rocky and steep with many cliffs, projecting headlands, and numerous offshore islands. It is also strongly embayed with a number of sheltered estuaries and harbours, notably the Bay of Islands, which penetrate deeply into the hinterland. Preliminary studies by Ritchie and Saul (1974; 1975) have shown that sand and gravel deposits in inner shelf regions tend to occur as isolated areas of limited size rather than as an extensive cover (Fig. 1.1). Most beaches are small, curved and pocket-like, and are exposed to the open ocean.

The irregular nature of the shoreline means that the actual shoreline distance is much greater than a simple distance between two points. Thus, although the straight line distance between Cape Brett and Bream Head is 80 km, the actual length of shoreline is in the order of 260 km. In this 260 km about 46% is exposed rocky shoreline, 15% exposed ocean beach, and 39% sheltered estuary and harbour shoreline (Table 1.1).

Table 1.1 - Distances and percentages of shoreline in the study area, divided into three main types. Compiled from 1:63,360 scale NZMS 1, Sheets N12, N16, N20, and N24.

Shoreline Type	Shoreline Distance (km)	(%)
(i) Exposed rocky shoreline	120	46
(ii) Exposed ocean beaches	40	15
(iii) Sheltered estuaries and harbours	100	39
Total	260	100

1.4 PREVIOUS RESEARCH IN THE STUDY AREA

This brief review is intended merely to define the extent of previous work by others in the study area. The works cited here will be discussed more fully in subsequent chapters of the thesis.

Previous work in the study area and its vicinity has been variable in subject and geographic coverage, and is also (with some exceptions) limited in quantity and depth of treatment. For example, apart from the work of Schofield (1967; 1970) on regional coastal sediment distribution and spit dynamics, no work has been done on sedimentary coastal processes in the immediate study area between Cape Brett and Bream Head. This is in contrast to the coast just south of the study area where some detailed coastal process studies have been done (Schofield, 1967; 1975). Coastal studies have also

been carried out in related areas along the exposed eastern Coromandel and Bay of Plenty coasts (Marks, 1975; Harray, 1977; Healy et al., 1977).

Early geological reports of the area by Bell and Clark (1909), and Ferrar (1925) make brief mention of the beaches and shoreline. Ferrar recognised "raised beaches" and early work tended to dwell on this topic. This has been reviewed for the area by Henderson (1926) and Gage (1953). Bartrum (1916; 1926) studied shore platforms for several localities along the coast. Work has also been done by Cotton (1951; 1958), who used the Bay of Islands area to illustrate coastal evolution in terms of Davisian concepts.

There have also been a number of geology thesis investigations done along this coast by workers from the University of Auckland. Allen (1951), Elliot (1966) and Le Couteur (1967) studied the geology of portions of the coastline and the hinterland. Quaternary studies have been done in depositional coastal areas to the north between the Karikari Peninsula and North Cape (Goldie, 1975; Hicks, 1975; Ricketts, 1975). In addition, Quaternary coastal and shelf sedimentation has been studied in the sheltered waters of the Waitemata Harbour (Searle, 1958; 1959; Gregory and Thompson, 1973; Thompson, S.A., 1975; Hicks and Kibblewhite, 1976).

Previous studies which are of more relevance to the study area have been done in the last two decades. Wellman (1962) included many Northland sites in his coastal reconnaissance of the Holocene of the North Island. Schofield (1960; 1967; 1970; 1973; 1974; 1975) has provided the largest contribution to sedimentary coastal studies in this region. His investigations have included

Holocene sea level changes in progradational coastal area, analysis of beach and marine sands, and the effects of waves, sea level changes, sediment supply, and inshore dredging on beach changes.

Open ocean continental shelf areas have not received as much attention as coastal and sheltered harbour areas. Some limited preliminary surveys were done primarily to assess the ecological impact of proposed dredging (Bioresearches, 1974; Ritchie and Saul, 1974; 1975). The only other shelf studies lie outside the immediate area and include Thompson, I. C. (1975) on surface sediments of the northern approaches to the Hauraki Gulf, and Summerhayes (1969a; 1969b) on recent sedimentation, submarine geology and geomorphology off North Cape. In addition, charts of bathymetry and surface sediment distribution for the shelf, at a scale of 1:200,000, have been produced by the New Zealand Oceanographic Institute (Eade, 1971; 1974). Charts of the Hydrographic Office, Royal New Zealand Navy also provide information on bathymetric and surface sediment types (Hydrographic Office, 1973).

1.5 EXTENT OF FIELD WORK

The majority of field work for this thesis was carried out in two separate summer field seasons of four to five months each. This was of advantage in measuring temporal changes in environmental controlling factors, and sedimentary responses (such as beach morphology and inner shelf sediment distribution).

The first field season (from December, 1975 to April, 1976), was directed mainly at surveying the coastal and inner shelf

deposits for their broad characteristics. During this time beach sediments were collected and beach profiles were established along the coast and surveyed a number of times. Some of the inner shelf deposits were surveyed using echo sounder and sub-bottom profiler equipment. Seabed sediment samples were collected for the Pataua area only.

The second field season (from December, 1976 to April, 1977) continued the beach profile survey and extended the profiles into the region between the beach and inner shelf. The major work completed in this second period was a detailed three month study of sediment movement processes at a depth of 18 m on the inner shelf deposit at Pataua. This work included instrument measurements of wave activity and sediment tracing studies, as well as changes in the bedform topography of the immediate seabed area. Sub-bottom coring was started at the end of this period and continued for three weeks in October, 1977. This extra visit also allowed for an additional survey of the beach profiles and the completion of beach to inner shelf profiles.

1.6 THESIS OUTLINE

It was mentioned previously that research for this thesis has entailed a number of wide ranging sub-investigations. The organisation of the thesis reflects this.

The first part consists of three chapters which are intended to serve as a background. These chapters gather together relevant

information existing prior to the present study. In Chapter Two literature on coastal and inner shelf sedimentation is briefly reviewed, both for overseas and within New Zealand. This chapter further defines the research context in which this study has been conducted by defining terminology and proposing a conceptual model. Chapters Three and Four are devoted to, respectively, geologic and geomorphic factors, and physical environment factors. These factors are described in terms of their relevance to the east coast of Northland, and the deposits of the study area. Chapters Three and Four also form the background against which field research results are presented in Chapters Five to Eight.

Chapter Five deals with coastal deposits and describes modern beach sediments, morphology, and dynamics as they occur in response to various marine processes. The nature of beaches is also related, where possible, to inner shelf regions adjacent to their locations. Chapter Six describes the characteristics of inner shelf deposits through the use of surface sediment mapping and seismic geophysical techniques. These investigations have provided a picture of the three-dimensional sedimentary character of the deposits. This has been used to interpret the origin and evolution of the deposits. Chapter Seven examines the Pataua area in detail since most of the work on inner shelf deposits was carried out in this area. This has included the preparation of detailed surface sediment distribution maps. These maps, along with sub-bottom core data, have been used to infer the stratigraphy and sedimentary history of this particular deposit. Chapter Eight focuses on research findings concerning contemporary processes of seabed wave activity,

sediment movement, and bed morphology on the mixed sand and gravel inner shelf deposit at Pataua. This chapter describes present day sediment activity and in this respect complements earlier chapters on longer term aspects.

Finally, the major conclusions of the thesis are drawn together in Chapter Nine and some suggestions for future research are made.

CHAPTER TWO

TERMINOLOGY, LITERATURE REVIEW, AND CONCEPTUAL MODEL

2.1 INTRODUCTION

This chapter reviews the terminology, literature, and concepts of sedimentation in coastal and shelf research which are considered as relevant to this thesis. A review of terminology is necessary because there is not as yet a completely standardised set of terms in coastal and shelf research. A review of the literature in these fields indicates some of the past characteristics and present developments. This shows the extent to which research concepts and results from other areas, both overseas and within New Zealand, can be applied to the east coast of Northland. Finally, a general conceptual model for coastal and inner shelf sedimentation is developed. This model is proposed as a means of examining the complex interactions which control sedimentation in the study area.

2.2 COASTAL AND INNER SHELF TERMINOLOGY

It was noted by Ingle (1966) that a lack of standardised terms existed among coastal workers. Since then beach and coastal terminology has become somewhat more established. Some currently used references on terminology include King (1972), Coastal Engineering Research Centre (CERC) (1973), and Shepard (1973).

Shelf terminology appears to be at a less developed stage with new terms being proposed for recently recognised features, and some new terms have not been widely accepted in the formal sense. Furthermore, significant changes are still taking place in concepts about shelf sediments, morphology, and environments (Stanley, 1969; Swift et al., 1972; Stanley and Swift, 1976).

2.2.1 Morphologic - Hydraulic - Sedimentary Provinces

The terminology used here follows the general system proposed by Swift (1976) for coastal and inner shelf areas, and is also applicable to the east coast of Northland. As a basis for classification Swift proposes that, when examined in cross-section, the coast and inner shelf consists of a regular succession of three morphologic provinces: the beach, shoreface, and inner shelf (Fig. 2.1). Each province is associated with a distinctive zone of hydraulic activity, and in addition, a related pattern of sedimentary provinces can be included in the classification. This pattern occurs at some, but not all, localities off the east coast of Northland. As will be shown later, the pattern is well developed off Pataua Beach and at the northern end of Ocean

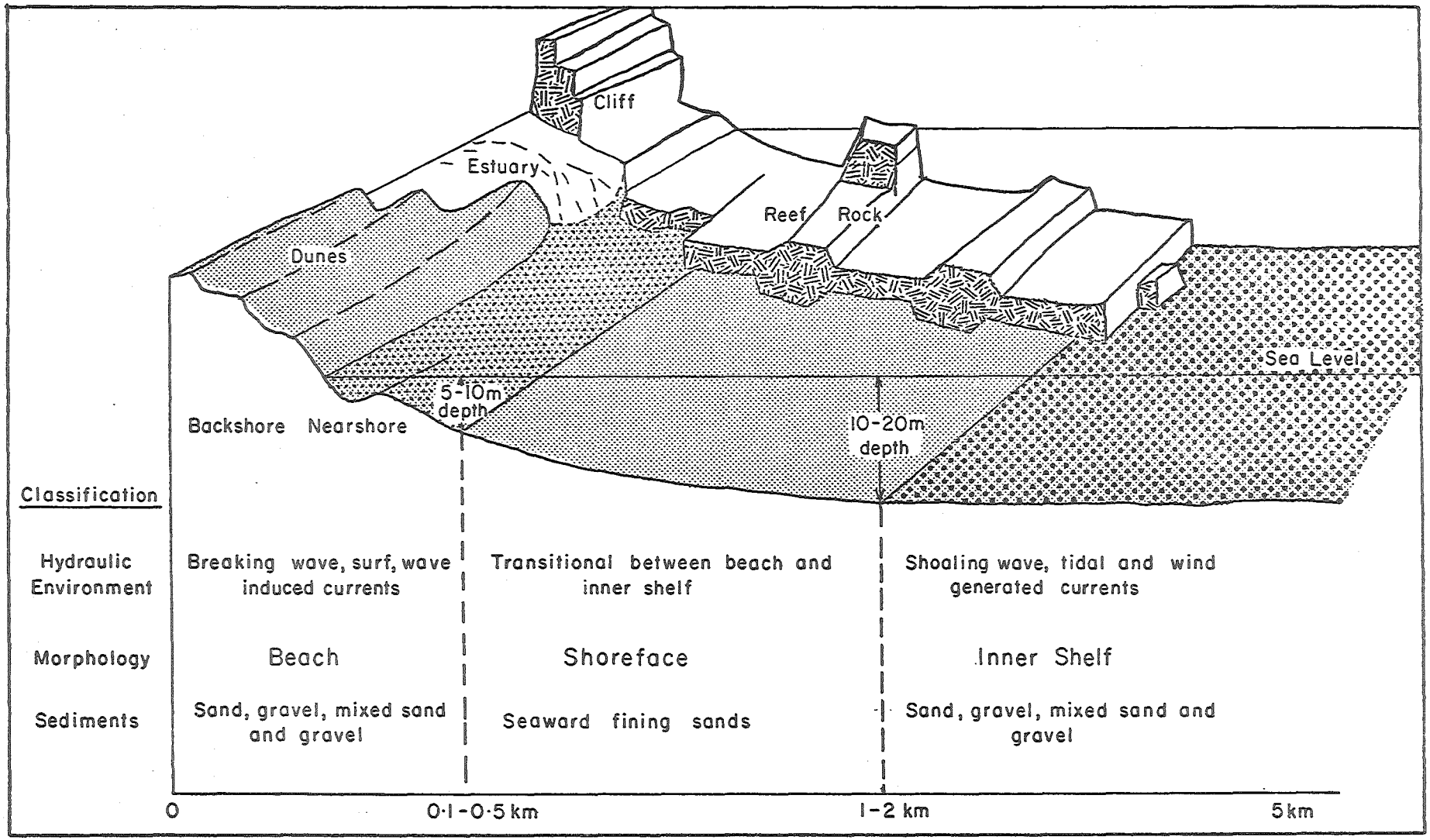


Fig. 2.1 - Coastal and inner shelf terminology. Showing the three major morphologic provinces (Beach, Shoreface, Inner Shelf), with the characteristics of the corresponding hydraulic and sedimentary provinces.

Beach. But at most locations beach sediments merge into rocky areas with no intervening sedimentary shoreface province, and are then replaced further offshore by inner shelf deposits of mixed sand and gravel.

Morphologic Provinces

The three major morphologic provinces are the beach, shoreface, and inner shelf. They are naturally delimited by changes in morphology and the submarine profile. The beach province is an area of complex morphology which consists of backshore, foreshore, and nearshore features. A more detailed description of beach morphology is given in Fig. 5.4. The shoreface usually shows a gently sloping, smooth, concave upward profile. Often there is also a very noticeable break in slope between the shoreface profile and the inner shelf. The inner shelf is flatter and more extensive than the shoreface province. The beach and shoreface areas extend to depths of respectively, 5-10 m and 10-20 m, depending upon wave exposure. In the study area the inner shelf is usually taken to extend out to a depth of 50 m.

Hydraulic Provinces

The related hydraulic provinces are based upon physical environmental factors such as waves, tides, and currents (Fig. 2.1). In addition, different processes of sediment movement are characteristic of each of the three provinces. Within the beach province hydraulic activity is dominated by breaking waves, surf, and wave induced current patterns. Less is known about hydraulic activity in the shoreface and inner shelf areas, but in general they are areas of transition between the wave dominated beach province

and the deeper shelf flow field which is less affected by proximity to the coast. Tidal currents and intermittent wind generated currents are normally thought to be more significant in the shoreface and inner shelf provinces than in the beach province. In terms of waves, the shoreface can be expected to be more strongly influenced by shoaling wave action than the inner shelf.

Sediment Provinces

The sediment provinces corresponding to the above described morphologic and hydraulic provinces reflect both sources of sediment and mechanisms by which sediment can be dispersed in the whole system, and within provinces. Beaches in the study area consist of sand, with mixed sand and gravel being less frequent. There may also be prominent sediment sorting phenomena within each beach. The shoreface typically displays finer sand size sediment with a seaward fining trend. This type of trend has been interpreted by other workers as due to either a sorting mechanism explained by the "null-line" hypothesis (Johnson and Eagleson, 1966), or by the fall out of suspended sand derived from the turbulent waters of the beach province (Murray, 1967; Cook and Gorsline, 1972). Shoreface sand may also be equated with the term "nearshore modern sand prism" (Swift, 1970), but as will be shown later, sand in the field area is probably not presently being derived from terrigenous sources in significant quantities, and instead represents the landward movement of marine derived sediment. Lastly, off the east coast of Northland, coarse inner shelf deposits are composed of sand, mixed sand and gravel, and gravel sediment in a discontinuous cover over the seabed. It will be shown later that the inner shelf deposits

are mostly "palimpsest" (Swift et al., 1971) meaning that they are reworked portions of older sediments.

2.2.2 Shelf Sediment Terminology

Much of the overseas work on shelf sedimentation has traditionally been concerned with surface sediment distribution. A brief review of the evolving concepts of shelf sediment terminology illustrates this.

Johnson (1919), in summarising earlier work, proposed that the shelf should consist ideally of an inner wave cut platform and an outer wave built depositional terrace. The outer portion was termed a "marine profile of equilibrium" with surface sediment showing a seaward fining pattern in equilibrium with the shelf slope and wave base processes. Johnson's concept of the "graded shelf" was challenged by later empirical observations of shelf sediment distributions (Shepard, 1932; Emery, 1952; 1968) which showed that most shelves are covered with a complex pattern of coarse and fine sediments, rather than a simple seaward finding trend. The coarser sediments found were considered to be "relict" and deposited under different conditions during lower stands of sea level in the Quaternary period.

Many shelf studies have since dealt with shelf sediment distribution and its interpretation (as reviewed by Swift, 1969; 1970; 1972; Swift et al., 1971). From these studies and earlier ones, a number of terms have been selected for use here, and which can be classified on the basis of sediment source and age definitions as follows:

Source Definitions

(i) terrigenous: sediment derived directly from the land through river or coastal erosion

(ii) biogenic: sediment of predominantly calcareous composition from marine molluscs

(iii) residual: sediment produced in situ from the erosion of submerged rock exposures

(iv) marine: seabed sediments of any initial source, which have been extensively transported along the shelf, or shoreward by marine processes

Age Definitions

(i) relict: remnant from a different or earlier environment of deposition

(ii) palimpsest: sediment which exhibits attributes of both earlier and later, usually modern, depositional environments

(iii) modern: sedimentary deposits which have been formed in equilibrium with marine processes since the stabilisation of sea level about 6,000 yr BP, or which are presently being supplied to the shelf by terrigenous, biogenic or residual sources

Finally, Swift (1976) has used the terms "allochthonous" and "autochthonous" to describe shelf sediment patterns resulting from different mechanisms of sediment dispersal. Allochthonous sedimentation occurs through the contemporary bypassing of river derived fine sediment across the beach and shoreface, to be deposited on the shelf. In contrast, autochthonous shelf sedimentation results from

sheets of sand, and/or gravel, which were generated locally on the shelf by the process of beach and shoreface retreat during transgressive phases.

2.3 LITERATURE REVIEW

2.3.1 World Studies

The geomorphology and sedimentology of coastal and continental shelf areas is the subject of a substantial amount of literature. However, it has been noted by Davies (1972) for coasts, and by Emery (1976) for continental shelves, that there is a significant degree of geographic bias in coastal and shelf studies. Davies remarks on the concentration of much coastal work in the mid to high latitudes of the northern hemisphere, especially on the east coast of North America and in Europe. Similarly, Emery estimates that the vast bulk of shelf research has been concentrated on only 10% of the world's shelf area. This area also tends to correspond geographically to the areas of coastal study concentration. This is relevant, since it may mean that results from these areas of concentrated study can only be applied tentatively to other areas. In this respect, it is also significant that the characteristics of eastern North American and European shelves include:

(i) wave environments showing marked seasonal storm wave variations (Davies, 1972, p 29);

(ii) hydraulic environments, in the case of the European shelves,

which are strongly influenced by tidal current action (Belderson and Stride, 1969; Kenyon and Stride, 1970);

(iii) a relatively large and recent supply of sediment to the coast and shelf from Quaternary glaciations; and

(iv) a tectonic situation characterised by relatively stable, old, and large "trailing-edge coasts" (Inman and Nordstrom, 1971).

None of these characteristics are typical of the present study area. In this respect, conditions more nearly approaching those of the study area appear to characterise the coast and shelves of southeast Australia. Southeast Australia has an extensive, rocky cliffed coast, with sand beach embayments forming separate sediment compartments (Bird and Dent, 1966; Davies, 1974; Thom, 1974; Gill, 1975). The shelf is narrow and steep, and is thinly floored with relict terrigenous sands (Phipps, 1963; Shirley, 1964; Bird, 1971), which have apparently been the source of present-day beach and barrier sands (Thom, 1965; Hails, 1968).

The most geographically broad research on inner shelf sedimentation has been that of Hayes (1964; 1967) which examined the world-wide distribution of inner shelf bottom sediment type. Hayes made the following conclusions:

(i) Bottom sediment types, except for shell, were most strongly related to climatic factors. Thus, mud is most abundant off areas with high temperature and high rainfall (humid tropics). Sand is everywhere abundant and increases to a maximum in intermediate zones of moderate temperature and rainfall. Gravel is most common off areas of low temperatures (polar and subpolar). Rock is generally more abundant in cold areas. As an exception, shell distribution is

uniform between the equator and the poles and is not diagnostic with regard to climate;

(ii) Climatic factors were thought to affect sediment type in a number of ways, primarily by controlling sediment availability through the determination of weathering characteristics of rocks, and through the relative abundance of major rivers from precipitation rates.

(iii) Alternative strong controlling factors were the inner shelf slope and the gradient of streams feeding sediments to the coast, both of which are determined primarily by tectonism. Rock was found to be more common on narrow than on wide inner shelves. Sand and gravel percentages showed little relation to source stream gradient, but mud increased as source stream gradient decreased. However, within a tectonic grouping, the effect of climate once again was shown to be the primary controlling factor;

(iv) Factors which exerted a local influence were source rock types, and hydraulic energy (waves, tides, and currents);

(v) Finally, the role of abundant relict Pleistocene sediment is of great importance on all shelves of the world. Thus, the starting point in interpreting present-day sediment patterns is the realisation that during the Holocene transgression a vast basal deposit of "coarse" sediments was left spread over the shelf, either as a result of covering subaerial deposits or of reworking and depositing littoral sediments. Hayes could have also added the production of coarse sediments from erosion, during Pleistocene transgressions, of steep, rocky coasts like that of the present study area.

Some of the more recent developments in shelf research include attempts to relate coastal sediments and geomorphology to adjacent inner shelf characteristics through research into

Quaternary histories (Hails, 1975), and wave refraction studies (Bird, 1971; Price et al., 1972; Goldsmith et al., 1976). In addition, process studies of shelf environments have been developed in recent times (as reviewed in Swift et al., 1972; Stanley and Swift, 1976). These process studies have revealed the complexity of shelf current velocity fields and the equally complex manner in which the sediment substrate responds to these currents. This topic is discussed further in Chapter Four.

2.3.2 New Zealand Studies

Coastal Research

In a recent review of coastal research in New Zealand McLean (1976a) described the coast as being long ($\geq$ 10,000 km) and diverse with abrupt changes from place to place. This diversity is apparent in the regional variations which exist in coastal sediments, processes, and responses.

New Zealand beaches are primarily composed of either sand, or mixed sand and gravel sediment. Regionally, sand of quartz-feldspar mineralogy predominates in the southern (Bardsley, 1972) and northern (Schofield, 1970) parts of the country, while most west coast beaches are composed of "ironsand" mineralogies (Summerhayes, 1967). Extensive mixed sand and gravel beaches are found on the east coast of both islands and are derived from the greywacke rocks of the main ranges (Kirk, 1969; McLean, 1970; Pickrill, 1977). There are also many other regions with distinctive, mixed textural and lithological characteristics. In this respect, the present study area has components of both sand quartz-feldspar, and

mixed sand and gravel greywacke sediments (Schofield, 1970). A biogenic component, in the form of shell detritus is also present in large quantities.

New Zealand beaches are largely dominated by wave processes rather than tidal or other ocean currents. Wave climates around the country basically vary between the large swell dominated west coast, and the lower swell wave environment of the east coast. However, swell and storm waves can occur from almost any exposed direction, and for local areas quite complex wave climates exist (Kirk, 1975b; Brown, 1976; Harray, 1977; Pickrill, 1977). Although New Zealand wave climates are known to vary from place to place, because of inadequate data a more exact definition must await further developments (Kirk, 1977a; NZOI, 1978). In this respect, an attempt is made in Chapter Four to identify some of the major components of the wave climate in the study area.

It has been estimated that as much as a third of the New Zealand shoreline may be eroding naturally (Kirk, 1977b). This erosion is probably occurring as a result of a number of causes. These include decreases in sediment supply to the coast from river or offshore sources, sea level changes, and gradual shifts in longshore drift accumulation (Schofield, 1967; 1975; Armon, 1974; Healy et al., 1977; Gibb, 1977; 1978). In addition, some areas appear to be experiencing man-induced erosion from beach and inshore dredging (Schofield, 1975; Healy et al., 1977), and from a reduction in sediment input from controlled rivers (Kirk et al., 1976). In contrast, most sections of the coast are in a state of apparent stability with only a small proportion showing progradation. The prograding sections are localised where large amounts of fluvial or

longshore derived sediment have accumulated (Pullar and Selby, 1971; Kirk, 1975b; McLean, 1976b; Pickrill, 1976; Healy, 1977; Williams, 1977). Compared to many places in New Zealand, the east coast of Northland represents an area of relative coastal stability, but as is shown in Chapter Five, it also exhibits significant natural fluctuations.

There are also significant regional variations in tectonism in New Zealand. This is another factor, along with the others described above, which militates against the areal extrapolation of research results within the country.

It has also been observed by McLean (1976a) that the total length of coast, as well as the number of topics investigated in coastal research have been small, and that because of this, large geographic and thematic imbalances exist in past research about the New Zealand coast. Geographic imbalances include the large amount of work carried out on the morphology, sediments, and dynamics of mixed sand and gravel beaches along the east coast of the South Island. This is in contrast to the more areally extensive ironsand and quartz-feldspar beaches of the North Island, although more research has recently been conducted in these latter areas (see review in Healy et al., 1977). Among thematic imbalances is the past emphasis on rocky shorelines (Cotton, 1974) and more recently on present-day beach process-response studies. There has been less work done on the evolution and development of larger scale coastal features, although this approach has recently been taken in some study areas (Armon, 1974; Campbell, 1974; Gibb, 1977; 1978). Included in this latter subject are the longer term relationships between coast and inner shelf deposits which form a part of this thesis.

In summary, as a consequence of the coastal diversity and limitations in past research noted above, the translation of research results from one coastal location to another in New Zealand is often impractical, which emphasises the need for specific regional studies such as the present one.

Shelf Research

The nature of continental shelf sedimentation around New Zealand is similar to that of the coast in terms of its diversity between regions (Carter, 1975). This is apparent in the variable contribution that modern terrigenous sediment makes to the shelf cover. This can vary from:

(i) an entire blanketing by modern terrigenous sands and muds, as off northwest Nelson (Norris, 1972) and Hawke's Bay (Lewis, 1973a);

(ii) an inner portion of modern terrigenous sand and silt, and an outer portion of modern terrigenous mud or relict terrigenous sands, gravels, and biogenic sediment, as off the western North Island shelf (McDougall and Brodie, 1967), and the Otago and Canterbury shelves (Andrews, 1973; Herzer, 1977);

(iii) shelves on which the sediment cover is almost entirely relict or residual terrigenous and biogenic. The extreme northern part of the North Island shelf is described as this type (Summerhayes, 1969a; 1969b), and as will be shown later is in many respects similar to the present study area.

This diversity in shelf sedimentation is due to the wide variation in bathymetric, lithologic, tectonic, climatic, and hydraulic conditions which act as controlling factors in shelf sedimentation around New Zealand (Carter, 1975). In this respect, the New Zealand

shelf shows almost as much diversity as Hayes (1967) described from a world-wide sample.

Although some of the regional relationships between shelf sediment type and controlling factors have been well defined, much still remains to be discovered about the nature of sediment distribution within local areas. In particular, the mechanisms of sediment dispersal during the Holocene and under contemporary shelf environments have not been investigated for much of the New Zealand shelf. The exception to this is the Southland-Otago-Canterbury shelf where an emphasis has been placed on the primary dispersal of sand and gravel by pre-Holocene rivers (Cullen, 1966; Carter and Ridgway, 1974), with a secondary dispersal taking place during Holocene and contemporary times by along the shelf movement under the influence of storm driven winds and currents, along with tidal and ocean currents (Andrews, 1973; Carter and Heath, 1975). In this region there is still much controversy over how "relict" or "modern" the sediment distribution and morphology may be, and over the role of currents, tides, and waves in contemporary shelf sediment-water interactions (Schofield, 1976). These regions probably represent the strongest examples of sediment dispersal along the shelf in New Zealand and may not be representative of other regions such as the more sheltered shelf between North Cape and East Cape. Here shelf sediment dispersal during Holocene and contemporary times may have been oriented more across the shelf.

Apart from some studies which have been situated in regions similar to that of the east coast of Northland, it must be concluded that previous studies from both overseas and within New Zealand can

only provide a limited amount of information about the possible nature of shelf sedimentation in the study area.

2.4 CONCEPTUAL MODEL OF COASTAL AND INNER SHELF SEDIMENTATION

Beginning with some early concepts, as summarised by Johnson (1919), numerous models have been proposed for the formation of continental shelf morphology and sediments. As well as conceptual models, a number of classification schemes for coastal and shelf areas have been proposed. These, like models, are valuable in providing a means of assessing the relative role that different factors take in producing the characteristics of coastal and shelf sedimentary systems (Hayes, 1967; Davies, 1972).

Notable conceptual models and classification systems which have been proposed for coasts and shelves include those of Johnson (1919), Krumbein (1963), Davies (1964; 1972), Curray (1964), Bloom (1965), Swift (1969; 1970; 1976), Inman and Nordstrom (1971), and Lewis (1974). Most of these models are fundamentally the same, and are equally applicable to either coast or shelf regions since they employ similar features including:

(i) initial geologic and tectonic control;

(ii) alteration of the landmass through environmentally controlled erosional and depositional processes;

(iii) distribution of sediments to the shelf, and on the shelf by sediment dispersal mechanisms; and

(iv) the added effects of time-dependent factors such as tectonism, changes in sea level, climate, and sediment supply.

Models which have incorporated sea level change as a factor are specifically referred to as "transgressive-regressive" models. These are very relevant to the evolution of present-day shelf sediment surfaces which have experienced many Quaternary changes in sea level, and most importantly the transgression associated with the latest "post-glacial" sea level rise.

One of the most often used approaches to the study of sedimentary systems is the process-response conceptual model (Krumbein, 1963; Krumbein and Sloss, 1963; Swift, 1969). This model has been adapted for use in this thesis and is presented in its fully developed form in Fig. 2.2. Most of the factors in the model have been described in the preceding discussion and it is of interest now only to make mention of a few features.

In the Input Elements of "Geologic and Geomorphic Factors" and "Physical Environment Factors" the model incorporates factors which accounted for the world-wide variations in inner shelf sediment type found by Hayes (1967). The model is also dynamic and incorporates a feedback loop which, for example, will allow changes in inner shelf morphology to affect changes in wave energy input to the coast.

Two of the sediment dispersal mechanisms have been called "shoreface bypassing" and "river mouth bypassing" (Swift, 1976). Shoreface bypassing refers to the process by which sediment is transferred from the beach or shoreface to the shelf through erosional shoreface retreat during marine transgressions. River mouth bypassing refers to the contemporary movement of fine sediment from

CONCEPTUAL MODEL OF
COASTAL AND INNER SHELF SEDIMENTATION

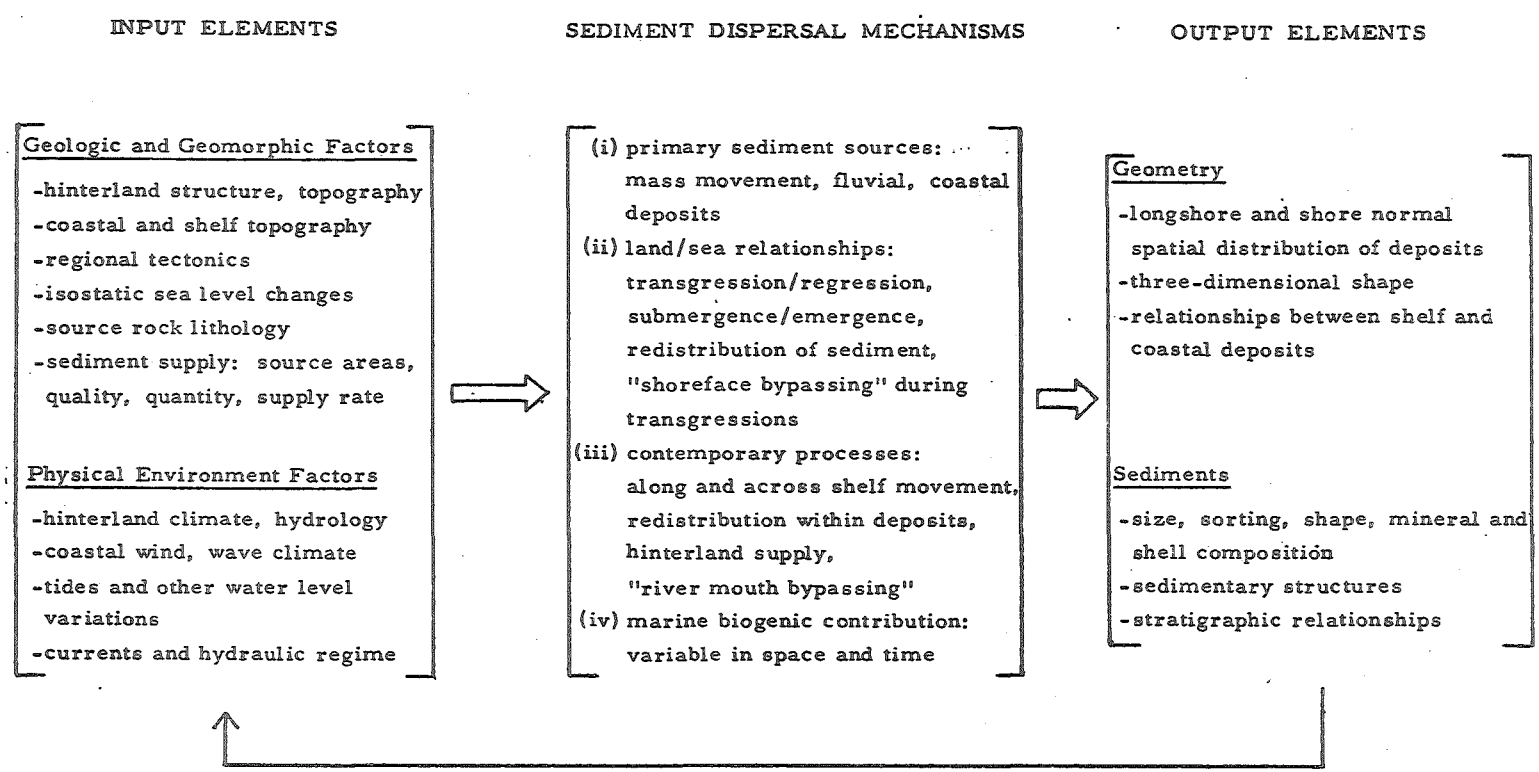


Fig. 2.2 - Conceptual model of coastal and inner shelf sedimentation.

rivers across the shoreface and inner shelf, to be deposited on mid and outer shelf areas.

The origin and evolution of coastal and inner shelf sediments in the study area is due to the complex interaction of the factors outlined in this conceptual model (Fig. 2.2). A large part of this thesis has been concerned with determining the role and relative importance of these factors, specifically, in Chapter Three on Geologic and Geomorphic Factors, and in Chapter Four on Physical Environment Factors.

2.5 SUMMARY

This review of the terminology, literature, and concepts of sedimentation in coastal and shelf research has discussed a number of features which are relevant to this thesis. The definitions of morphologic-hydraulic-sedimentary provinces, and seven sediment terms based on sediment source and age definitions, will facilitate the description and interpretation of research results in later chapters. A review of coastal and shelf research literature from both overseas and within New Zealand demonstrates the extent of the geographic diversity which exists, the limitations of past research, and the need for specific regional studies such as the present one. On the other hand, most general concepts of coastal and inner shelf evolution and development, such as the roles of geomorphic and geologic factors, physical environment factors, and sediment dispersal mechanisms, can be usefully applied to the present investigation.

CHAPTER THREE

GEOLOGIC AND GEOMORPHIC FACTORS

3.1 INTRODUCTION

The interpretation of present-day landscapes is usually made possible by considering the past influence of geologic and geomorphic factors (Thornbury, 1969). In this context, geologic and geomorphic factors have contributed significantly to the character of present-day coastal and inner shelf deposits in the study area through providing not only the basic structural and topographic framework for depositional locations, but also the source of material for sedimentary deposits. Furthermore, past climatic and geomorphic events and sea level changes have also had significant influences. This chapter illustrates the nature and extent of these influences in the study area through the synthesis and interpretation of relevant studies. Some hypotheses are also presented for the evolution of coastal and inner shelf areas and these are examined in more detail, along with supporting evidence, in later chapters.

To further familiarise the reader with the study area, the general topographic and erosional-depositional features of the coast, inner shelf, and adjacent hinterland are described. This includes a description of inner shelf bathymetry and surface sediment characteristics on a regional scale, which is intended to form a background for

the presentation of results from more detailed studies in later chapters.

In order to fully appreciate the relevance of geologic and geomorphic factors they are viewed in a larger spatial and temporal context than merely the present time and the local study area. The pre-Quaternary geology of Northland is outlined in terms of the structure and lithology of the rocks, and the influence of tectonic events on the probable mode of formation of the continental terrace. Next, hypotheses for the geomorphic evolution of the continental shelf and hinterland during the Pleistocene epoch are presented. Consideration of paleoclimatic and paleogeomorphic factors on land, and the likely affects that glacio-eustatic sea level changes have had on continental shelf development are discussed.

Finally, this description of the evolutionary history of the study area is completed with an outline of Holocene events. These have been dominated by the submergence of the shelf by the last "post-glacial" sea level rise. This submergence, with its related sediment dispersal processes, probably represents the event which has had the strongest influence on the present-day characteristics of coastal and inner shelf sand and gravel deposits.

3.2 GENERAL CHARACTERISTICS

3.2.1 Coastal Deposits

Exposed ocean beach deposits occupy only 15% of the shoreline (Table 1.1) and occur as isolated deposits of limited size (Fig. 3.1; Plate 3.2; 4.1; 4.2). Beaches usually occur as pockets of sediment at the mouths of narrow, alluvium filled valleys and are often backed by Holocene age, swampy flats landward of low, prograded coastal dunes.

3.2.2 Inner Shelf Bathymetry and Sediments

The inner shelf off the east coast of Northland has been arbitrarily taken to extend to the outer depths (50m) of the deposits located in Fig. 1.1. The inner shelf is narrow and steep, and almost everywhere along its length reaches a depth of 50 m within 5 km of the coast (Fig. 3.2). Off Cape Brett, where the shelf is very steep, depths of over 100 m are reached within 2 km of the coast. Profiles along the inner shelf, taken from approximately 1:50,000 scale Navy charts, show topographies and slopes for selected points along the coast (Fig. 3.2; 3.3). Profiles off capes and headlands (1, 2, 4) have the steepest overall slopes of 1.3^{o} with maximum slopes of about 10^{o}. Profiles off embayments (3, 5, 6) are flatter (0.3^{o}), and for depths less than 30 m show irregular, rock reef, bottom topographies. In contrast, at depths greater than 30 m on most profiles, the seabed is relatively smooth. The significance of this is inter-

preted in Section 3.4. Profiles off beaches (5, 7) can show either an irregular bottom topography, or in the case of Ocean Beach, a smooth concave profile which is typical of the submarine portions of other large beaches immediately south of the study area (Schofield, 1975).

In Fig. 3.2, inner shelf sediments can be seen to consist almost exclusively of gravel and sand. This pattern changes to muddier sediments at mid-shelf depths and then back to sand on the outer shelf and upper slope. Eade (1974) indicates that the sand and gravel sediments at inner shelf depths are almost entirely free of fines (silt and clay). It should be noted that Fig. 3.2 does not show the high frequency of rock which outcrops on the seabed in inner shelf areas as shown in the chart of the Hydrographic Office (1973). This probably indicates a relatively thin, discontinuous cover of inner shelf sediments rather than one which is thick and extensive.

3.2.3 Hinterland Characteristics

The topography and drainage catchment of the east coast hinterland is shown in Fig. 3.1. The hinterland is rolling to steep (Plates 3.1; 4.2) with summit elevations in excess of 450 m within 5 m of the coast. Thus, as a broad regional comparison, the hinterland is approximately 5 times as steep as the inner shelf, 5^{o} as opposed to 1^{o} respectively. The hinterland is also deeply dissected by a dense, essentially dendritic drainage network. At the coast the two contrasting geomorphic regions of the hinterland and inner shelf are separated by the beaches described above and by near-vertical cliffs developed in the basement rocks. The cliffs locally exceed

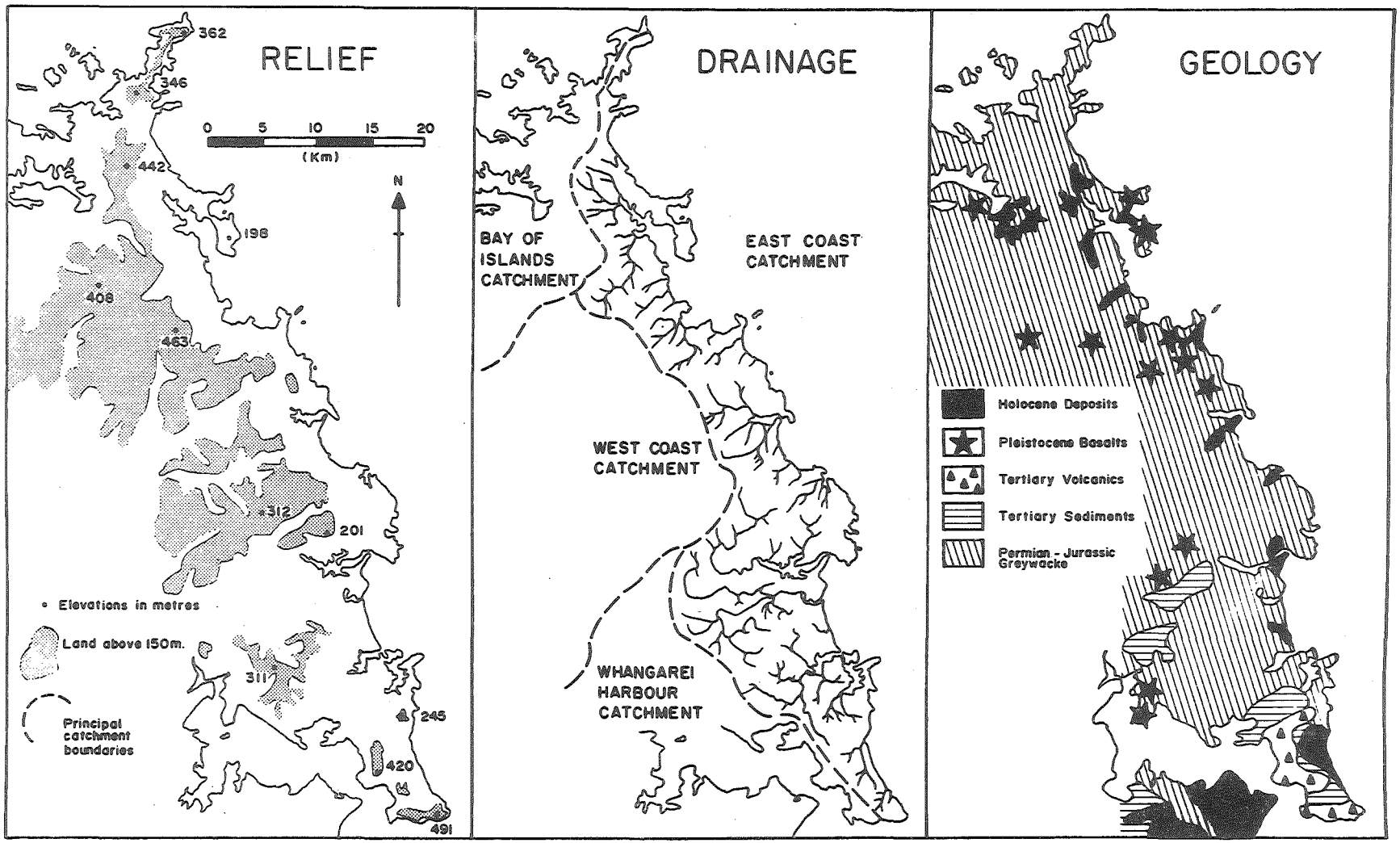


Fig. 3.1 - Relief, drainage, and geology. Relief and drainage from NZMS 18, Sheets 1, 2. Geology from Kear and Hay (1961), and Thompson (1961).

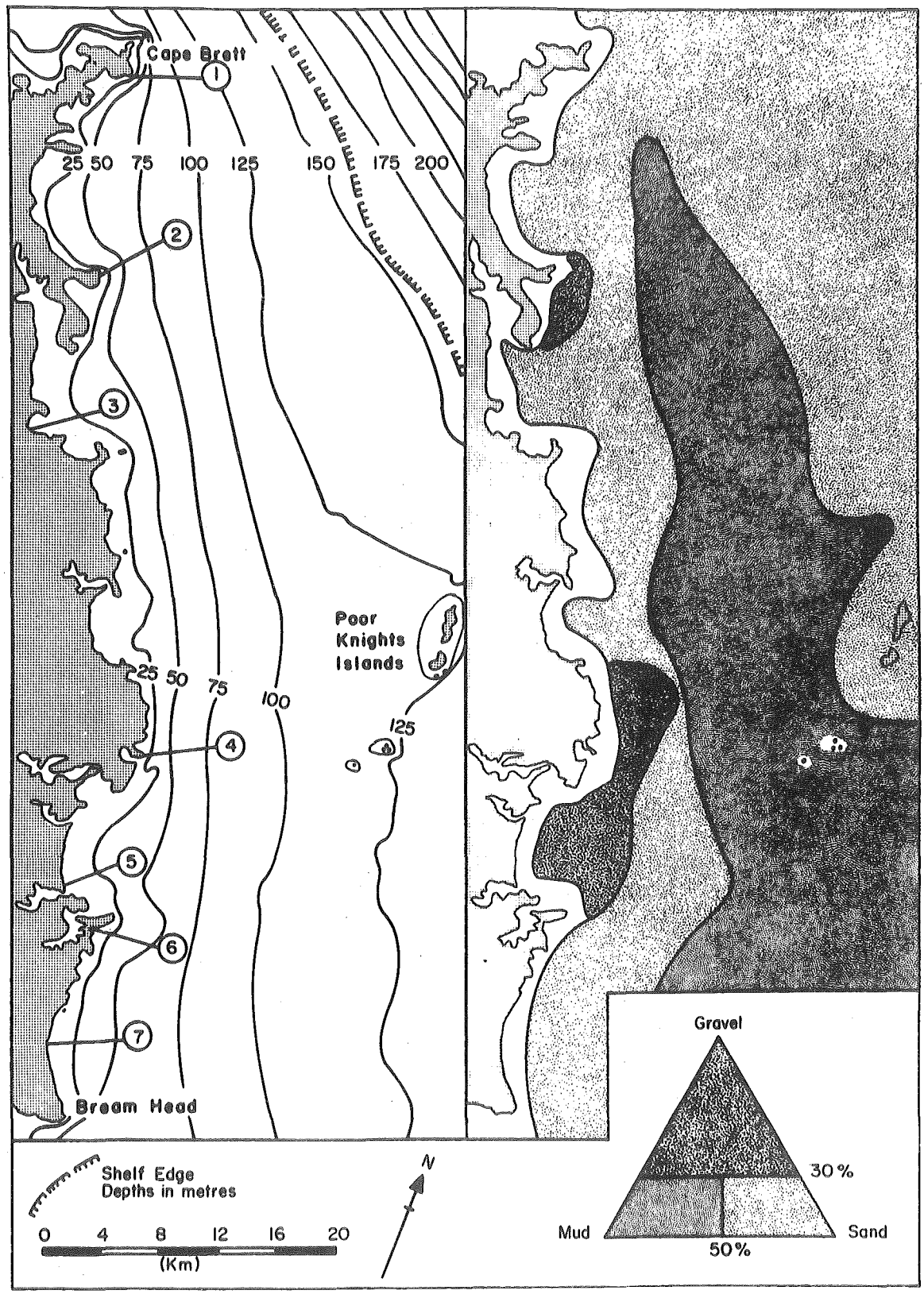


Fig. 3.2 - Shelf bathymetry and surface sediments. Simplified from Eade (1971; 1974). See Fig. 3.3 for inner shelf profiles (1) - (7).

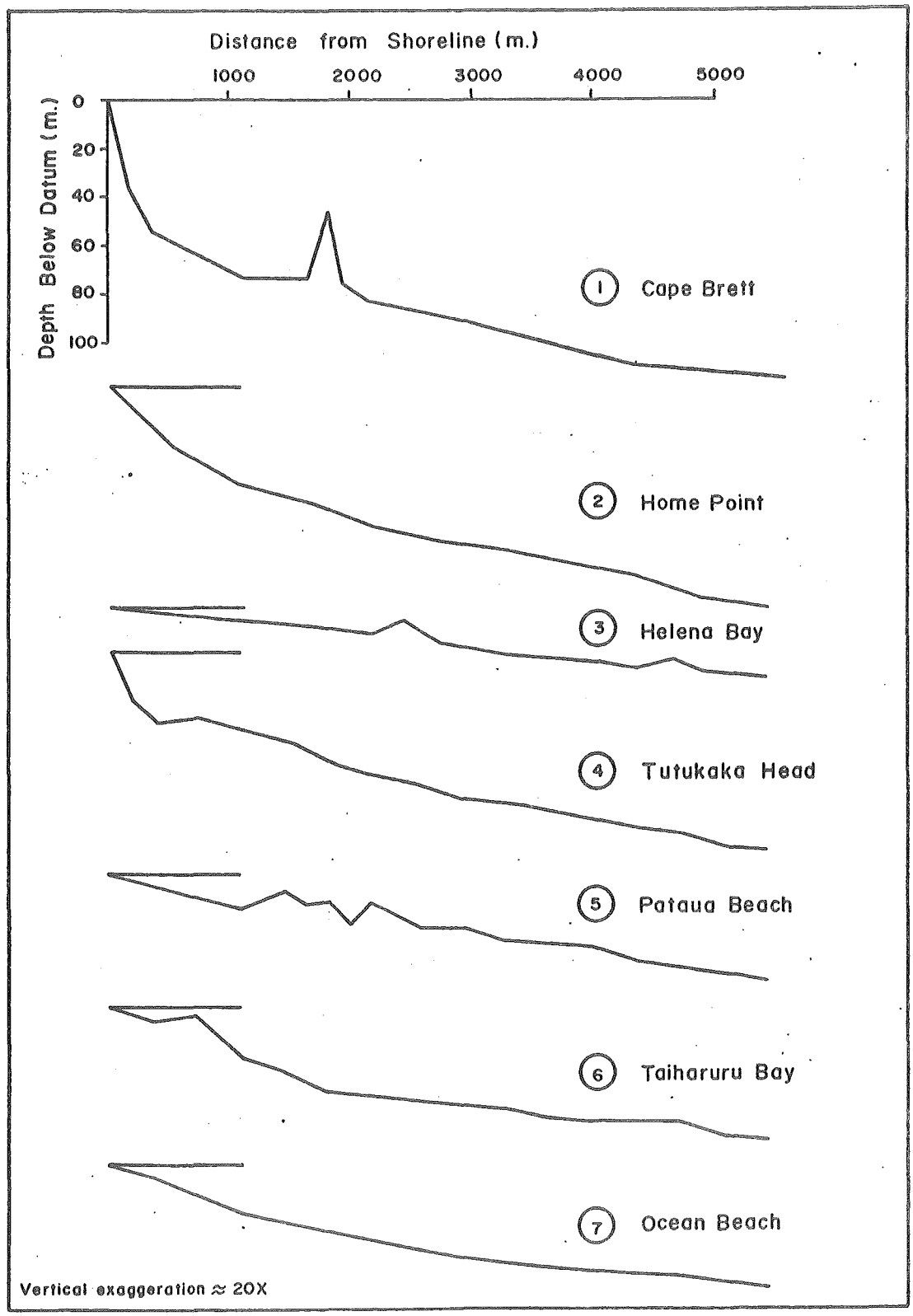


Fig. 3.3 - Inner shelf profiles. For locations of profiles see Fig. 3.2. Depths at 5000 m from the shoreline vary from 30 m to 113 m. Slopes vary from 0.3° to 1.3° with a maximum of 7.8°. Data for profiles from Charts 521/10, 20, 30, 32 of Hydrographic Office, RNZN.

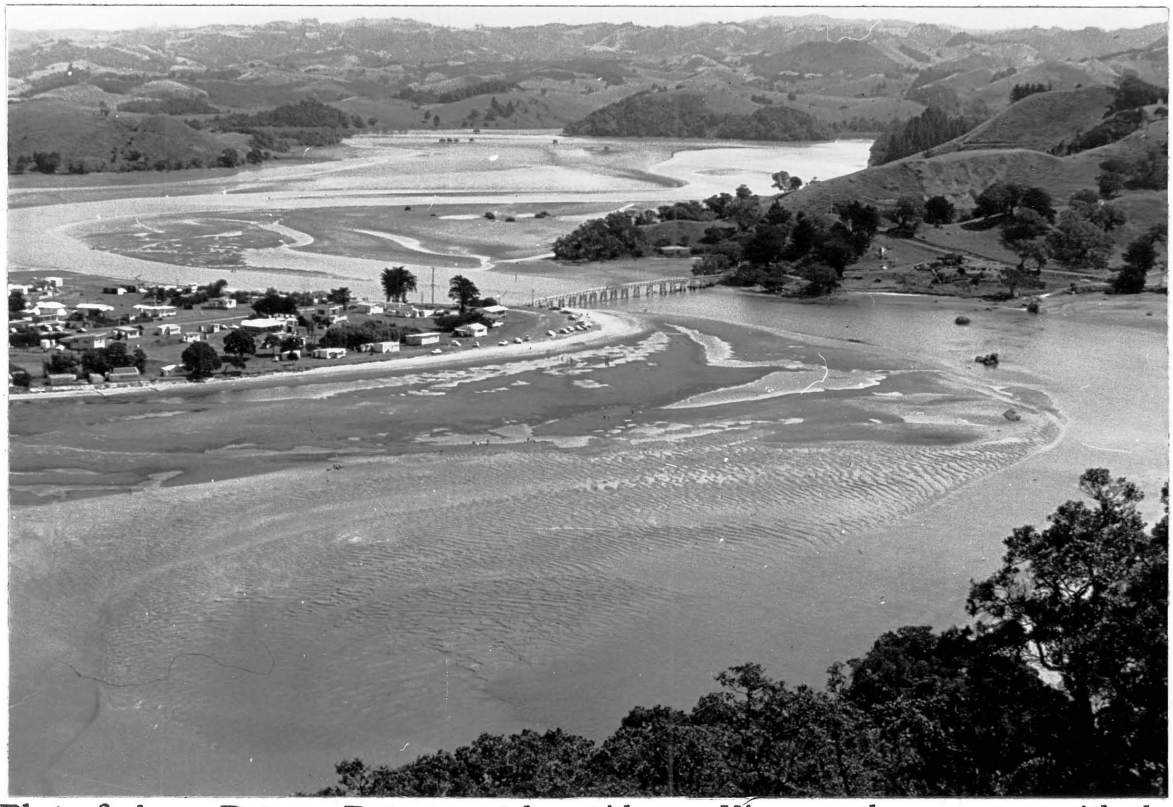


Plate 3.1 - Pataua Estuary at low tide. View up the estuary with the inlet off the lower right of the plate. Sediments consist of terrigenous fines in the upper reaches and marine sands and shell detritus in the lower reaches.

Plate 3.2 - "Wiwiki Beach", north of the Bay of Islands, is typical of the isolated, exposed, pocket beaches along this rocky coast. Note the development of high cliffs and shore platforms. The Ninepin prospecting area lies off the distant headlands.

300 m in height (as at Cape Brett), but they are generally in the order of 50 to 100 m (Plate 3.2).

The hinterland catchment boundary lies very close to the east coast, in places less than 5 km distant (Fig. 3.1). Therefore, although stream gradients are steep, no major rivers are developed along the east coast because of the small catchment areas.

On land, weathering of the bedrock has occurred to a depth of 20-30 m, producing a mantle of fine material. This mantle is believed to be the product of a warm, wet climate and forest vegetation acting over a very long period of time without a major renewal of weathering surfaces (Smidt et al., 1977). Only in the upper reaches of steep stream gorges and along coastal cliffs is unweathered greywacke bedrock exposed. Where streams leave the hills, coarse sand and gravel sediment is presently being stored as bed and floodplain deposits, with floods removing finer sediments to the sea. Coarse sediments are probably not presently being supplied to the coast from stream and river sources.

3.3 PRE-QUATERNARY GEOLOGIC HISTORY

The geologic structure of the Northland Peninsula (as identified on maps by Kear and Hay (1961), and Thompson (1961)) consists of north-northwest trending major faults and outcrops of rock units with Permian-Jurassic greywackes of the east coast forming the apparent basement rock (Fig. 3.1). The coastal and hinterland rock of the study area consists almost totally of these greywackes, which are known as the Waipapa Group (Bell and

Clark, 1909; Ferrar, 1925; 1934). They have been inferred to be a deep water geosynclinal facies termed the Hunua Facies (Kear, 1971). The greywacke rock is intensely deformed, jointed and sheared with locally complex structures and is well indurated with secondary quartz veining. Also present within the greywackes are argillites, chert and associated manganese, and interbedded basic marine volcanics.

A north-northwest structural trend is also suggested within the greywacke rocks by the strike of regional chert bands and the general trend of bedding planes which commonly dip west-southwestward at angles of 40^{o} - 70^{o}. Elliot (1966) postulated that block faulting has divided the region into distinctive physiographic units such as the high standing block between Matapouri and Ngunguru and the lower standing area extending south from Ngunguru. This alternation of high and low standing physiographic units continues along the coast both to the north and south (Plate 4. 2), and accounts for the location of the major coastal embayments such as Ngunguru Bay, Sandy Bay, Whangaruru Harbour, and the largest - the Bay of Islands (Fig. 1. 2). Elliot also states that cherts outcrop as erosion resistant ridges which are irregular in distribution and extent. Furthermore, there is no marked accordance of summit elevations as postulated by Turner and Bartrum (1929) for their interpretation of an old peneplain surface.

3.3.1 Continental Terrace Formation

The formation of the continental terrace off the east coast of Northland can be examined by reference to the general concepts of Lewis (1974) and to regional studies by Brothers (1974) and Ballance (1976). Lewis proposed that the development of a continental terrace should be considered in terms of three main stages:

(i) first, the primary formation of a major discontinuity between continental and oceanic crust;

(ii) second, the deposition of sedimentary strata; and

(iii) third, Quaternary modifications to form the present topography.

The primary formative stage in Northland was initiated in the uppermost Oligocene with a reversal of subduction polarity along the Indian-Pacific plate boundary. The situation that resulted from this event would seem to correspond most closely to the "modern continental accretion-orogenesis" primary origin type of Lewis.

Later, in the lowermost Miocene, the Kaikoura system of orogenesis, sedimentation, and volcanism reached its tectonic climax in Northland (Brothers, 1974). At this time the second stage of continental terrace development occurred as a gravity slide emplacement of a shelf of upper Cretaceous-Oligocene trench sediments on to the greywacke basement rock. This development stage continued through the Tertiary with epicontinental marine sedimentation and concurrent arc forming volcanism. The apparent completion of the Kaikoura Orogeny in Northland occurred in the form of upper Miocene block faulting on a regional scale. In addition, speculation on evolution during the late Tertiary (Ballance, 1976) suggests that Northland was

being removed progressively westward away from the influence of the arc-plate boundary which presently takes the form of the Kermadec Ridge and Trench system, some 600 km to the northeast. Thus, since before the lower Miocene, Northland has been a region of behind arc volcanism which has largely taken the form of basalt flows in Pliocene-Pleistocene times. These basalt flows occur as isolated remnants within the east coast block of greywacke rock (Fig. 3.1). It is also noteworthy that marine sediments of Pliocene age are absent in Northland (Brothers, 1974), so that at the end of the Miocene the east coast of Northland probably had a cover of upper Cretaceous-Miocene sediment and volcanic rocks over its greywacke basement rock. There is presently little remaining of this cover along the east coast study area.

3.4 PLEISTOCENE GEOMORPHIC HISTORY

Pleistocene geomorphic events along the east coast of Northland have occurred under conditions of relative tectonic stability in comparison to late Tertiary times. For coastal and shelf regions, the large eustatic sea level changes caused by global glacial-interglacial stages in higher latitude areas, seem to have had a predominantly erosional influence on the continental shelf. Hinterland evolution has probably taken place under a warm, moist climate similar to that of the present with normal humid, temperate subaerial processes of erosion being modified only slightly by fluctuation in base levels due to sea level changes.

3.4.1 Tectonics

A tectonic stability map of Northland for the late Quaternary (Lensen, 1977) does not show any active faults in the region and indicates that there was no tilting of sediments as old as upper Miocene. Furthermore, Northland is presently considered to be essentially aseismic with the largest known recent event being an isolated shock of Richter magnitude 5.2 near Kaitaia in 1963 (Eiby, 1964; 1971).

Vertical earth movements in the Northland region, which are apparently independent of faulting or tilting, have occurred very slowly though. Vertical movements are estimated by Lensen to have local rates of $\pm$ 0.2 mm/yr, which is equivalent to $\pm$ 20 m/100,000 yr. Lensen's estimate is most likely based on work which has been done on a flight of coastal terraces in the South Kaipara-Southwest Auckland region (Brothers, 1954; Chappell, 1970; 1975) (Fig. 1.2). Chappell (1975), after establishing eustatic sea levels over the last 250,000 years, gives a mean vertical uplift rate of 0.3 mm/yr for a 260 km distance along the South Kaipara-Southwest Auckland coast.

As far as is known, no studies of vertical earth movements have been made in the immediate study area, and it is assumed that the values cited above are representative of the whole Northland region. There is some evidence for this assumption. In describing the Quaternary geology of the Parengarenga Harbour area near North Cape, Ricketts (1975) inferred a 17-23 m terrace as being cut by the sea level high of the last inter-glacial Oturian stage (peaking at approximately 120,000 yr BP). There are also other Oturian age

coastal features identified along the east coast of Northland. An Oturian marine terrace is recognised behind the estuary of Omaha Bay (New Zealand Geological Survey, 1973). In addition, Oturian raised marine and dune deposits have been recognised at low heights above sea level at Onewhero Bay in the Bay of Islands (Ferrar, 1925; Wellman, 1962), and One Tree Point just inside the entrance to Whangarei Harbour (NZGS, 1973). Thus, it is possible, assuming a uniform rate, that vertical earth movements in the study area may have been in the order of +10-20 m for the last 100,000 years.

3.4.2 Sea Levels

The significance of +10-20 m of vertical movement in the last 100,000 years must be considered in relation to the independent eustatic sea level changes which have taken place over the same period, if the processes which have formed the hinterland and the continental shelf are to be understood.

In this context, the Northland region can be regarded as relatively stable in comparison to the greater rates of oscillatory Quaternary sea level changes which are thought to be in the order of 100 m in 20,000 years (Fig. 3.4).

Recent advances in the study of Pleistocene sea level oscillations (Broecker et al., 1968; Chappell, 1974; Bloom et al., 1974) over earlier work (Zeuner, 1959; Fairbridge, 1962) have shown eight major transgression-regression cycles in the last 250,000 years. Furthermore, at only two times, at 215,000 yr BP and 125,000 yr BP, did sea levels reach the height of the present sea level (Fig. 3.4).

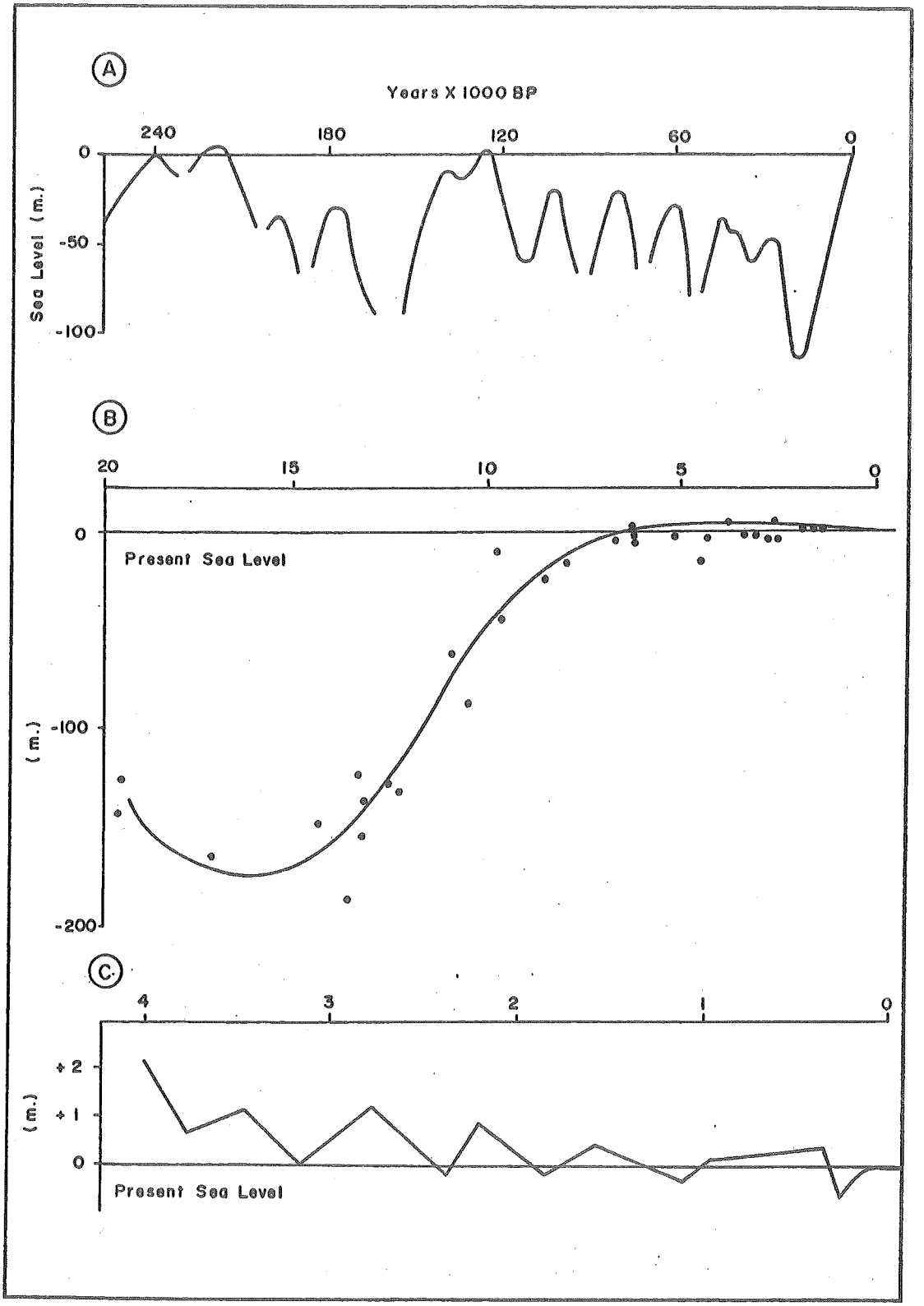


Fig. 3.4 - Pleistocene and Holocene sea level changes. From (A) Chappell, 1975; (B) Kirk, 1975c (unpub); and (C) Schofield, 1977.

Modifications of the continental terrace off the east coast of Northland by these Pleistocene sea level changes (the third stage of the Lewis model) have occurred mostly as marine erosion in the form of planation during transgressive stages. Summerhayes (1969a) found that the shelf off North Cape had received little Pleistocene or modern terrigenous sediment and that the Cretaceous-Tertiary sedimentary and volcanic rock basement is covered by only a thin, discontinuous veneer of relict and modern biogenic sediment. This does not seem to be the case though for the shelf immediately south of the study area, across the northern approaches to the Hauraki Gulf. Here sub-bottom geology indicates a 200 m thickness of unconsolidated sediments over consolidated sediments and greywacke basement rock (Ferguson, 1974). The unconsolidated sediments are largely sands derived from the Hinuera Formation when the Waikato River flowed over the now submerged extension of the Thames Plains (Schofield, 1967). This sand facies (Thompson, I. C., 1975) extends into the southern part of the study area, but the narrowness of the shelf at this point appears to form a boundary to any further northward occurrence. Thus, shelf sediments in the more southern part of the study area may form a transition between the Hauraki type and the North Cape type of shelf sedimentation.

3. 4. 3 Hinterland Evolution

While the shelf was being planed by sea level changes throughout the Quaternary, the hinterland was evolving to its present deeply weathered, maturely dissected form. This evolution probably

took place under a warm, wet climate very similar to that of the present except for slightly cooler periods characterised by glaciations in higher altitude North and South Island regions (Harris, 1953). There is no evidence to suggest that Northland was subjected to periglacial conditions of deforestation or near-snowline processes (Willet, 1950; Cranwell, 1940). In fact, hinterland greywacke rocks show deep alteration by chemical weathering which has given a thick (20-30 m) zone of red to yellow-brown soils and weathered rock, even on steep slopes. Thus, it would appear that the availability of sedimentary material from rivers in the past would have been similar to today.

3.4.4 Effects of Pleistocene Sea Level Changes on Inner Shelf and Hinterland.

Stream and river base levels would have been lowered a number of times up to a maximum of over 100 m by sea level falls in the last 250,000 years (Fig. 3.4). However, except in cases where the shelf is extremely narrow (as off Cape Brett), a lowering of base level would not have resulted in large increases in the gradient of the lower reaches of streams and rivers. This is because of the 10 to 20 km horizontal distances over which this lowering would have occurred (Fig. 3.2). Therefore, any stream downcutting that occurred subsequent to a sea level fall is not likely to have been much greater than that which is presently occurring, and the supply of sediment was also therefore not likely to have been greater. The most likely effects of lowered sea levels were to bring the outer shelf in closer proximity to the supply of finer fluvial

sediments, and to create in the upper reaches of former rivers (which are presently inner shelf areas) a storage area for coarse fluvial sediments. In the latest sea level rise of the last 15,000 years these latter deposits would have been submerged.

Sea levels near the present have occurred, most lately, during the last 6,000 years. In this short time high cliffs (100 m) and shore platforms have been developed in the rock hinterland (Plate 3.2). It is also possible that the cliffs are in fact polycyclic and have only been rejuvenated by the latest sea level high. But, prior to 10,000 BP, sea level had only risen to within about 20-40 m below the present at four-five different times, and was last near the present level in 125,000 BP, Therefore in the last 125,000 years it is probable that extensive cliffing and shore platform development would have occurred in equilibrium with sea levels 20-40 m below that of the present. During these lower sea levels much material suitable for coarse beach and inner shelf deposits would have been produced from coastal cliff erosion and a wide, smooth rock platform would have been cut. It is probably more than coincidental that all of the mixed sand and gravel deposits except one (Pataua) shown in Fig. 1.1 and 6.1 are found immediately seaward of high, cliffed coasts at water depths of 20-50 m, and where there is no apparent immediately relict or modern fluvial sources of sediment. It is therefore postulated that, with the possible exception of Pataua, the mixed sand and gravel deposits have been formed from coastal cliff erosion in late Pleistocene times. Evidence supporting this primary origin of the deposits from coastal erosion is presented in Chapter Six.

This hypothesis is not in agreement with a previous one for a relict fluvial origin of the deposits (Anon, 1974a; Gibb, 1974). However, it is also likely that there are relict fluvial gravel deposits along the east coast of Northland which would occur off the seaward extensions of existing river valleys. But, these relict fluvial deposits do not appear to be extensive on the seabed surface (Fig. 3.2), and may be buried beneath sand deposited under more recent shelf environment conditions. Therefore, it would also appear that gravel deposits off cliffed coasts have not generally been sites of deposition for covering sand deposits.

3.5 HOLOCENE GEOMORPHIC HISTORY

The Pleistocene/Holocene boundary is usually set at 10,000 yr BP, although in the subdivision of the New Zealand Quaternary this is only roughly equivalent to the start of the Aranuian post-glacial stage which is taken to be 14,000 yr BP (Gage, 1977). Furthermore, as can be seen from Fig. 3.4, an eustatic rise in sea level started about 20,000-15,000 yr BP, which is at least 5,000 years before the recognised start of the Holocene. Therefore, because this section is concerned with marine deposits and the influence of sea level changes on these, the Holocene is more usefully taken to mean the longer period of sea level rise and subsequent stabilisation which has occurred since about 15,000 yr BP (Fig. 3.4).

At the peak of the last glaciation, about 20,000 BP, sea level around New Zealand was over 100 m below its present level. The shoreline off the east coast of Northland at that time would have been at least 10-20 km further east than at present, reaching almost as far as the Poor Knights Islands (Fig. 3.2). Therefore, much of what is now the mid and inner continental shelf would have been under the influence of subaerial erosional and depositional processes, such as weathering, mass movement, and fluvial action.

From about 15,000-6,000 BP, sea level rose rapidly to near ($\pm$ 2 m) its present level in what is generally termed the "post-glacial" or "Holocene" transgression. Since 6,000 BP sea level has either been stable, or shown vertical oscillations of the type indicated by Schofield in Fig. 3.4.

Under the sea level conditions of the past 15,000 years a number of relevant coastal and inner shelf sediment responses were likely to have occurred. In chronological order, these would have included:

(i) Submergence and possible longshore and shore-normal dispersal of existing fluvial and mass movement deposits, and the formation of coastal deposits;

(ii) Shoreface bypassing of coastal sediments, especially in large embayments, under transgressing shoreline conditions;

(iii) Erosion and/or rejuvenation of rocky coastal cliffs and shore platforms. In either case, the material produced by this process would have been deposited directly off the cliffed coasts in inner shelf areas at depths of 30-50 m;

(iv) Formation of coastal deposits in positions similar to those of today with the approximate sea level stabilisation at 6,000 BP;

(v) Infilling of newly formed estuaries with fine modern terrigenous sediments and coarse marine sediments (Plate 3.1) in a manner similar to areas along the southeast coast of Australia (Thom, 1974; Roy and Crawford, 1977);

(vi) Oscillation, both landward and seaward, of the position of depositional shorelines if sea level oscillated (Fig. 3.4) and the Bruun hypothesis is valid (Brunn, 1962); and

(vii) Finally, river mouth bypassing of fine modern terrigenous sediment through coastal and inner shelf areas. This is probably still occurring under contemporary conditions.

3.6 SUMMARY

The inner shelf off the east coast of Northland is narrow and steep with a discontinuous and therefore probably thin cover of sand and gravel sediments. The gravel deposits under study in this thesis (Fig. 1.1, 6.1) generally occur adjacent to lengths of rocky, cliffed coast at water depths of 30-50 m. In addition, relict, fluvial gravel deposits (not studied in this thesis) may be found in large embayments seaward of existing rivers and valleys, but these may also be buried beneath more recent sand sediments.

The predominant source of inner shelf gravel sediments are coastal and hinterland greywackes. The greywackes are only extensively exposed along coastal cliffs with the inland portions being covered in a deeply weathered mantle of soil. Regional structural trends account for the location of major coastal embayments between high standing blocks which form lengths of cliffed coast and

projecting headlands. As regards sediment supply, paleoclimatic evidence does not suggest that the fluvial supply of sediments to the coast in the Pleistocene was much different than that at present.

The evolution of the continental shelf in Pleistocene times has occurred under conditions of relative tectonic stability (+10-20 m vertical movement in 100,000 years), in comparison to the greater rates of oscillatory sea level changes (100 m in 20,000 years). In particular, it is hypothesised that the occurrence of many sea level highs of 20-40 m below present in the last 100,000 years (Fig. 3.4) has produced a marine planation surface at depths of 30-50 m. In turn, these planed surfaces have been sites of deposition for gravel sediments eroded from adjacent coastal cliff exposures.

The chronology of events in inner shelf and coastal areas since 15,000 BP has been dominated by the "post-glacial" rise in sea level of over 100 m. This has submerged former terrigenous and coastal sediments and possibly rejuvenated erosion of the rocky cliffed coast. Since 6,000 BP sea levels at or near present have allowed for the development of coastal deposits and the evolution of inner shelf deposits under conditions similar to those of the contemporary physical environment, which is now discussed in Chapter Four.

CHAPTER FOUR

PHYSICAL ENVIRONMENT FACTORS

4.1 INTRODUCTION

The purpose of this chapter is to describe the contemporary physical environment of the study area. This description does not examine the mechanics of individual processes. Rather, it attempts to identify the types of processes which are relevant to the consideration of coastal and inner shelf sediments and morphology. It also attempts to evaluate the magnitude, frequency, and significance of these processes, as far as this is known for the study area. This is intended to provide necessary background information for the interpretation of research results in subsequent chapters.

Coastal and inner shelf systems are regions of complex interaction between environmental factors such as winds, waves, tides, currents and the sedimentary deposits. In these systems environmental factors are considered to play a modifying role in causing responses in sedimentary deposits. The complete environmental system would be made up of all the contributing components from the individual atmospheric, oceanic, and hydrologic environments. However, the major factors which are considered here include only the following:

4.2 - General Climatic Characteristics

4.3 - Hydrologic Inputs

4.4 - Coastal Wind and Wave Climate

4.5 - Tides and Other Sea Level Variations

4.6 - Currents and the Hydraulic Regime

Most of the information in the following is from already published sources, but it is presented here for the first time in a synthesised form. Original data summaries by the author are also presented.

4.2 GENERAL CLIMATIC CHARACTERISTICS

The Northland Peninsula forms a distinctive climatic region within New Zealand. It thus exhibits not only local features peculiar to the area, but also the general climatic and weather regime of the country as a whole. General descriptions of New Zealand's weather and climate (Garnier, 1950; 1958; Maunder, 1971; 1974) outline a number of features which are due to a southern hemisphere, mid-latitude, oceanic position.

Firstly, because of a mid-latitude position, the climate is temperate and the global belt of westerly winds exert a prevailing influence. Associated with this westerly wind belt are weather patterns characterised by successions of anticyclones alternating with troughs or depressions. These systems pass across the area from west to east and cause rapid weather changes.

Secondly, because of a position in a large area of the South Pacific Ocean, the weather systems arriving here exert a moderating influence on the landmass in terms of both temperature and precipitation. There is a comparatively small range of daily and yearly temperatures, especially in coastal areas, and rainfall is usually sufficient throughout the year.

The Northland Peninsula exhibits the general climatic features described above, and also has some local variations due to its most northerly (equatorial) position in the country and its proximity to the sea. According to de Lisle (1964) and Tomlinson (1976), Northland has warm humid summers with mild winters. The mean annual temperature is 15°C, with mean monthly temperatures of 20°C in February and 10°C in July. The annual precipitation is 1000-1500 mm along the east coast and lower altitude regions, rising to over 2, 500 mm in higher altitudes (Fig. 4. 1).

There is a marked winter maximum of rainfall with approximately one-third of the annual total falling in the three winter months (June, July, August), and only one-fifth in the summer months (December, January, February). In this respect the climate has so-called Mediterranean features. The prevailing winds are southwest with occasional stormy gales from the northeast to east. The frequency of occurrence of these weather systems is discussed further in Section 4. 4.

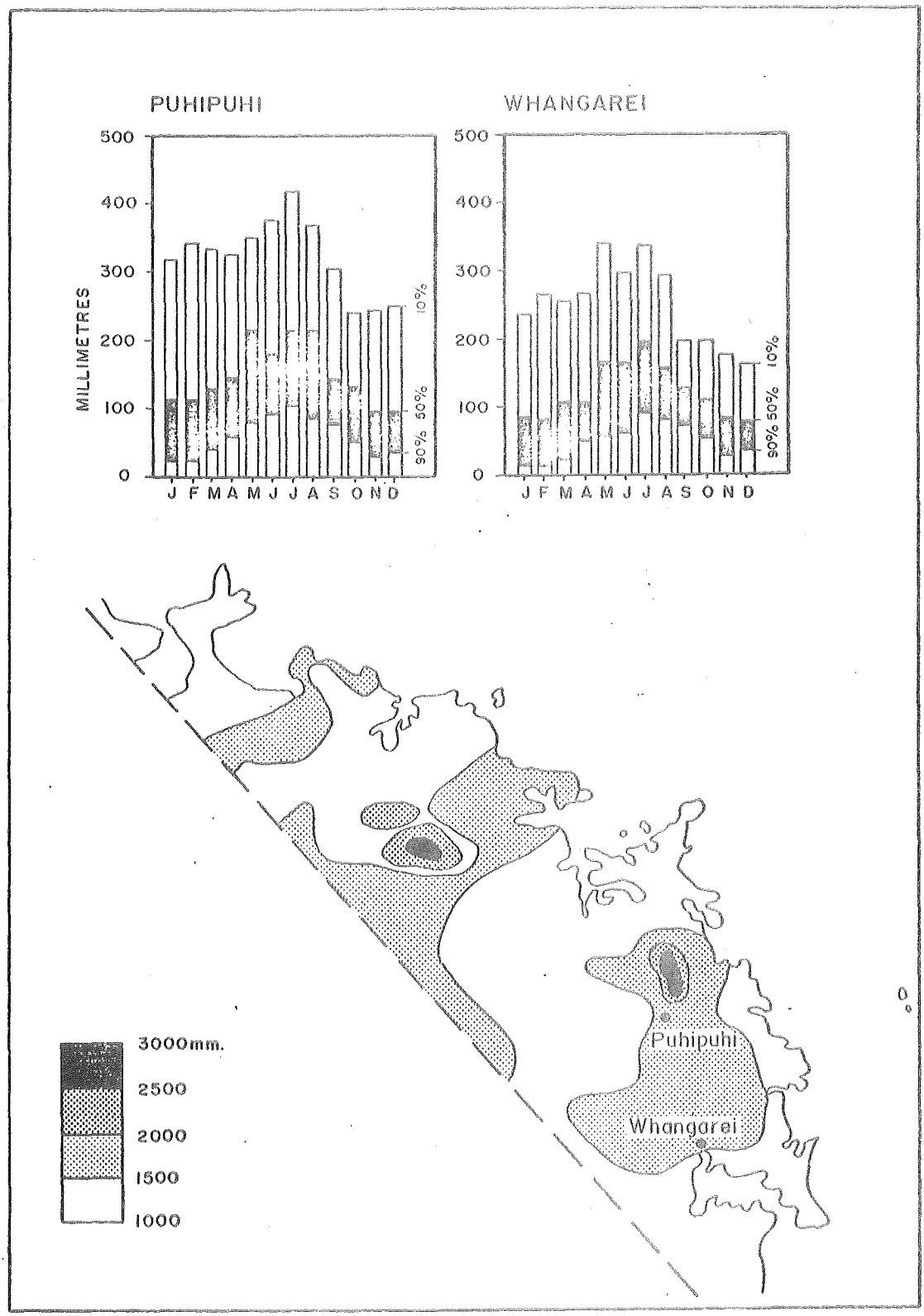


Fig. 4.1 - Spatial and temporal distribution of rainfall over the hinterland region of the east coast of Northland (from de Lisle, 1964). For hinterland catchment areas see Fig. 3.1.

4.3 HYDROLOGIC INPUTS

Rainfall may affect the coast both directly and indirectly in a number of ways. The direct effect of rainfall on the beach causes raindrop impact, water saturation of the beach sediment, runoff of both sheet and rill form, and an elevation of the beach water table. All of these effects may contribute to beach erosion as shown by Harrison et al. (1971), Russell (1971), and Pickrill (1978a). The degree of erosion will vary with the intensity and duration of the rainfall event as well as the antecedent level of the beach water table and exposure of the beach by the tides.

The indirect effects of rainfall on the coast are related to the coastal hinterland catchment conditions such as water and sediment discharge, as well as to infiltration into the beach water table.

All of the effects noted above may operate on the coast but their importance depends to a large extent on the general features of precipitation and catchment response. In this respect there are a number of features of the east coast of Northland which are of relevance. The first three concern the amount, and the spatial and temporal distribution of rainfall, as discussed above and shown in Fig. 4.1.

The fourth feature is the relatively high variability of both annual and monthly rainfall. The region is characterised by periods of flood and drought (Coulter, 1966), and Seelye (1940) shows that the percentage variability of annual rainfall is 18-20% for the region, which is one of the highest values for the country. Individual months show even more variability with January and April being the greatest.

The fifth feature is the frequency of heavy rainfalls (Table 4.1) and the nature of catchment response to this. Northland is

subject to rainfall of high intensity and flooding is a potential problem in any month of the year. In this respect, it has been noted that the weathered soils of catchments impede water penetration and encourage flash flooding (Smidt et al., 1977). In the period 1920-1953, 103 floods were listed with the following distribution: spring (12), summer (27), autumn (21), and winter (43) (Soil Conservation and Rivers Control Council, 1957). These floods carry much fine sediment to the coast and may leave coastal waters visibly discoloured for 3-6 days after a flood, as was observed in both the 1976 and 1977 field seasons.

In summary, it is the marked seasonal distribution, and the annual and monthly variability, which are the two features of rainfall which probably have the most important affect on the coast. The degree to which this is evident will be examined, along with wind and wave systems, in the following section.

Table 4.1 - Frequency of heavy rainfalls. Maximum 24 hour rainfall in millimetres occurring on the average once in every two, ten, and fifty years (de Lisle, 1964).

Station	Return Period (yr)		
	Two	Ten	Fifty
Puhipuhi	147	229	302
Whangarei	102	191	268

4.4 COASTAL WIND AND WAVE CLIMATE

4.4.1 Introduction

The east side of the Northland Peninsula represents a leeward coast with respect to prevailing southwesterly weather systems. For this reason, the study area is not exposed to the large swell waves of southwest facing coasts in this part of the world. Instead, it experiences the generally lower energy waves of an "east coast swell environment" (Davies, 1972, p. 43). Furthermore, because it is a lee coast, wave conditions are more temporally variable than would be the case of the persistently regular, westerly wave environments. Finally, there is the added influence of tropical and sub-tropical cyclones with high energy east to northeast wind and wave components. The incidence of these latter storms, from month to month and year to year, is quite variable as indicated by the rainfall data (Fig. 4.1).

The following attempts to define more exactly the above mentioned and related features of the wind and wave climate of the study area. Detailed observations are also given in following chapters dealing with specific field studies.

4.4.2 Characteristic Weather Systems

According to Tomlinson (1976, p. 82), when a regular weather pattern is present in the New Zealand region, the interval of time between successive weather systems passing over the country is usually between 5-11 days with a marked preference for 9-10 days. Tomlinson also notes that regular patterns of weather are only present

for about half of the time and that there is no apparent seasonal variation to this. Thus, New Zealand weather systems consist as much of irregularly occurring systems as a regular succession of a few systems. This variability is very apparent in Northland where five weather systems have been defined as responsible for producing distinct wind and wave conditions. These five systems are described below with typical weather charts illustrating each type in Fig. 4.2. In addition, corresponding wave records are presented in Fig. 4.3. The wave records have been taken from tracings made available by the Leigh Marine Laboratory which is located just north of Cape Rodney (Fig. 1.2). The records were obtained over the period 14 June - 13 July, 1973, from a wave recorder positioned on the seabed off the Leigh Laboratory. Summary wave statistics of average wave period (T) and significant wave height (H 1/3) have been calculated for each five minute record.

Weather Systems

(1) Anticyclone west of the North Island

This system is common in summer (Browne, 1975) and often maintains fine weather for 2-3 weeks by a process of anticyclone replacement (de Lisle, 1964). The winds associated with this system are light to moderate southwest (offshore), to variable with afternoon sea breezes. No onshore directed waves of significance are generated off the east coast, so that the prevailing wave conditions are low swell.

(ii) Trough depression or cold front passing southwest to northeast over the North Island.

This situation tends to produce northwest winds ahead of the front with strong southwest winds behind. Strong southwesterly winds occur most frequently in spring from this situation. These winds tend to flatten any incoming waves so that only low swell wave conditions are

present (Fig. 4.3). This low swell can be regarded as a "background" wave condition which is probably always present, but which is not as apparent during larger wave conditions.

(iiia, b) Blocking anticyclone to southeast of the South Island (a) without, or (b) with a depression moving southeast from Australia.

According to Browne (1975), blocking anticyclones occur throughout the Australia-New Zealand region, but they are more common east of New Zealand in all seasons, especially winter. These situations produce fresh east to northeast winds in the study area. When a depression also lies to the northwest, then there are strong to gale force northeasterlies. Wave conditions for both (a) and (b) are shown in Fig. 4.3. In 1976, the months of February, March, and April experienced a very high frequency of these conditions which caused extensive beach erosion as discussed in Chapter Five.

(iv) Tropical cyclone or deep sub-tropical depression near the coast.

This situation occurs when a very intense depression originating in the tropics or sub-tropics tracks across the north of New Zealand. Pressures are very low (down to 940 mb), and winds reach up to hurricane force with intense rainfall. Wave conditions are similar to or greater than those of (iiib) and may be short lived if the centre of the storm lies too near the coast so that wave generation is fetch limited. Barnett (1938) and Kerr (1962) indicate that tropical cyclones are largely confined to the summer-autumn season of February-May, while there is a more frequent occurrence of less intense sub-tropical storms in winter. The sea level surge accompanying these storms is also significant as discussed in Section 4.5.

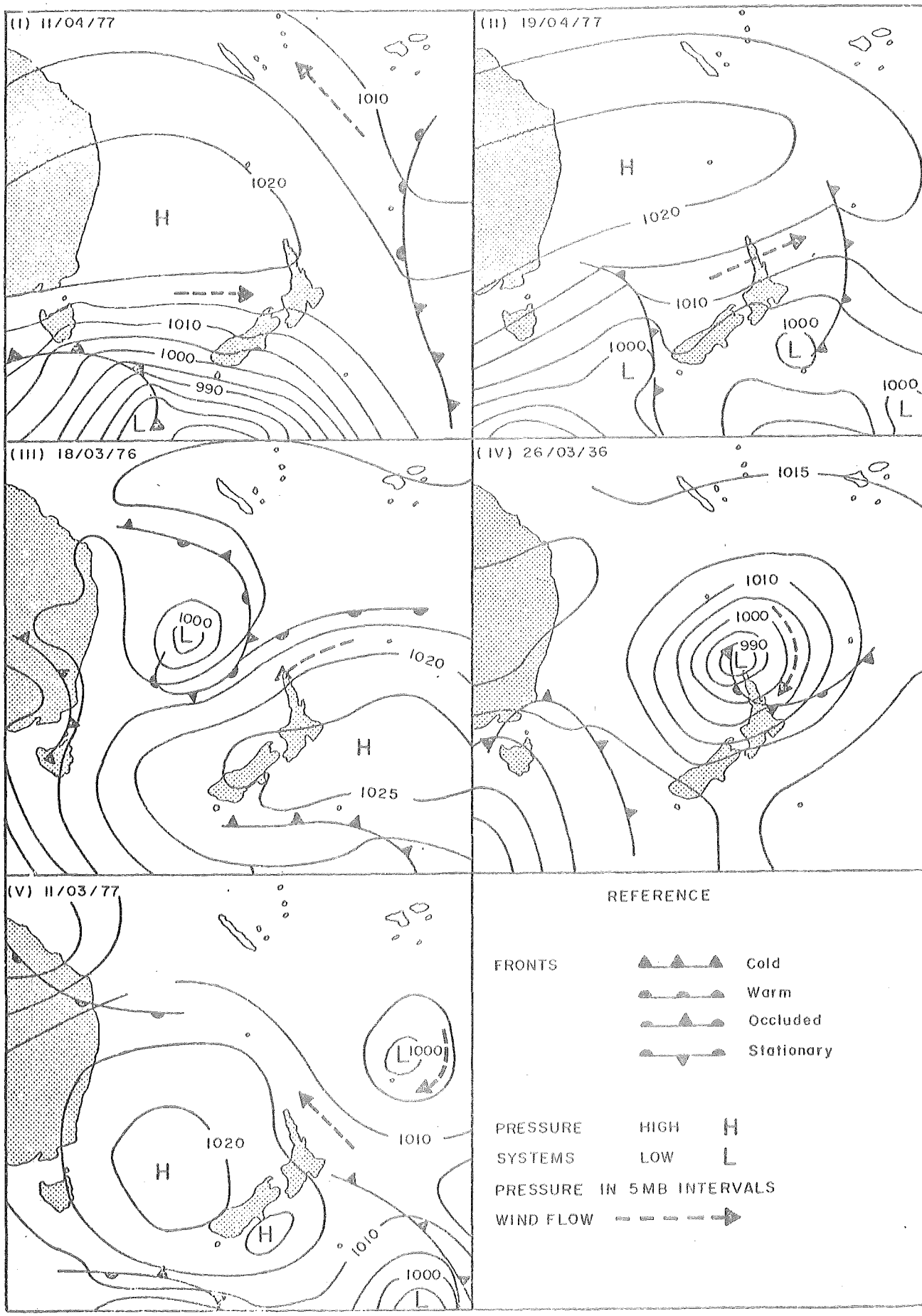


Fig. 4.2 - Characteristic weather systems causing wind and wave conditions along the east coast of Northland (from N. Z. Met. Service daily charts and Barnett, 1938).

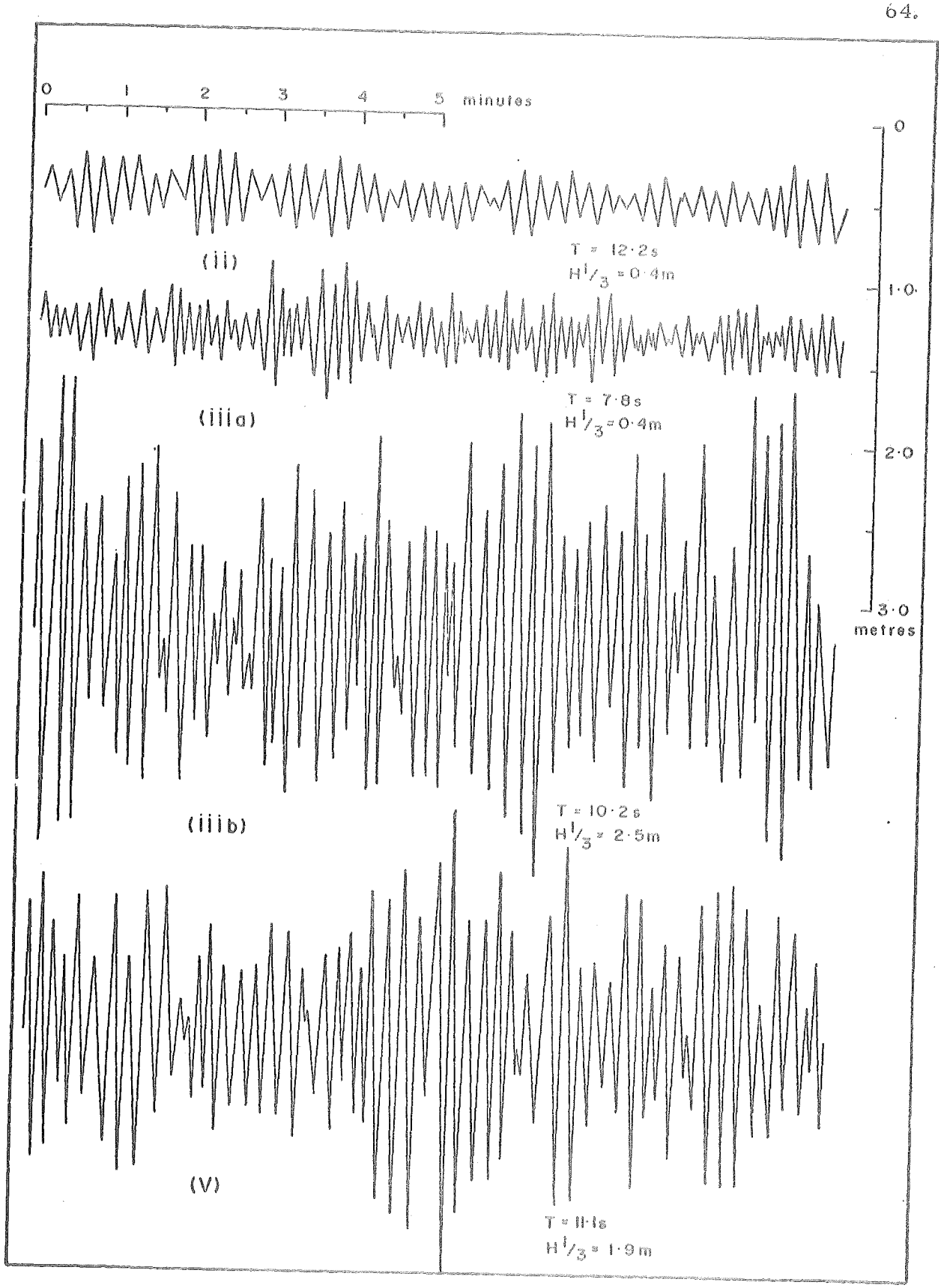


Fig. 4.3 - Wave records for weather system types shown in Fig. 4.2. Tracings taken from Leigh Marine Laboratory wave records.

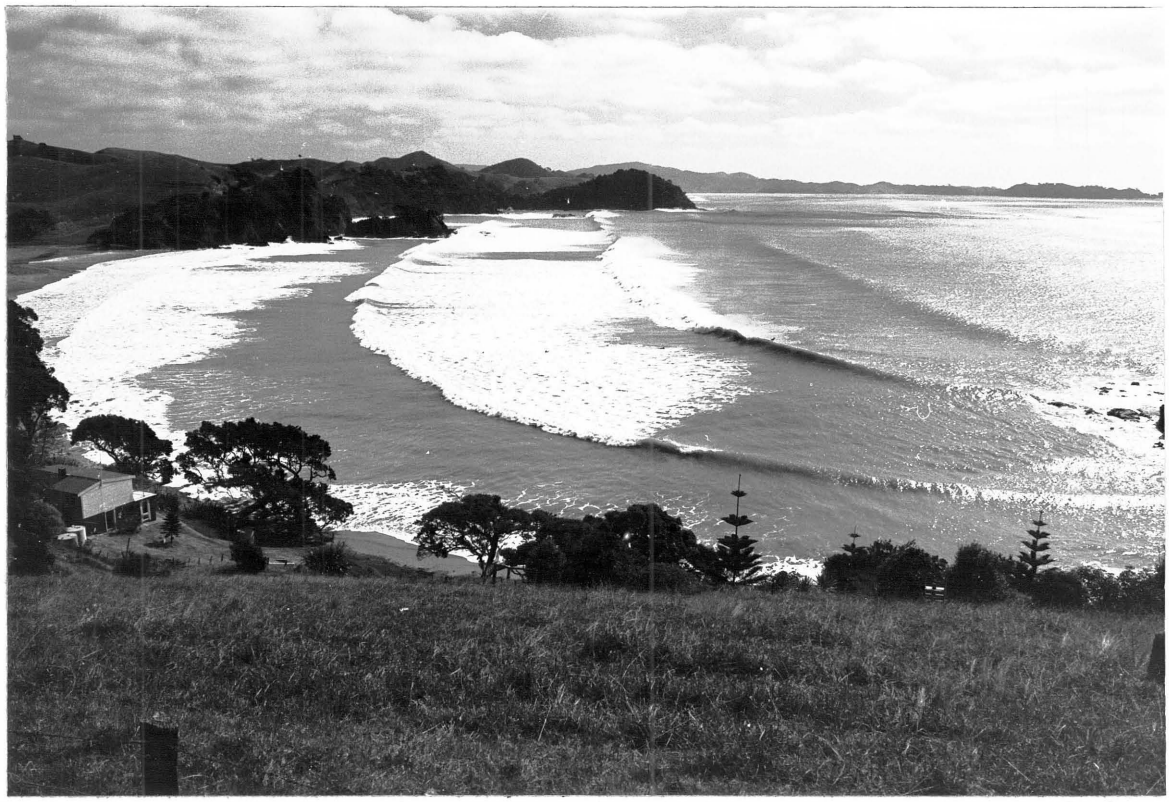


Plate 4. 1 - Large swell wave conditions at Sandy Bay after the Easter storm of 18-21 April, 1976. Wave characteristics of height = 1. 5-2. 5 m, period = 10-12 sec. Note surfers near outside breaking wave for scale.

Plate 4. 2 - Ebb tide flow off Pataua Inlet. The tide rip extends north into the bay over shoreface and inner shelf deposits. Pataua Beach (2. 5 km long) is backed by a narrow belt of low sand dunes which merge into drained swamp deposits.

(v) Tropical cyclone or sub-tropical depression passing northeast of Northland.

In this case, the storm passes some 500-1,000 km to the northeast in the vicinity of the Kermadec Islands. Large swell may be produced for a number of days (Fig. 4.3) with calm to light southwesterly offshore winds on the coast.

4.4.3 Wind Summary

The long term wind climate of the study area will be determined by the frequency of occurrence of the above described weather systems, and within any year, by the seasonal distribution of these same systems. Table 4.2 presents a summary of wind data from various sources which represent observations over varying lengths of time in the Northland region. The main features of the summary are:

(i) For most of the year, and particularly during spring, (September, October, November) the wind climate is dominated by west to southwest winds;

(ii) Onshore winds (northeast to southeast) are most common in summer and autumn. The winds are largely from the northeast to east with southeast winds being rare;

(iii) The occurrence of gale producing cyclones, with winds and storm seas from a northeasterly quarter, is most likely during May, June, and July, with a minimum in November and December;

(iv) Although there are seasonal features to the wind climate, what cannot be shown by Table 4.2 is the variability from one year to the next. Thus it is possible for one late summer-autumn season to experience many easterly gales, and for the same season the following

Table 4.2 - Summary of wind data.

Author	Location and Duration of Record	Summary Characteristics
Barnett (1938)	Northern New Zealand 1898-1936	Average annual frequency of cyclone storms is 6.7, and for severe storms 1.3. Maximum frequency of occurrence is May, June, July with a subsidiary maximum in February, March and a minimum in November, December.
Kidson (1950)	Auckland up to 1936	Easterly quarter winds: summer, autumn = 11% winter, spring = 8.7% Southwesterly winds: summer, autumn = 18% winter, spring = 22%
Garnier (1958)	Whangarei Airport 11 years to 1948	Annual trend for prevailing southwesterlies
de Lisle (1964)	Whangarei 1950-1960	Annual trend for prevailing southwesterlies Winter, spring: % southwesterlies greatest Summer, autumn: % easterly quarter equals southwesterlies Spring windiest from southwest, Summer and autumn calmest
Morton and Chapman (1968)	Mokohinau Island 1950-1957	Generally stronger winds than Whangarei Northeasterly and easterly gales are as common as southerly gales over the year.
Tomlinson (1975)	Northland various periods	Slight predominance for southwesterly winds occurring as 20-35% of all winds Winter is two to three times as gusty as summer with either northeasterly or west to southwest directions for maximum gusts.
Gordon and Ballantine (1976)	Leigh Marine Laboratory 1967-1975	Winds from a westerly quarter prevail in all seasons, and in the summer months are almost equalled by northeasterlies and easterlies.

year, to experience few easterly gales. This was the case for the two years of study, 1976 and 1977.

4.4.4 Wave Records

There are no existing long term (1-10 yr), instrumented wave records for the east coast of Northland. Therefore, New Zealand Meteorological Service daily visual observations of sea conditions from the Cape Brett lighthouse were examined. It was concluded that these observations were inadequate.

Observations from the Leigh Marine Laboratory for the nine years (1967-1975) are more complete and representative, and have been used here. The Leigh data consists of daily sea condition reports using the Beaufort Scale (Appendix 1), and daily observations of the vertical range of wave rise and fall on a 30° rock slope for the largest wave in a three minute period (Gordon and Ballantine, 1976, p 65). Because of wave run-up effects on the sloping rock surface, wave heights are likely to be greater by two to four times than the corresponding deep water wave height (CERC, 1973, p. 7-15). At the same time, the observation site at Leigh is situated in a sheltered position, in comparison to the more exposed coast north of Bream Head. Therefore, the wave data presented in Fig. 4.4 and 4.5 have not been corrected and are probably about 50% too large.

The main points of the Leigh data are:

(i) There is a good correlation between Beaufort Scale and wave run-up heights in Fig. 4.4. This suggests that the data and the seasonal distribution can be relied upon;

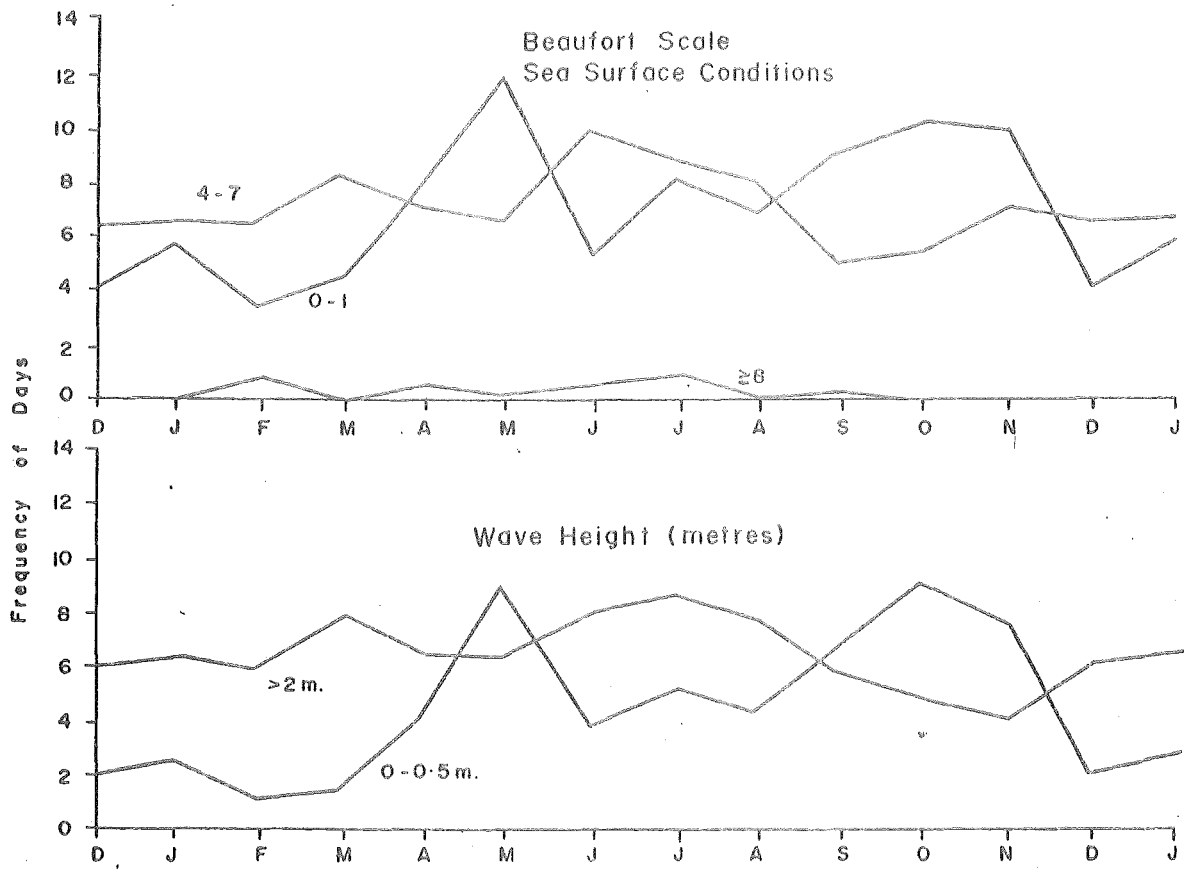


Fig. 4.4 - Seasonal distribution of sea surface conditions and wave run-up heights, Leigh Laboratory.

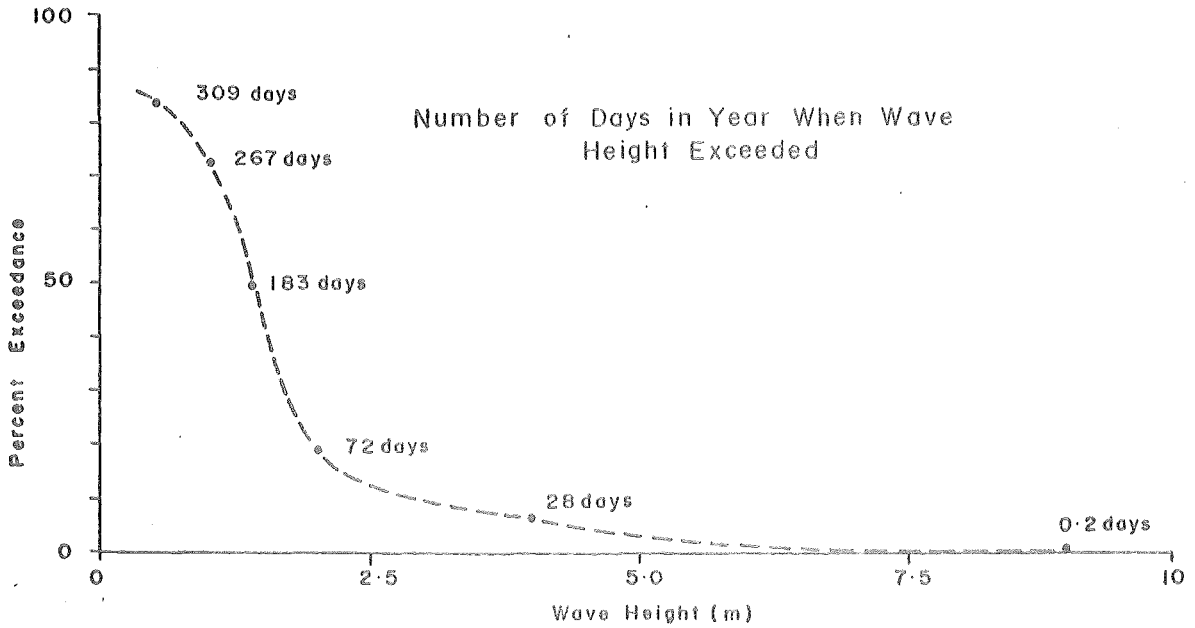


Fig. 4.5 - Percentage exceedance of wave run-up heights for nine year record, Leigh Laboratory.

(ii) The calmest months are May and October-November, while the generally roughest waves occur in June-July. Very rough seas (≥ 8) occur most frequently in June-July with a second peak in February;
(iii) As regards the annual frequency of occurrence of wave heights (Fig. 4.5), the mean wave height of 1.4 m occurs on half of the days of the year. Waves of 4 m can only be expected 28 days/year, or about once every 13 days on the average. Waves of 9 m are expected to occur every 5.5 years.

4.4.5 Summary and Significance of Wind and Wave Data

By correlating all of the observations on precipitation, wind, and waves the following seasonal pattern is proposed:

(i) Spring - Early Summer (September, October, November, December, January).

This is a period of low precipitation. There are generally off-shore southwest to calm winds and low swell wave conditions predominate.

(ii) Late Summer - Autumn (February, March, April, May)

This is a period of moderate precipitation, but with a high variability from year to year. There is a variable annual occurrence of strong easterly quarter winds from weather conditions (iii), (iv), and (v) of Fig. 4.2. There is also a variable annual occurrence of low swell, storm seas, and large swell.

(iii) Winter (June, July, August)

This is a period of consistently highest rainfall. There is an equal proportion of northeast and southwest gales, but sub-tropical depressions are more common than in any other period. This period also has the highest regular incidence of stormy seas.

Based on world-wide observations of profile changes on sand beaches (as discussed in Davies, 1972, p. 119 and King, 1972, p. 315) it has been found that beach erosion occurs under storm sea conditions with onshore winds, and that beach accretion occurs under swell wave conditions and is aided by offshore winds. On this basis the three periods described above can be expected to have the following beach response characteristics:

(i) Spring - Early Summer: usually a period of beach accretion;

(ii) Late Summer - Autumn: variable, some years accretional, others erosional;

(iii) Winter: usually a period of beach erosion.

Support for this pattern is presented in Chapter Five which discusses beach dynamics for the study period.

4.5 TIDES AND OTHER SEA LEVEL VARIATIONS

Temporal variations of sea level in the study area can occur with different magnitudes and frequencies depending upon the source of the variation. The most common contribution to sea level changes comes from tides at a semi-diurnal frequency. Short term variations are also induced by winds, waves, and barometric changes. Seasonal changes are produced by climatic-oceanic influences. In addition, the longer term (50-100 yr) mean sea level is rising, probably due to glacio-eustatic effects. The following examines the nature of variations in sea level in the study area and interprets their significance in terms of effects on coastal and inner shelf sedimentary processes.

4.5.1 Astronomical Tides

The influence of tides as a process variable in coastal and inner shelf environments is important. Tides along the east coast of Northland are dominated by the Southwest Pacific amphidromic system consisting of a nodal point some 3,000 km southeast of New Zealand around which there is an apparent progression of the tide in the form of a wave (Dietrich, 1963). This tidal wave is predominantly a principal, lunar, semi-diurnal M_2 type, and off the open coast has a mean spring range in the order of 1.5 m (Bye and Heath, 1975). The tidal range is considerably distorted on passing over the continental shelf and on entering harbours. At Waiiti Bay in the Cavalli Islands the mean spring range is 1.7 m, changing to 2.2 m at Marsden Point at the entrance of Whangarei Harbour, and becoming 2.5 m at the head of Whangarei Harbour (Marine Division, MOT, NZ, 1978). On the open coast maximum spring tides have a range of 2.2 m, while neap tides have a range of 0.9 m. Thus, the sea level during spring tides may extend 0.65 m vertically further up the beach than during neap tides. This is of relevance to beach dynamics should a storm wave event correspond to a spring tide.

4.5.2 Short Term Meteorological Effects

The magnitude of variations in sea level resulting from short term meteorological effects ranges from 10-20 cm (due to barometric changes of 10-20 mb and strong sea breezes), to over 100 cm in extreme cases (due to storm surges). No previous studies of these effects have been made for the east coast of Northland so that the following may be regarded as tentative estimates.

Wave setup, which is defined as the elevation of the still water level at the shoreline, is caused by wave action alone. This may occur without any local weather effects and be due entirely to cyclonic storms over 1,000 km out to sea which are sending large swell waves against the shore. An estimate of the magnitude of wave setup can be obtained by using the following equation and design wave characteristics (CERC, 1973, p. 3-81).

$$Sw = 0.19 \cdot \left[1 - 2.82\,(Hb/gT^2)^{\frac{1}{2}}\right] \cdot Hb$$

$$= 0.48 \text{ m}$$

where Hb = wave breaker height, 3.0 m

T = wave period, 10 sec

g = acceleration of gravity, 9.8 m/sec^2

Therefore, the effect of wave setup alone can be in the order of 0.5 m.

When cyclonic storms occur closer to the coast, so that there are direct weather effects, then a storm surge may result as well as the wave setup effect. The storm surge results from the combined effects of low barometric pressures and wind setup (which is defined as the vertical rise in the still water level at the shoreline caused by wind stresses on the surface of the water). The magnitude of the surge also depends upon seabed bathymetry and the storm's motion. All of these factors have been combined into one storm surge estimate which was developed for the east coast of the U.S.A., but which also seems to apply to the east coast of Australia (Hopley, 1974). The general equation is of the form shown below (CERC, 1973, Fig. 3-51 to 3-54).

$$Sp = (Si) \cdot (Fs) \cdot (Fm)$$

where Sp is the predicted peak storm surge

Si is the peak surge based on storm intensity

Fs is the bathymetric shoaling factor

Fm is the storm motion factor

When this equation is applied to the east coast of Northland using a central pressure of 970 mb, a relatively steep shore inside of 20 m, and a storm approaching the coast from the east at about 30 km/hr, then the resulting surge is 0.67 m. When this is combined with a wave setup of 0.5 m, then a total water elevation of 1.2 m above the predicted tide can be produced. The effects of currents resulting from this magnitude of storm surge in embayments such as Pataua may be significant (as discussed in Section 4.6).

4.5.3 Seasonal Sea Level Variations

Heath (1976) has identified oceanographic influences around New Zealand as being responsible for producing seasonal variations in mean sea level with ranges in the order of 0.1-0.2 m/yr. Seasonal oceanographic influences include changes in the density of sea water (due to temperature and salinity) and oceanic circulation, although the latter may also be non-seasonal. Seasonal wind stress and atmospheric pressure effects may also enhance the purely oceanographic effects. Thus, for example, continual onshore winds and low atmospheric pressures will cause a prolonged sea level high.

Along the east coast of Northland changes in the oceanic waters of the East Auckland Current, the adjacent coastal waters, and atmospheric effects appear to produce a sea level high in April-July

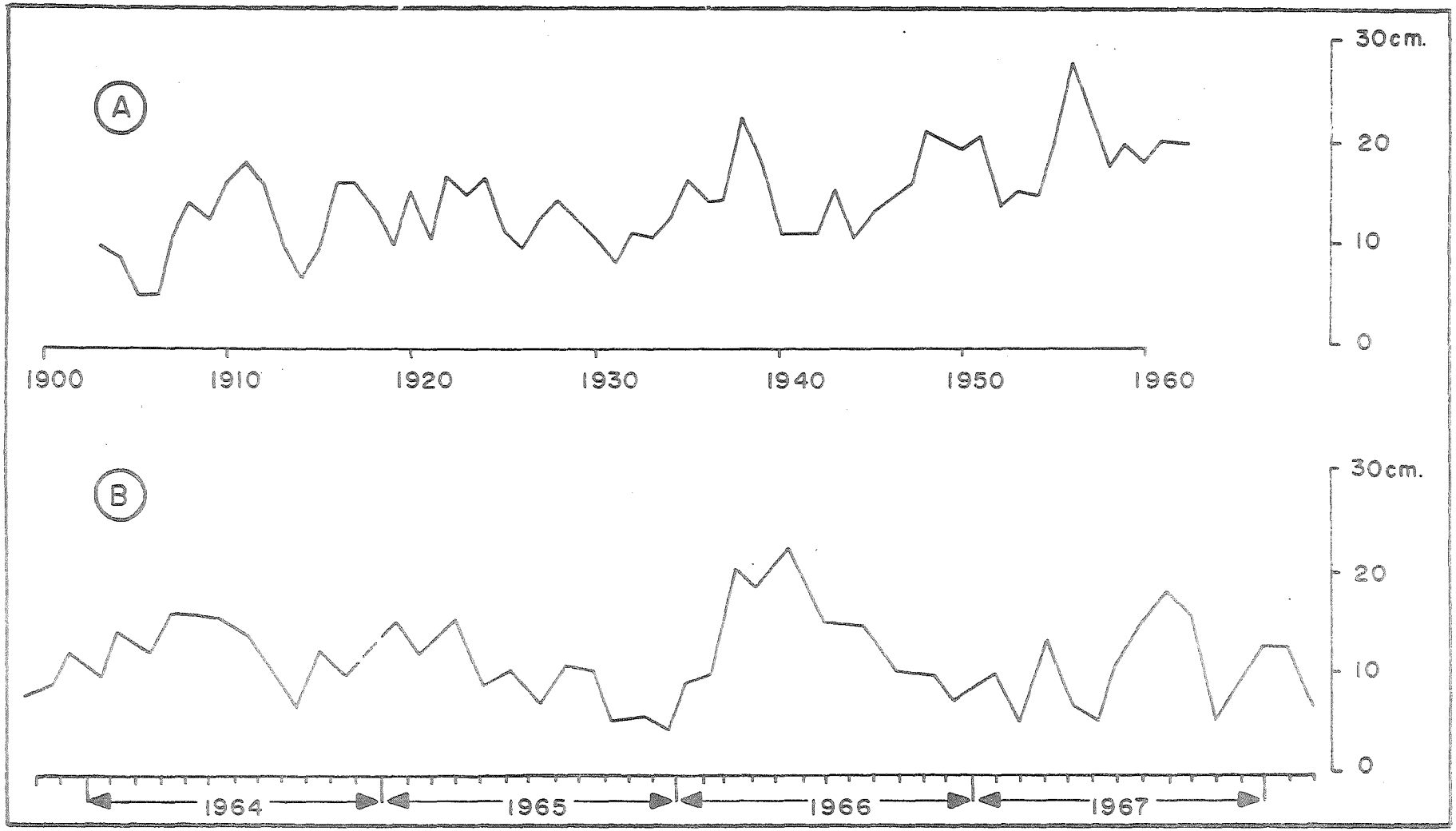


Fig. 4.6 - Long term (secular) and seasonal sea level changes for (A) Queen's Warf, Auckland (Schofield, 1967), and (B) east coast of Northland (Schofield, 1975; Heath, 1976). Annual changes are in the order of 10-20 cm amplitude, with a long term sea level rise of 11 cm.

which is about 15 cm above that of the low in September (Fig. 4.6). This pattern is not entirely repeatable each year and may be altered to a significant extent by wind stress effects (Schofield, 1975).

4.5.4 Long Term (Secular) Changes in Sea Level

It has been found from the study of long term tidal gauge records throughout the world that mean sea level has been rising at a rate of 1.0-1.1 mm/yr since the 1890's (Gutenberg, 1941; Fairbridge, 1961; Lisitzin, 1974). This sea level rise is independent of vertical movements of the earth's crust and is thought to be largely a glacio-eustatic effect produced by a general climatic warming which has promoted deglaciation, mainly in northern hemisphere regions rather than the Antarctic. The warming of the oceans over the same period may also be a contributing factor to the sea level rise (Lisitzin, 1974, p. 179).

The existence of a rising sea level has also been demonstrated in the New Zealand region (Schofield, 1960; 1967; Heath, 1976). Schofield found that tidal records at Queen's Wharf in Auckland showed a sea level rise of 110 mm between 1910 and 1960 (Fig. 4.6). Furthermore, the rise until 1930 was at a rate of 1 mm/yr and since 1930 at 2 mm/yr, although Heath cautions that it is possible the Auckland tide gauge may be sinking at about 0.5 mm/yr.

4.5.5 Significance of Sea Level Variations to Sedimentary Processes

The significance of tidal and other sea level changes to coastal and inner shelf sedimentary processes is due to the direct effects of

vertical sea level changes and indirect effects such as the development of currents. The latter are discussed in Section 4.6.

The direct effects of sea level changes are most pronounced at the shoreline and in shallow coastal areas (less than 20 m) since there are greater relative changes here than in deeper areas. As originally proposed by Bruun (1962), the effect of a sea level rise is to induce shoreline erosion, where the rise is seen to play a permissive role rather than a causative one. It is wave and current processes which are the effective agents. Support for the Bruun effect has been demonstrated on a number of temporal and spatial scales (Strahler, 1964; Schwartz, 1965; 1967; Dubois, 1975; 1976; Schofield, 1975; Pickrill, 1978b; Rosen, 1978).

With respect to this study, the combination of spring tides, storm surges, and wave setup effects are likely to cause quite large (1.0-2.0 m) short term sea level rises above a mean sea level. Short term rises can occur in any month and therefore cause beach erosion in any month. But, on an annual basis, the higher incidence of strong onshore winds in winter and the seasonally high sea levels in April-July are likely to increase the probability of coastal erosion in these months.

Lastly, the continued long term (secular) rise in mean sea level is probably contributing to regional shoreline erosion. There is some evidence for the last effect occurring in a number of areas along the northeast coast of the North Island (Cox, 1974; Schofield, 1975; Gibb, 1977; Healy et al., 1977), although other factors such as negative sediment budgets and human activities (dredging) vary geographically in importance.

4.6 CURRENTS AND THE HYDRAULIC REGIME

4.6.1 Introduction

Sediment transport and resulting spatial sediment distributions are often related to water currents within coastal and inner shelf regions. Although this relationship is generally accepted, the direct observation of sediment transport processes is usually not made, and observations have tended to be indirect and inferential. For example, sediment distribution patterns are used as an interpretive aid to defining current patterns. In addition, known current patterns may be used to account for sediment distribution patterns, or a knowledge of currents may be used to evaluate their role in sediment transportation.

This section of the study gives consideration to coastal and inner shelf currents with particular reference to their character along the east coast of the Northland Peninsula. The discussion is not intended to be exhaustive since this would be beyond the scope of this thesis. It would also be premature to attempt to be conclusive since knowledge of currents in this area is quite incomplete and consists only of some limited surface current observations rather than more meaningful bottom current observations. What will be presented is an attempt to outline briefly the role and relative importance of the various forms of currents which operate in the study area. This approach has recently been used by Carter and Heath (1975) to review the role of various currents in determining bottom sediment transport on the New Zealand continental shelf. The specific role of wave

activity in terms of present-day processes of coarse sediment movement on inner shelf deposits will be examined more extensively in Chapter Eight.

Recent discussions of coastal and shelf currents (Swift et al., 1971; Weggel, 1972; Mooers, 1976) recognise a variety of currents as being important in producing and modifying sediment distribution patterns. In addition, the nature of current motions appears to be spatially and temporally complex and highly variable. Within an individual geographic area the relative importance of different currents varies between the beach, shoreface, and inner shelf regions (Fig. 2.1). Currents may also vary in importance between geographic areas (Craegar and Sternberg, 1972). Finally, seasonal patterns and storm versus fair weather effects, or more general temporal variations in the intensity, frequency and duration of currents, may exert a strong influence in some areas (Beardsley and Butman, 1974; Shepard and Marshall, 1973; Huyer et al., 1975).

4.6.2 Oceanic Currents

These are large scale, semi-permanent currents generated by oceanographic factors outside the immediate shelf area, but which are also modified by their intrusion into shelf areas. To the east of North Cape and along the east coast of Northland there is good evidence for a consistent southward directed flow which was first defined by Brodie (1960) and named the East Auckland current, and later also recognised by Barker and Kibblewhite (1965). The water in the East Auckland Current has sub-tropical affinities and has resulted in the

development of the warm-temperate Aupourian biogeographic province along this coast (Powell, 1961; Knox, 1963).

Although the East Auckland Current has been identified, little is actually known about its characteristics such as the spatial and temporal velocity distribution, and how it is modified close to the shore and the seabed. Garner (1961) derived a drift rate of 0.1 m/sec for surface water movement based on the release of drift cards. Barker and Kibblewhite have indirectly calculated a maximum surface geostrophic current of 0.8 m/sec for a point about 50 km off the coast. The New Zealand Hydrographic chart for this area shows maximum net velocities of 0.3 m/sec for a number of locations along the coast.

It must be remembered that this current data is for surface, offshore points and will probably be significantly different in both strength and direction close to the seabed and the coast. In fact, according to Mooers (1976) the effects of oceanic currents are only predominantly exerted on the outer shelf and the continental rise and slope. However, the only detailed direct measurement made of currents along this coast (Booth, 1974) concluded that in the Bay of Islands water circulation appeared to consist of an anti-clockwise movement of at least the surface water, induced by a north-west moving current, possibly derived from the East Auckland Current.

Attempts have also been made to infer current direction from coastal sediment distribution and morphology. Both Summerhayes (1969a) and Schofield (1970) have inferred nearshore, northward directed currents along this coast which they believe to be due to eddy reversals of the offshore East Auckland Current. This same mechanism has been suggested off Banks Peninsula (Carter and Heath, 1975) and the Otago Peninsula (Andrews, 1973). Although reversal mechanisms may exist,

their role would appear to be confined to the transport of suspended fines (silt, clay) rather than the bedload transport of coarse material (sand, gravel) along beaches. As will be shown in the following, tidal, storm wind and wave induced currents are usually much stronger than oceanic currents in coastal and inner shelf regions. Therefore, it is more likely that explanations for observed sediment patterns in coastal and inner shelf regions will be found from a consideration of these other currents.

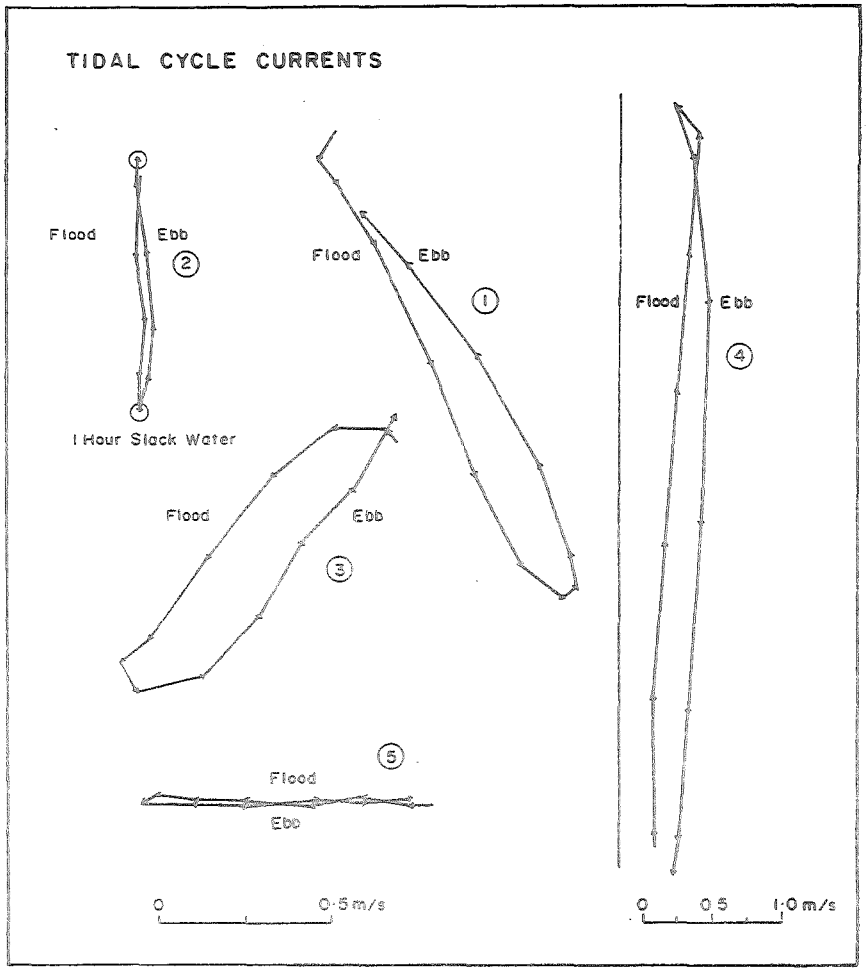
4.6.3 Tidal Currents

Tidal streams or currents are periodic horizontal water movements and are the direct effect of the tide (which is strictly speaking a vertical movement), and the tide's interaction with the continental shelf and coastal configuration. Tidal currents are generally slow moving and rotary with no residual component off the open coast. They are enhanced and diversified in coastal areas due to the constricting effects of both bottom topography and coastal outline. Tidal currents attain their strongest development in narrow constrictions between islands and the mainland, and particularly at coastal inlets opening into large estuaries. At these locations tidal currents tend to exhibit a cyclic, reversing pattern often with a residual component.

It has been shown overseas, particularly in the southern North Sea and English Channel (Caston and Stride, 1970; Kenyon and Stride, 1970), and in New Zealand in Cook Strait and Foveaux Strait (Cullen, 1967; Gilmour, 1960; Pantin, 1961), that where they are sufficiently strong, tidal currents exert a constant influence on bottom sediment movement and morphology. It is also possible for weaker

tidal currents to combine with oscillatory wave motion to produce a net residual sediment movement. In this respect, limited current measurements made on the New Zealand continental shelf indicate that in general maximum tidal current speeds are of the order of five-ten times greater than the mean currents (Carter and Heath, 1975, Fig. 3). Mofjeld (1976, p. 53) also makes a valid comment in pointing out that tidal currents are especially effective agents of sediment transport since they operate all the time, whereas other types of water motion, particularly those associated with storm events, are episodic.

Along the east coast of Northland the tidal stream sets northward with a rising tide and southward with a falling tide, except in the Hauraki Gulf, where these directions are reversed. The actual situation, as shown in Fig. 4.7 is more complicated because the primary deep water movement is distorted in passing over the continental shelf and into the inner shelf and coastal region. As can be seen in Fig. 4.7, the flood currents tend to be directed towards the coast (generally southwestward) and the ebb currents away from the coast (to the northeast). The magnitude of the currents is representative of spring tide conditions for the surface water only, and thus would be the maximum to be expected. It is also interesting to note that although the directions of the tidal currents are distorted from their deep water character, the measured magnitudes shown in Fig. 4.7 agree favourably with those predicted using simple tidal theory. For example, if the tidal wave can be considered to be a progressive sinusoidal wave, then the equations for Airy wave theory are applicable. Also, since tidal wavelengths are long compared to the depth of water they travel in, then the maximum surface tidal current speed is,



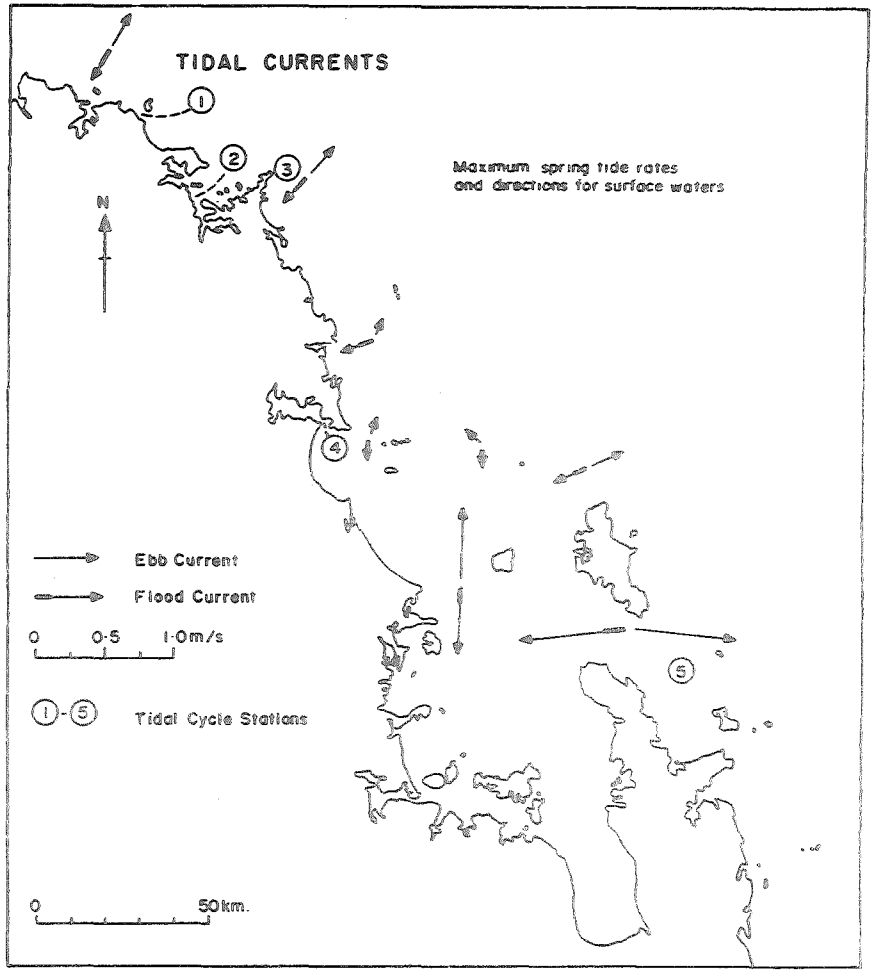


Fig. 4.7 - Tidal currents in the study region and approaches to the Hauraki Gulf. Tidal cycle currents are for hourly intervals during spring tides. Data from Hydrographic Office, RNZN, Charts 52, 521, 522, 532, 512, 5122, 5213.

$$u = (H/2)\ (g/d)^{\frac{1}{2}}$$

$$= 0.33 \text{ m/sec for d=50m, and } 0.23 \text{ m/sec for d=100 m}$$

where H = wave height, 1.5 m

d = water depth, 50 m, 100 m

g = acceleration of gravity, 9.8 m/sec.

The currents shown in Fig. 4.7 give a more detailed picture of tidal currents along the coast. All the examples show a pronounced reversing rather than a rotary pattern. The residual components are between 0.05-0.1 m/sec except for stations (1) and (4) which are about 0.25 m/sec, and which are probably induced by local topography. The strongest tidal currents are found at estuary inlets such as Whangarei Harbour where maximum surface currents reach 1.5 m/sec for most of the tidal cycle. These velocities tend to be spatially concentrated and only exert a local influence. Also, these are surface observations and currents will be less near the seabed. Gilmour (1960) demonstrated that tidal current speeds in Cook Strait can decrease by as much as two-thirds near the bottom, and Carter (1977) shows that tidal currents in the entrance to Wellington Harbour have a maximum speed of 46 cm/sec at the surface but only reach 19 cm/sec at 1 m above the seabed.

4.6.4 Density Currents

Density currents are produced through the mechanism of thermohaline forcing. They occur as a result of spatial differences in the temperature and/or salinity distributions of continental shelf waters. The usual gradient of seaward increasing salinity because

of freshwater input to the coast, causes a seaward drift of surface water, and more importantly a slow return landward drift of bottom water which may be deflected along the coast by any Coriolis effect. According to Swift (1969), density currents are not capable of entraining traction load, but could affect sediment movement by their coupling with stronger wave and tidal induced currents.

The importance of density currents along the east coast of Northland is not known but because of the relatively low normal discharge of river waters into coastal and shelf waters, any thermohaline forcing should be slight.

4.6.5 Wind-driven Currents

These are water currents produced from momentum transfer of wind stress over the water surface. The nature of the wind stress can vary from diurnal land-sea breezes, to large scale meteorological phenomena such as cold fronts and tropical cyclones. The effects of the wind are not limited to surface currents only and can produce mid-water and bottom currents in the order of 20-40 cm/sec (Smith, 1974), and up to 1 m/sec (Forristall, 1974). Onshore storm winds usually produce a vertical circulation pattern with onshore flow at the surface and offshore flow near the bottom (Murray, 1972). Strong onshore winds also contribute to the phenomenon of storm surge. In contrast, strong offshore winds produce coastal upwelling caused by shoreward directed bottom waters replacing the seaward moving surface water. Wind-driven currents must play a significant role in sediment transport because they usually also occur at the same time as relatively high wave induced oscillatory surges on the seabed.

Along the east coast of Northland strong northeast to east winds associated with tropical cyclones and extra-tropical depressions should generate wind-driven currents resulting in offshore currents on the seabed. Conversely, southwesterly winds associated with the passage of cold fronts will produce an onshore seabed drift. Because of the broken nature of the coast and inner shelf regions, the wind driven circulation probably does not extend continuously along the whole coast and is probably broken up into cells in large bays such as Bream, Ngunguru, Sandy, Mimiwhangata, and the Bay of Islands.

According to Mooers (1976) the influence of wind driven circulations may be expected to be relatively most prominent on the inner shelf region. In this region the circulation response to large magnitude wind events is dramatic, and although only transient in duration, may be the predominant influence in the net drift. Similarly, according to Smith and Hopkins (1972) the wind driven circulation for a severe storm occurring once every few years may have more geological significance than a number of less severe storms. Smith and Hopkins also found that wind driven circulations tended to be typified by bottom flows which are alongshore or offshore, and which would be opposite to flow directions produced by fair weather wave induced currents.

4.6.6 Wave Induced Currents

While the dominant primary form of wave particle motion is oscillatory with little residual drift in outer shelf regions, significant wave induced currents may be developed in inner shelf shoreface and beach regions. Residual wave oscillatory motion, known as mass transport, is an important current in the direction of wave propagation

normal to the shore. This is especially true in shoaling water where wave fronts tend to be aligned more parallel to the shore than in deeper water, and where mass transport is intensified. This tends to be a fair weather phenomenon and can be enhanced by offshore winds as discussed previously.

The currents developed along the coast inside the point at which waves rapidly steepen and break are very complex and are the predominant influence on coastal sedimentation and morphology (Komar, 1976). The only exception to this in the study area would be around sheltered river inlets, and where tidal streams have a stronger influence.

4.6.7 Summary

From the previous discussion the relative importance of various currents in inner shelf, shoreface, and beach regions along the east coast of Northland may be suggested as follows:

Inner Shelf

Fair weather currents would be dominated by weak oscillatory bottom wave surge motion with a slow onshore mass transport residual current. Onshore/offshore tidal flow should not produce any residual flow, except where this is locally produced by topography.

Under storm conditions strong oscillatory bottom wave surge motion can be expected, with a possible longshore to offshore directed bottom current due to storm wind-driven currents.

Shoreface

Under fair weather conditions a moderate oscillatory bottom wave surge can be expected with a stronger onshore mass

transport than in the inner shelf. With storms, intense oscillatory bottom wave surge is likely and a strong, offshore directed bottom return flow.

Beach

Wave induced currents predominate at all times, with strong rip and longshore currents during storms. Locally, tidal currents will be important at inlets.

4.7 SUMMARY

Based on a review and synthesis of information on a variety of physical factors the coastal and inner shelf environment of the study area can be briefly summarised as follows.

As an east facing coast in a mid-latitude westerly wind belt with an additional sub-tropical influence, weather patterns and wind and wave climates show not only a seasonal variation, but also variation from year to year for the same season. Thus the combination of northeasterly seas, high rainfalls, and seasonally high sea levels in winter can be expected to cause beach erosion, although the variable nature of late summer - autumn weather patterns can also produce beach erosion. In contrast, spring and early summer are most likely to be periods of beach accretion. It should also be emphasised that the combination of high spring tides and storm surge effects can create short term (monthly) episodic beach erosion in any month of the year. Long term (secular) sea level change may also be causing slow but steady beach erosion.

The effects of currents on sediment transport in inner shelf regions may be separated into fair-weather versus storm periods. Oceanic and density currents are not likely to have significant effects at any time. Under fair-weather conditions low oscillatory bottom wave surge motion may couple with tide generated currents to produce local net directions of transport. Under storm conditions, tidal currents when coupled with moderate to high bottom wave surge motion are likely to have significant effects in most inner shelf regions. In this respect, storm current conditions probably have a predominating influence on sediment transport, especially for coarse sand and gravel sediments.

This summary has provided some necessary background information against which results on beach dynamics in Chapter Five, and inner shelf sediment transport processes in Chapter Eight, are interpreted.

CHAPTER FIVE

COASTAL DEPOSITS

5.1 INTRODUCTION

Field research began in December, 1975 with a survey of coastal deposits. This work had two purposes. The first was to establish the extent of relationships between coastal and inner shelf deposits. The type of relationships envisaged included similarities in sediment type and contemporary sediment transfers between the two types of deposits. It had also been suggested that dredging-induced changes in the inner shelf sediment cover and bathymetry could affect the adjacent beaches, even though no direct sediment transfers were occurring. In these latter cases it was thought that the removal of the sediment cover would make the seabed a less effective absorber of wave energy, and that changes in wave refraction patterns might alter wave energy distribution along the coast and eventually lead to localised erosion and changes in beach configuration.

The second purpose of the coastal survey was to provide a bench mark or baseline description of coastal sediments, morphology, and natural changes in beach cross-sectional area. This was to be done so that any future natural or possibly man-induced changes could be compared against baseline characteristics.

It became apparent after some initial fieldwork that in most cases the likelihood of contemporary relationships existing between beach and inner shelf deposits in the vicinity of the prospecting areas was low (Fig. 1.1). In particular, most of the prospecting areas are located off cliffed, rocky coastlines with either no beach deposits on the adjacent coast, or no present-day connection to beach deposits further along the coast.

With respect to the second purpose (the baseline survey), it was apparent that beach sediments, morphology, and the nature of cross-sectional beach changes, varied considerably between beaches within the study area. This variation seemed to be related to different sources of beach sediment, and the morphologic response of beach sediment to variations in exposure to wave energy. This chapter has therefore largely concentrated on illustrating variations in these characteristics within the study area.

The description to follow is based on extensive field survey and laboratory analyses. Ten beach profiles were surveyed a number of times to illustrate variations in beach dynamics. Sixty-four beach sediment samples were collected and analysed to show variations in sediment type. Analysis of air photos demonstrates the extent of beach changes in historical times and submarine profiles (taken by boat and echo sounder) have been used to illustrate the nature of the seabed between the beach and inner shelf areas.

5.2 GENERAL CHARACTERISTICS

As described previously in Chapters One and Three, coastal deposits of sand and gravel constitute only a minor percentage (15%) of shoreline types in the study area. Furthermore, this amount is distributed along the coast as small isolated deposits. Apart from the coastal deposits at Ocean Beach, Pataua Beach, Ngunguru Spit, and Whananaki Spit (Fig. 1.2) (each of which is over 1 km in length and about 1 km^2 in area), there are only a few other deposits of coastal origin which are greater than about 0.5 km long and 0.5 km^2 in area. This contrasts with the coastal deposits immediately south of the study area in Bream Bay, which stretch continuously for about 25 km and which have an area of about 30 km^2 contained in the one deposit.

The width of Holocene coastal deposits in the study area is at its maximum at the above mentioned localities and does not exceed about 0.5 km in other areas, with most deposits showing less than 0.1 km of coastal progradation. The depth of deposits at the shoreline is also limited. Studies at Marsden Point, at the northern end of the Bream Bay system, show bedrock beneath about 20-50 m of marine sands (Broadbent, 1972). Such bedrock depths within the study area would probably only be approached by the Ocean Beach deposits. The other large deposits would be unlikely to exceed depths of 10-20 m, and in a manner consistent with other dimensions, most of the deposits would have depths to bedrock of less than 5 m. This is evidenced by the common occurrence of rock outcrops in the nearshore areas of most of the beaches studied (Plate 3.2).

Coastal sand and gravel deposits are present in the study area as pocket beaches, bayhead beaches, spits across river inlets, and

in the southern portion as two relatively large open beaches (Pataua and Ocean Beach). Because of its projecting headlands the coast is one of impeded longshore transport so that to a large extent each embayment forms a closed sediment compartment with predominantly onshore/offshore sediment movement, although it is possible for redistribution of sediment alongshore within each compartment.

Beach sediment types vary considerably between coastal compartments in the study area. Sediment size varies from fine sand to granule and pebble sizes with most of the beaches consisting of sand. A small number are of mixed sand and gravel, and gravel. There is also a variable, but significant amount (5-90%) of biological calcium carbonate in beach sediments, both as whole bivalve shells, comminuted shell, and other carbonate detritus.

Beach processes, as expressed in cross-sectional beach changes, also vary depending on beach sediment type and exposure to ocean waves. The sections to follow in this chapter are concerned with a detailed description of these features of the study area.

5.3 SAND AND GRAVEL SEDIMENTS

5.3.1 Introduction

Schofield (1970, Fig. 14) has defined three major coastal sand facies along the east coast of Northland between North Cape and the northern entrance to the Hauraki Gulf (Fig. 5.1). These facies are termed, from north to south, "Parengarenga", "Bay of Islands", and "Hauraki (B)". The present study area lies almost entirely within the

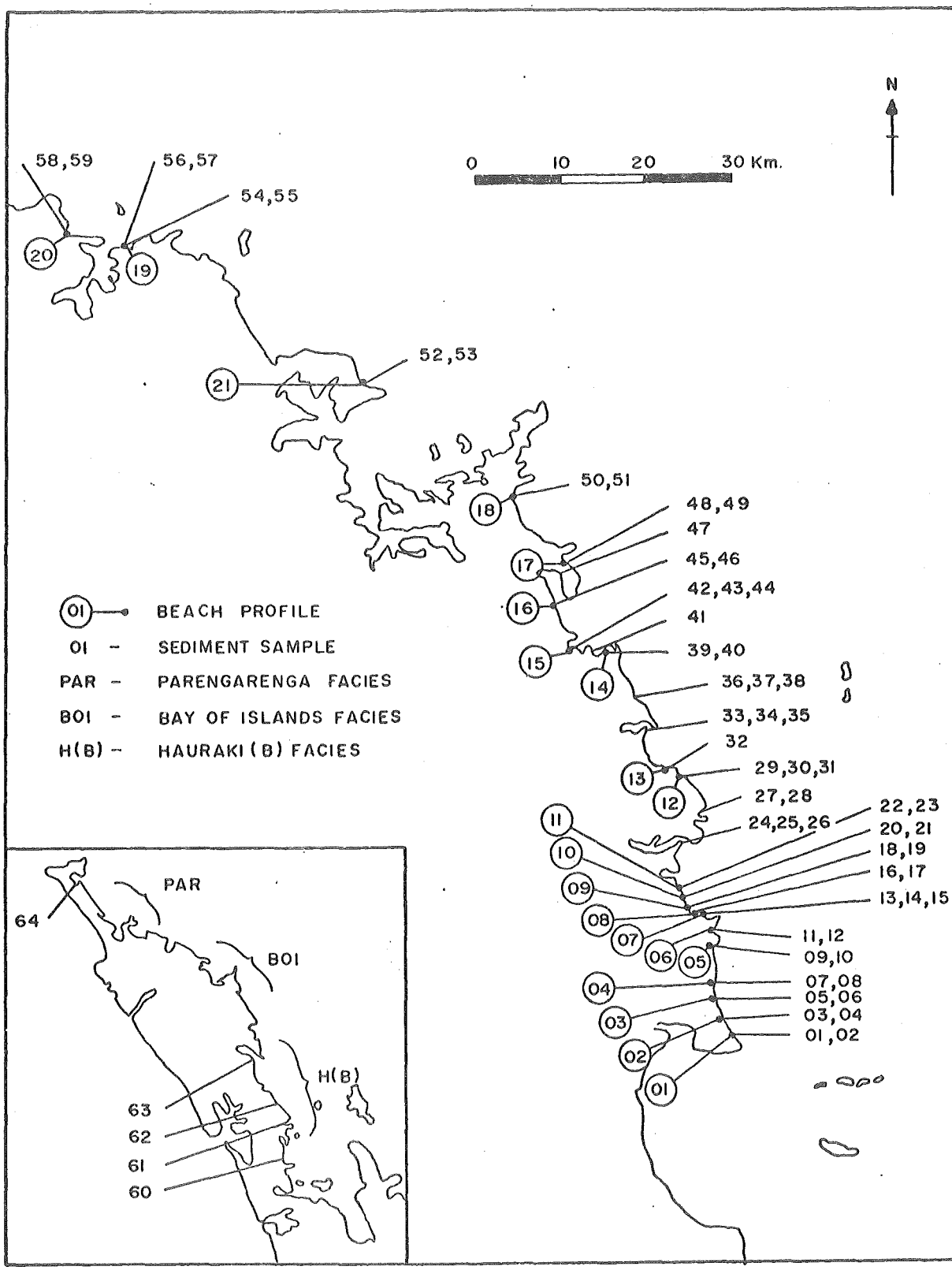


Fig. 5.1 - Beach profile and sediment sample locations. Included on the inset map are the regional sand facies of Schofield (1970) and five sediment samples collected from outside the immediate study area.

Bay of Islands Facies. Only the extreme southern portion at Ocean Beach is within the Hauraki (B) Facies or what Schofield (1975) has also recently termed the "Ocean Beach-Mangatawhiri Sand System". Immediately north of Ocean Beach, at Pataua Beach and Ngunguru Spit, there is a minor transitional facies consisting of mixed portions of the two adjacent major facies, namely Bay of Islands and Hauraki (B).

The Parengarenga, Bay of Islands, and Hauraki (B) coastal sand facies differ markedly in their characteristics (Schofield, 1970). The Parengarenga Facies consists of extensive, uniform deposits of fine sands with very high quartz contents, normally in excess of 90%. These sands are mainly sub-angular in shape and are thought by Schofield to be derived from nearby mature sandy podsols, i. e. they have a pedogenic origin.

In contrast, the Bay of Islands Facies consists of small, localised coastal deposits which are quite variable in their composition. Generally, the Bay of Islands Facies is characterised by fine to medium sands with high percentages of angular rock fragments and shell material, each of which can be greater than 75% by weight of the total sample. On a shell free basis, quartz and feldspar are present in approximately equal proportions and may make up to 60% by weight of the mineral sand grains. Schofield concluded that these sands are derived from local coastal erosion of greywacke rocks. This is also supported by Smidt et al. (1977) who have shown that feldspar sand grains are almost completely absent (less than 1%) in hinterland sandy stream sediments in this region. Therefore, a moderate amount (10-20%) of feldspar in beach sands would likely indicate a substantial supply from local coastal rock exposures, rather than a supply of feldspathic poor sands from the deeply weathered rocks of the hinterland.

The Hauraki (B) Facies occupies an extensive region of coastal progradation between Ocean Beach and Mangatawhiri Spit. The facies has relatively uniform fine to medium sands, which are subangular to subrounded and highly feldspathic with a mean total feldspar content of 67%. Sand size rock fragments and shell material are infrequent, with rock fragments less than 10% and shell usually less than 5%. The Hauraki (B) sand facies is derived from inner shelf deposits termed the Hauraki (A) Facies. This facies was originally derived from the Hinuera Formation of the Central Volcanic Area. Sands were transported via the Waikato River when it flowed across the floor of the Hauraki Gulf during the last glaciation (Schofield, 1965; 1970).

Schofield (1970, p. 767) notes that his description of Northland coastal sand deposits was intended to form a basis for further more detailed research in the future. The present study has examined the highly variable Bay of Islands Facies with the intention of further defining the description given to this facies by Schofield.

5.3.2 Sample Collection and Analysis

For the present study 64 samples of beach sediment were collected from many localities along the east coast of Northland (Fig. 5.1). Most of the sample sites lay within the Bay of Islands Facies. Some samples have also been analyzed from other facies for comparative purposes.

Samples of beach sediment were normally collected during the initial period of the beach profile survey (December, 1975).

Samples were taken from the surface of the beach at the mid-tide level of the foreshore. Some backshore samples were also collected for comparison. As well, where gravel was present on the beach, a sample of this was collected. This gravel was normally concentrated on the upper foreshore or backshore of the beach in the form of cusps (Plate 5.5). Sample weights varied between approximately 0.5 kg for sand, and 2-3 kg for gravel samples.

The initial laboratory treatment for each sample consisted of washing with fresh water in a five litre beaker. This was done to remove salt and any plant detritus present. It also allowed for an assessment of the amount of fines (silt and clay). In all cases, fines formed an insignificant amount ($< 1\%$) of the total sample. After washing the samples were heated in an oven at $60^{\circ}C$ until dry.

The samples were then either analysed in total or split into small subsamples depending upon grain size. For gravel samples, the whole sample was sieved at approximately 0.5 ϕ intervals. Procedures for sieve analysis followed those outlined in Folk (1974). If the sample was mixed sand and gravel, then the whole sample was sieved and if the sand fraction was appreciable ($>20\%$) this was saved for further size analysis using a settling tube. Sand samples were analysed using a commercial settling tube. Sample weights were set at either 2.5 gm for coarser sands or 1.0 gm for finer sands. The settling tube results, which are determined in terms of settling velocities, were converted to particle diameters from a calibration curve for glass spheres in distilled water at $18^{\circ}C$ (Gibbs et al., 1971). Grain size data from the settling tube have thus been represented in terms of a hydraulically equivalent diameter. Shell material was not removed prior to either sieving or settling tube analysis.

5.3.3 Sediment Size Characteristics

The results from all analyses of beach sediment are presented in Tables 5.1 and 5.2. All particle sizes have been expressed in the $\emptyset$ scale, which is $-\log_2$ (mm) of the particle diameter (Appendix 3). For each sample the two Folk parameters of Graphic Mean and Inclusive Graphic Standard Deviation have been determined, according to the procedure outlined in Folk (1974), and in Appendix 2.

Of the 59 samples from the study area, 9 have mean sizes in the gravel range. This should not be taken to mean that 9/59 or 15% of beach sediments in the study area are gravel, because on all of the beaches from which gravel samples were obtained the dominant sediment was sand (Plate 5.3, 5.5). In fact, as a rough estimate, gravel size material probably accounts for less than 5% of beach sediment in the study area.

The sand samples are more representative of the total distribution of sediment types. The beach sands range in mean size from very coarse sand to fine sand with most of the samples being in the medium to fine sand range. Most of the samples are very well sorted with standard deviations of less than 0.35 $\emptyset$ units. Samples from Ocean Beach, Ngunguru and Whananaki Spits, and other large beaches are well sorted, whereas samples from smaller pocket beaches tend to be only moderately well sorted to well sorted. The exception to this is Pataua Beach which is a large beach, but with many samples which are only moderately well sorted. This may be due to the coarser fraction of sands which are present in Pataua Beach, which are naturally less well sorted than finer beach sands (Folk, 1974, p 6).

Table 5.1 - Summary of analysis of beach sediment samples.

Sample No.	Grid (1) Reference	Location	Folk Parameters Mz (ϕ units)	σ_I	Percent $CaCO_3$(2)	Percent Rock (3) Fragments	Type of Sample
01	N24/085834		1.82	0.30	17.1	5-10	foreshore
02	"		1.49	0.31	10.1	5-10	backshore
03	N24/074853		1.76	0.25			foreshore
04	"	Ocean Beach	1.52	0.33			backshore
05	N24/065874		1.71	0.29			foreshore
06	"		1.59	0.35			backshore
07	N24/063985		1.96	0.25			foreshore
08	"		2.01	0.22			backshore
09	N20/062943	McGregor's	2.39	0.36	57.2	50-75	foreshore
10	"	Beach	-3.83	0.91			foreshore
11	N20/062963	Taiharuru	-1.32	1.28			foreshore
12	"	Beach	0.18	1.80	35.0	>90	foreshore
13	N20/048980		2.37	0.30	21.0	75-90	foreshore.
14	"	Fishers Beach	1.47	0.66			backshore
15	"		-3.10	1.64			step
16	N20/043979	Kaoiti Beach	1.96	0.40	31.4	50-75	foreshore
17	"		1.69	0.44			berm crest
18	N20/033984		2.01	0.31	22.7	50-75	foreshore
19	"		1.13	0.55	24.7	75-90	dune base
20	N20/031988	Pataua Beach	2.15	0.26	21.1	25-50	foreshore
21	"		1.45	0.52	23.0	>90	dune base
22	N20/025000		1.31	0.52	25.5	25-50	foreshore
23	"		0.80	1.03	22.9	75-90	backshore
24	N20/024082		2.23	0.32	13.8	25-50	foreshore
25	N20/018075	Ngunguru Spit	2.25	0.28	12.8	10-25	foreshore
26	N20/013065		2.20	0.30	14.0	10-25	foreshore
27	N20/043111	Rocky Bay	0.33	1.32			foreshore
28	"		0.77	1.04	2.3	>90	backshore
29	N20/015164		1.06	0.97	92.7	75-90	l foreshore
30	"	Matapouri Bay	2.01	0.30	86.5	>90	u foreshore
31	"		1.64	0.37	45.1	>90	backshore
32	N20/998167	Woolleys Bay	2.18	0.26			foreshore
33	N16/974221		2.40	0.33	42.0	>90	foreshore
34	N16/978225	Whananaki Spit	2.28	0.32	54.3	>90	foreshore
35	N16/970212		2.48	0.21	29.8	75-90	foreshore
36	N16/959236		1.59	0.33	34.4	>90	foreshore
37	"	Moureeses Bay	1.91	0.27	19.6	25-50	foreshore
38	"		0.01	0.51			foreshore
39	N16/927316	Mimiwhangata Bay	2.66	0.22	61.3	50-75	foreshore
40	"		2.55	0.29			backshore
41	N16/312903	Ngahau Bay	1.30	0.92			foreshore
42	N16/871317		1.95	0.47	42.6	>90	foreshore
43	"	Helena Bay	-2.32	0.47			cusp horn
44	"		0.80	0.85			backshore
45	N16/852373	Oakura Bay	2.75	0.16	45.4	50-75	foreshore
46	"		-2.49	0.73			backshore
47	N16/861423	Whangaruru Hb.	-1.73	0.45			foreshore
48	N16/862426	Bland Bay	2.77	0.21	47.8	>90	foreshore
49	"		-2.53	0.45			foreshore
50	N12/798526	Akau Bay	-2.08	0.39	29.6	>90	foreshore
51	"		-1.31	1.21			foreshore
52	N11/603660	Wiwiki Beach	1.63	0.33	41.7	75-90	foreshore
53	"		1.51	0.43			backshore
54	N8/296836	Marble Bay	0.41	1.20			foreshore
55	"		1.54	0.46			backshore
56	N8/288833	Tauranga Bay	2.10	0.37	62.5	75-90	foreshore
57	"		1.79	0.51			cusp horn
58	N8/215844	Taupo Bay	2.06	0.41	81.4	>90	foreshore
59	"		1.74	0.42			backshore
60	N38/226904	Red Beach	2.12	0.33	2.4	5-10	foreshore
61	N34/292230	Omaha Bay	1.78	0.44	5.2	<5	foreshore
62	N29/241341	Pakiri Beach	1.63	0.37	2.6	<5	foreshore
63	N24/983781	Marsden Pt.	2.19	0.22	0.4	<5	foreshore
64	N4/450000	Parengarenga Hb.	2.05	0.25	0.6	0	dredged

Note (1) Grid references to NZMS 1 maps. Sheet N4(1967), N8(1972), N11(1969), N12(1970), N16(1970), N20(1964), N24(1968), N29(1969), N34(1967), N38(1974).
(2) Percent $CaCO_3$ determined for sediment $\leq$ 0.0 ϕ.
(3) Percent rock fragments determined on shell free basis.

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Table 5.2 - Shell material in beach sediments generally coarser than 0.0 ∅ expressed as a weight percentage for each size fraction. (nd) indicates shell present in fraction but not determined.

Sample Number, Location	M_z Total Sample (from Table 5.1)	Size Fraction (∅ units) ← pebble →				← granule →			← v. c. sand →
		-4.0	-3.4	-3.0	-2.6	-2.0	-1.5	-1.25	-0.5	0.0
10 McGregors	-3.83	0	0.4	1.4	3.1	4.2	nd	4.2	nd	nd
11 Taiharuru	-1.32	0	0	0	2.2	1.0	4.7	11	nd	nd
12 Taiharuru	0.18	0	0	0	0.9	3.3	3.2	3.8	nd	nd
15 Fishers	-3.10	0	1.9	0	0	<1.0	0	<1.0	<1.0	nd
29 Matapouri	1.06	0	0	0	0	0	0	0	0	100
43 Helena Bay	-2.32	0	100	11	7.3	6.8	nd	nd	nd	nd
46 Oakura	-2.49	100	55	39	40	nd	30	nd	nd	nd
47 Whangaruru Hb.	-1.73	0	0	2.8	1.5	2.8	<1.0	<1.0	nd	nd
49 Bland Bay	-2.53	nd	59	30	16	14	nd	nd	nd	nd
51 Akau Bay	-1.31	0	0	11	28	30	25	30	25	nd
54 Marble Bay	0.41	0	0	0	0	43	42	32	nd	nd

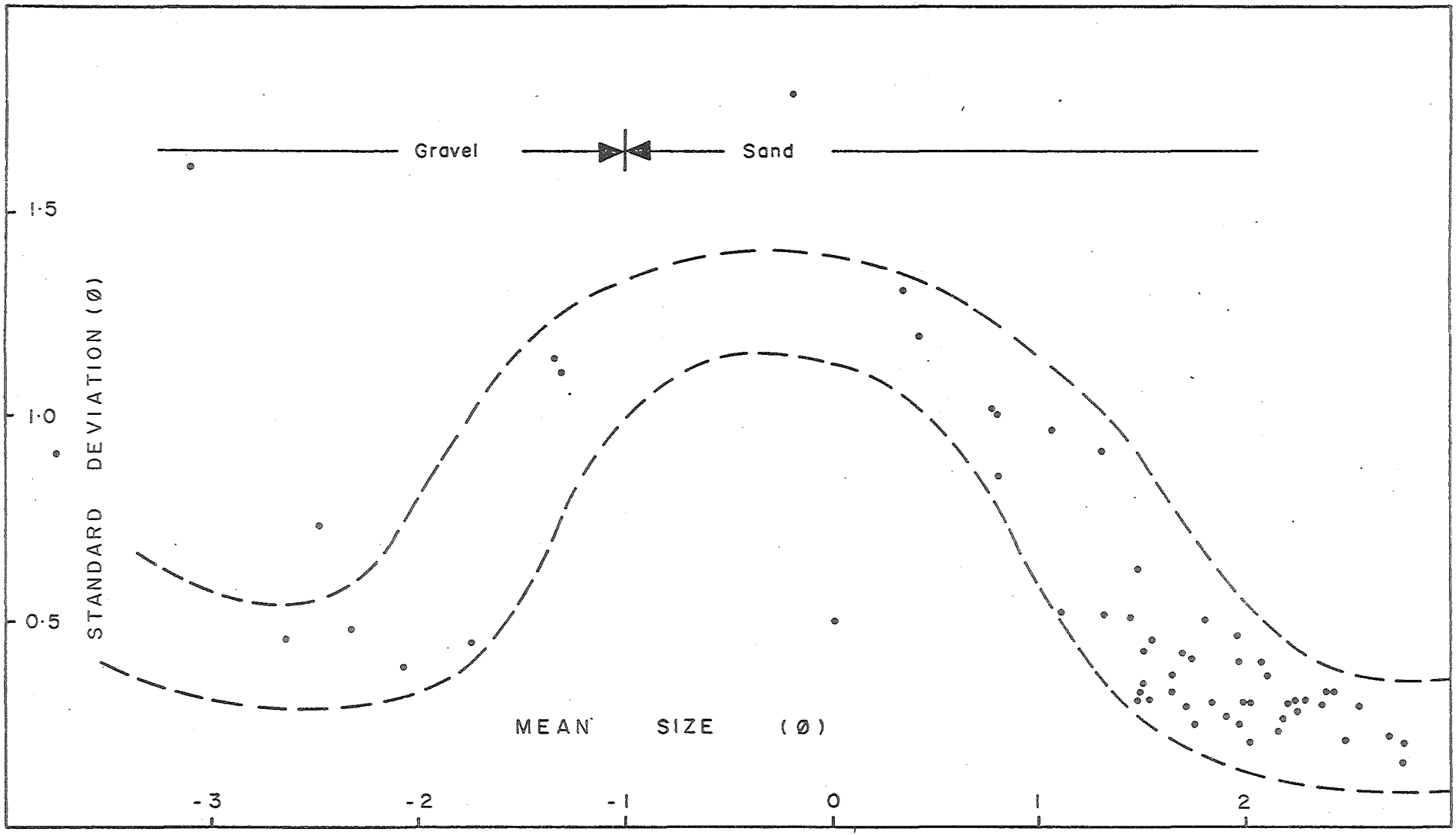

Fig. 5.2 - Relationship of standard deviation (sorting) to mean size for beach sediment samples. The two samples with standard deviations greater than 1.5 Ø are bi-modal. The dashed lines represent the approximate boundaries of the trend.

A scatter plot of standard deviation against mean size (Fig. 5.2) shows a portion of the sinusoidal trend which has been recognised by numerous workers (Folk, 1974) and which is usually attributed to source area characteristics and hydraulic sorting factors. From the plot it can be seen that the best sorting occurs at about 2.8 ∅ (fine sand) and again at -2.5 ∅ (pebble), while the poorest sorting generally occurs between 1.0 to -1.0 ∅ (coarse and very coarse sand). Roughly similar results have been found at other locations in New Zealand by Andrews and van der Lingen (1969), and McLean and Kirk (1969).

The trend in Fig. 5.2 is probably due to different sources of material and hydraulic factors. The moderate to well sorted pebble samples probably occur in response to initial, characteristic rock breakage size. In addition the samples have been preferentially sorted into cusp features. Poorly to moderately well sorted coarse and medium sands occur in response to the mixing of rock fragments and shell detritus with finer grained quartz and feldspar particles. Finally, some of the best sorting is found in the lithologically homogeneous samples of Ocean Beach and Ngunguru Spit, although in the case of other samples (39, 45, and 48) a high degree of sorting is also achieved in lithologically heterogeneous samples with significant shell contents. These latter samples are from partly sheltered bay beaches where more selective, lower wave energy levels may have aided the development of hydraulically equivalent sediments.

5.3.4 Rock Fragments

The rock fragments (RF) content of beach sands (Table 5.1) was determined for the samples upon which calcium carbonate analyses

had been done (see Section 5.4). The RF content was estimated by simple examination of samples with a 10X hand lens and has been expressed as a percentage on the basis of seven classes: <5, 5-10, 10-25, 25-50, 50-75, 75-90, and >90%. The remainders of the shell-free samples predominantly consisted of quartz and feldspar particles, with the exception of sample 37 at Moureeses Bay which had a moderate amount of mafic minerals.

The RF material is virtually all of greywacke origin. Within the study area RF content is lowest at Ocean Beach, Ngunguru Spit, and in a few of the Pataua Beach samples. At no other sites sampled in the study area is the RF content less than 50%, and it exceeds 90% in many samples. In comparison, sites outside the study area (samples 60-64) have very low RF values.

These RF results are in agreement with those of Schofield (1970). In addition, the low RF content of Ngunguru Spit samples, and therefore higher quartz and feldspar content, indicates that a substantial amount of the sediment in this feature is the same as that in Schofield's Hauraki (B) facies. As well, in the Pataua samples with high RF contents, the rock fragments form the coarser fraction of the sample with the finer fractions being composed entirely of feldspar and quartz. Therefore, it is proposed that the most northern coastal extent of the Hauraki (B) facies is Pataua Beach and Ngunguru Spit. In comparison, at the next large embayment to the north (Sandy Bay), the Whananaki Spit samples show very high RF contents which indicates that these sands are typical of the Bay of Islands Facies.

Finally, some of the Pataua beach samples are composed of 25-50 wt% of sediment in the coarse to very coarse sand size range (1.0 to -1.0 ϕ). This may be significant since a large fraction of the

Pataua inner shelf sediment is of this size range (Chapter Seven and Fig. 8.3). Thus, inner shelf sediment may have been in the past, or may presently be, a source of the coarser fraction of Pataua Beach sediments, although a fine sand shoreface facies presently intervenes between these two deposits (Chapter Seven).

5.4 CALCIUM CARBONATE IN BEACH SEDIMENTS

5.4.1 Introduction

In the field it was observed that a large amount of biogenic calcium carbonate material was present in the sediments of many beaches. This carbonate material was commonly mollusc shells (usually bivalves) and shell fragments ranging from gravel down to and including sand sizes. Other carbonate material was present in the form of bryozoan, sponge, and echinoid fragments, and foraminifera tests.

Previous investigations of beach sediments in the study area have demonstrated a significant contribution from biogenic carbonate sources. Samples of beach sand in the Bay of Islands Facies (Fig. 5.1) were found to have carbonate contents ranging from 3-52 weight percent (wt%) (Schofield, 1970). In another study, beach sand collected just south of Mimiwhangata (Fig. 6.1) gave carbonate contents ranging from 30-87 wt% with a mean of 64 wt% for eight samples (Ballantine et al., 1973). Drift shell was also very common in this area and consisted almost entirely of offshore or rocky shore species. The offshore species morning star shell (Tawera spissa),

large dog cockle (Glycymeris laticostata), and coarse biscuit shell (Dosinia anus) together accounted for 50-80 wt% of drift shells on the beach, whereas the sandy ocean beach species tuatua (Amphidesma subtriangulatum) usually accounted for only 10 wt%. It was also noted that the high proportions of offshore species present on the beach as drift shell probably reflected the high standing crop observed in local offshore populations of these species, the resistance of their thick shells to breakage and wear, and the ability of local waves to move the shells toward and up the beach.

In addition, from samples of drift shells and shell fragments collected along the exposed beach of Omaha Bay (Fig. 1.2), Schofield (1967) was able to show that the offshore species Tawera spissa commonly accounted for 60-90 wt% of the shell fragments in the size fraction coarser than -2.5 Ø. Thus, although sand size beach material in Omaha Bay is low in carbonate content (Schofield, 1970), offshore shell beds have supplied a significant amount of material to the coarse fraction of beach sediments.

5.4.2 Methods of Laboratory Analysis

Calcium carbonate concentrations were determined for 37 sand samples (Table 5.1) and 11 coarse sand and gravel samples (Table 5.2). For the coarse sand and gravel samples shell material was separated by hand for each sieved fraction and expressed as a weight percentage per size fraction.

For sand samples a 1 gm subsample from the total sample was analysed. Initially, the titration method described by van der Linden (1968) was used, except that it proved unnecessary to crush the sample.

After a number of titration determinations, it was found that analyses could be done more simply and quickly using the weight loss after acid digestion method. A comparison of the two methods showed that the titration method gave slightly higher values (1-5 wt%) than the weight loss method. Glasby (1971) has criticised the titration method and states that it is only accurate in increments of 10 wt%, above 20 wt%. But, in a study comparing four different carbonate analysis methods, Siesser and Rogers (1971) have shown that the weight loss method is accurate to about 5%, and generally only over estimates by 3-10% beach samples with carbonate contents in the range 20-80 wt%.

5.4.3 Results and Discussion

The results from the coarse fraction analysis (Table 5.2) show variable carbonate contents between samples which appear to be related largely to location and mean sediment size. High percentages in the coarsest fractions are present at Helena Bay, Oakura Bay, and Bland Bay, which are all partly sheltered ocean beaches in shallow bays, and with total sample mean sizes coarser than -2.0 ϕ. Most of the shells on these beaches were the sandy beach species tuatua. In contrast, on more exposed beaches or on beaches without shallow floored bays, such as Taiharuru, Akau Beach, and Marble Bay, the highest percentages of carbonate are in the finer fractions (finer than -2.0 ϕ), indicating that these sediments have shell fragment proportions which may be due to shell breakage in higher energy wave environments.

Carbonate contents in beach sands (Table 5.1) within the area of study are highly variable and range from 2.3-92.7 wt% for individual samples. However, variations in carbonate content within beaches is

much less, as can be seen especially for the Pataua Beach and Ngunguru Spit samples, and also less so for Ocean Beach, Matapouri Bay and Whananaki Spit samples. When composite means are computed for these within beach samples and included in a grand mean, carbonate content averages 39.7 wt% with a standard deviation of 20.6 wt% and a range from 2.3-82 wt% (Fig. 5.3). A comparison of carbonate content against mean size of the sample does not show a strong relationship between these two variables (Fig. 5.3).

Within the study area (samples 01-59, Table 5.1) carbonate contents are generally lowest in two cases. The first case is that of the southern beaches (Ocean, Pataua, and Ngunguru) in which most of the beach sediment is similar to the northernmost extension of the Hauraki (B) Sand Facies. Therefore it would appear that calcium carbonate production is either relatively lower in the vicinity of the southern beaches, or more likely that the feldspathic Hauraki (B) sands have been supplied to these beaches in such large quantities that the shell material is relatively "diluted" (Davies, 1972, p. 114). The second case of low carbonate content occurs in the sediments of beaches in Rocky Bay and Moureeses Bay, which are small bays located along exposed portions of steep, rocky coastlines. Here sediment supply has chiefly come from local coastal erosion of greywacke rock as indicated by high rock fragment percentages for both samples. Therefore, these beaches and offshore areas must not form favourable sites of production and deposition for calcium carbonate material.

In contrast, carbonate contents are highest in the case of the most northern beaches (Tauranga and Taupo) and in large bay beaches such as Matapouri, Mimiwhangata, and Bland Bay, as well as others.

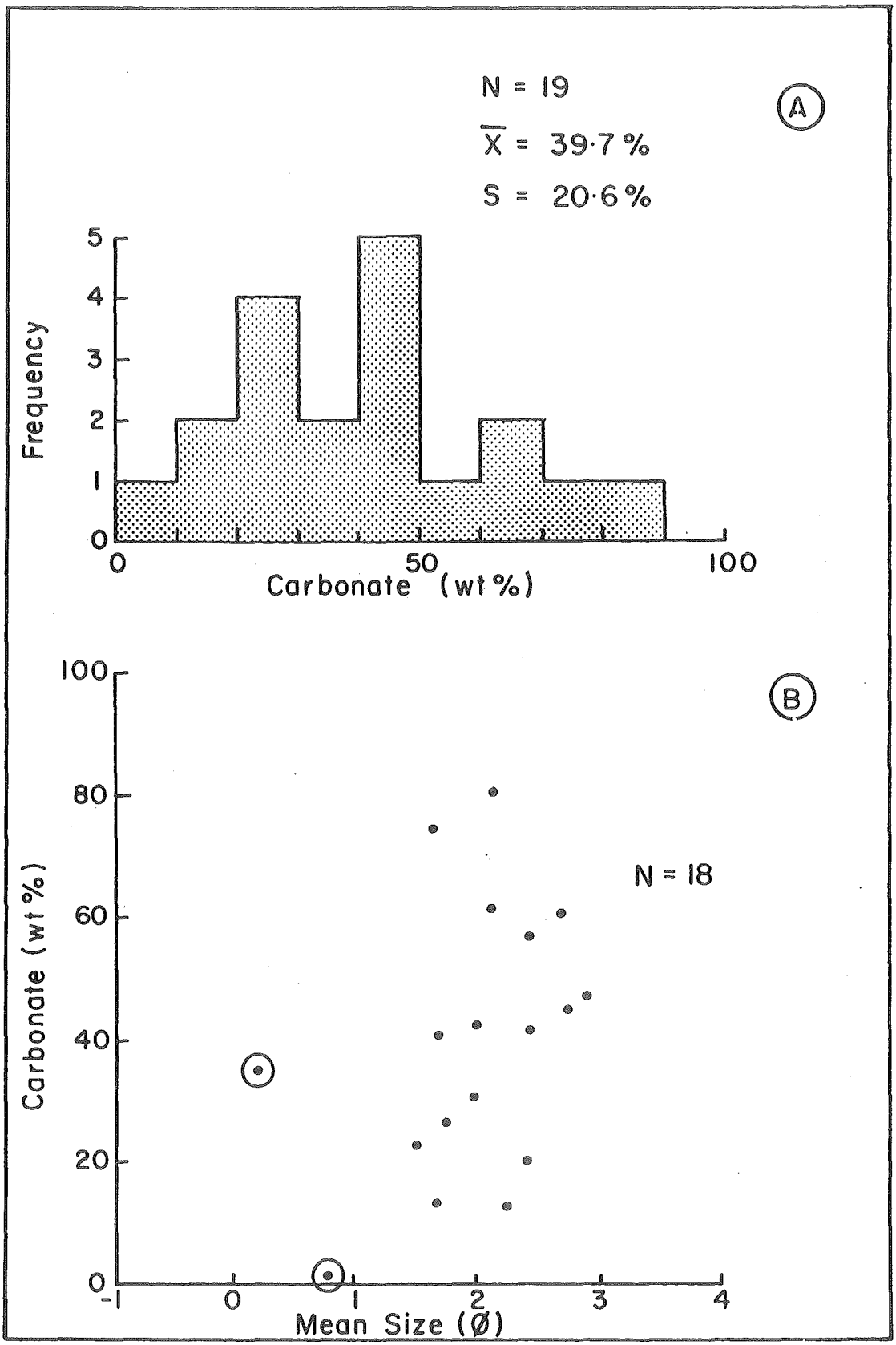

Fig. 5.3 - Carbonate content of beach sands expressed as: (A) frequency of occurrence and (B) the relationship to mean size of the total sample. The two circled samples have bimodal size distributions.

In these cases high biogenic production rates appear to compete with or exceed the supply of beach material from other sources. These large embayments must also be favourable sites for the deposition of carbonate beach sediments.

In addition, samples from outside the area of study (samples 60-64) have much lower shell contents which are in agreement with those determined by Schofield (1970) for the Hauraki (B) and Parengarenga Sand Facies (Fig. 5.1). In these cases dilution of biogenic sands by much higher quantities of mineral sands is the probable reason for low carbonate percentages.

In summary, calcium carbonate in beach sediments within the study area is variable (range of 2.3-82 wt%) but appreciable (mean of 39.7%). Differences between beaches are due to the combination of three factors: shell production, transport and deposition, and "dilution" of shell material by other sources of beach sediment.

5.5 SCALE OF BEACH AND COASTAL CHANGES

It is possible to consider beach and coastal changes as occurring over a range of spatial and temporal scales. For example, Schwartz (1968) has used this approach to describe the Bruun effect of sea level rise as a permissive factor in shore erosion (Bruun, 1962). Table 5.3 presents a time and spatial magnitude scale which is proposed for use here. The scale is based first, on time intervals over which characteristics of the geologic and physical environments can be expected to change, and second, on the magnitude of the spatial response which is likely to be produced in the beach or coastal system

Table 5.3 - Time scale of beach and coastal changes proposed for the study area. Note the overlap in the range of responses.

Time Scale (years)	Geologic and Environmental Factors Producing Changes	Response Magnitude Horizontal Change (metres)
Short Term ($\leq 10^{-2}$)	-Single storms, storm surges	$\pm$ 0.1 to 5.0
Quasi-seasonal and Annual (10^{-1} to 10^{0})	-Periods of storminess with higher than average sea levels -Possible coincidence of storms with spring tides -Annual cycle of sea level changes	Dynamic Equilibrium $\pm$ 1.0 to 25
Historical (10^{1} to 10^{2})	-Storm cycles of 2-20 years, with sea level changes -Secular sea level changes of 10 cm/century -Possible shore-normal sediment budget changes	Trends of instability $\pm$ 10 to 50
Long Term (10^{2} to 10^{3})	-Climatic changes (storminess, wind directions) -Post-glacial sea level rise to near present ca. 6,000 BP and possible changes of $\pm$ 1-2 m since -Sediment budget changes from terrigenous, marine and biogenic source areas	Chronic Erosion, Deposition $\pm$ 50 to 100

by these changes. Thus, it is the scale of the cause of beach changes, rather than the scale of the effect, which is primary.

In a manner similar to Thom (1974) changes in the main characteristics of sediment supply, degree of storminess, and sea level are considered as possible causes of coastal change. The magnitude of coastal responses is not as clearly associated with a particular time scale, but some of the characteristic response magnitudes have been suggested. In particular, the concept of a beach profile in dynamic equilibrium has been confined to time interval scales up to and including the first part (10's of years) of historical changes. Time intervals and corresponding magnitudes of change greater than 10's of years have been termed trends of instability as opposed to dynamic equilibrium conditions.

The scale has general application to other beach and coastal areas but some features which are specific to the east coast of Northland would include the probable lack of significant sediment budget changes from longshore transport, or supply from rivers for time intervals less than the last 10^3 years. As well, the magnitude of long term coastal changes is confined to values in the order of 100 m since this characterises the maximum width of most of the coastal deposits in the study area.

Sections of this chapter have directly investigated beach profile changes which are due to events occurring between 10^{-2} and 10^0 years (a week to a year). In addition, an analysis of air photo sets has allowed some determination of the changes occurring on the time scale of 10^1 years, specifically the interval 30-40 years. Before these time scales are examined, coastal changes on a 10^2-10^3 year time scale are considered in the following.

5.5.1 Long Term Coastal Dynamics

Long term coastal changes have been defined in Table 5.3 as those which have occurred on time scales of 10^2-10^3 years, or following the termination of the Holocene (last post-glacial) marine transgression about 6,000 - 4,000 BP. The evolution of coastal features over this period may be considered to depend on varying sources and rates of sediment supply, possible eustatic sea level changes in the order of $\pm$ 1-2 m, and changes in other factors such as the wave climate, shoreline geometry, and offshore bathymetry. The Northland landmass can be regarded as relatively stable over this period (see Section 3.4.1).

Although some study has been done on the post-glacial evolution of coastal features along the east coast of Northland, it is limited in its depth and extent. Wellman (1962) in his coastal reconnaisance discussed the stratigraphy exposed by marine erosion at about ten sites in this area. He found air-fall ash and sea-rafted pumice present in coastal deposits indicating an age of the deposits in excess of 1800 yr BP. More recent work has also established the presence of ash and pumice in coastal deposits along the east coast of Northland (Pullar et al., 1977). With sea-rafted pumice presently being exposed in deposits by coastal erosion, this may be an indication that at a number of locations the position of the presently eroding shoreline is similar to the shoreline of 1,500 - 2,000 BP.

Schofield (1960; 1967; 1968) infers the age of development of many coastal features along this coast and in the Hauraki Gulf to be about 4,000 BP on the basis of a postulated sea level fall of 2.1 m since that time (Fig. 3.4). This sea level fall has been marked by

about half a dozen second order regression/transgression cycles of about 1 m vertical range which are also likely to have produced some horizontal responses in coastal development.

Some spits and beaches may have taken from 2,000 - 4,000 years to reach their near-present form, so that they would be at most 2,000 years old. Gibb (1977) has argued that Ohope Spit in the Bay of Plenty was initially developed only about 2,000 BP, and that a stable harbour entrance has been established only within the last 500-1,000 years. By contrast, the evolution of spits and beaches along the southeast coast of Australia seems to have occurred very rapidly after sea level stabilisation (Thom, 1974). They are therefore somewhat older than the New Zealand examples just discussed.

In summary, it must be admitted that very little is known about the Holocene evolution of coastal features in the study area. It would seem probable though that the present coastal deposits originated at the time of sea level stabilisation (as long ago as 6,000 BP) and may have still been evolving up to 1,000 BP. It is also probable that this evolution would have differed from beach to beach owing to variations in amounts and rates of sediment supply.

Whether or not long term sediment budgets have reached an equilibrium is not certain. Sediment may still be supplied to beaches from offshore sources and the possibility of river derived sands cannot be completely ignored. Conversely, contemporary sea level rise may be causing slow shoreline retreat and negative sediment budgets. The following section on historical coastal changes suggests that equilibrium conditions may not presently exist on some beaches in the study area.

5.6 HISTORICAL COASTAL CHANGES DETERMINED FROM AIR PHOTOS

5.6.1 Introduction

The determination of coastal changes over the period of the last 30-40 years is commonly made through the comparison of time sets of vertical air photographs. Recent New Zealand examples of the use of this method are provided by Schofield (1967), Kirk (1975a), McLean (1976b), Gibb (1977), Healy et al. (1977), and Williams (1977). These studies have shown periods of coastal progradation and retrogradation which have occurred at different times, and with varying magnitudes and rates between geographic areas.

In this study there have been two purposes in carrying out an air photo analysis for coastal changes. The first purpose was to determine the extent of coastal changes beyond those which had been measured from the two years of beach profile surveys (see Section 5.7). This information was needed to establish the historical stability of coastal features in the study area. The second purpose was to determine if measured coastal changes were one-way net changes, or alternatively, if they were simply fluctuations about a generally stable coastline.

Due to the limitations of analysing coastal changes from time sets of air photos, it is not entirely certain that these two purposes have been achieved. This is because of the dynamic nature of beaches in the short term. Thus, the magnitude of beach changes can be independent of the time interval between surveys, so that as great a change can occur in a few years as in 10-20 years (CERC,

1973, p. 4-59). Therefore, in the case of the first purpose, the maximum possible change may not be present on a particular set of photos, and in the case of the second purpose, a large change over a short period of time may not necessarily represent a long term trend. In this latter case, additional geomorphic field evidence may help to resolve the question.

5.6.2 Photographic Coverage

For this study a partial selection of available photography was purchased from the Lands and Survey Department, Wellington. The areal coverage included most of the beach profile locations shown in Fig. 5.1, and extended in time from initial dates in 1942 or the early 1950's, up to the 1960's and 1970's. The scale of the initial photography was approximately 1:16,000, while later coverage sometimes required enlargements of 3X-7X to produce final scales of 1:8,000-1:9,000. The 1:16,000 originals and 3X enlargements were found to provide satisfactory definition of shoreline detail. But, greater enlargements, especially 7X from an original at a scale of 1:63,000, were not completely satisfactory if beach features were not well defined on the original photos. In this last respect, sandy beach and dune areas which were poorly vegetated were often photographically overexposed because of their high reflectance characteristics. This was also a problem with some of the unenlarged photos.

5.6.3 Methods of Determining Changes

Changes were determined by comparing recognisable coastal features on the two sets of photographs. The feature most often used for comparison was the face of the frontal dune. This was sometimes clearly marked by a sharp vegetation/exposed sand boundary or a small erosional scarp. At other times the line of the berm crest was used if it was visible on both photos. In some cases neither of these two features were well marked. This was the case on wider, flatter beaches with a sparse vegetative cover in dune areas.

Positioning control for comparative measurements was achieved in two ways. For single point measurements distances were measured from coastal features to permanent positions on both photos. The permanent positions were near sea level to reduce radial distortion effects and included the corners and sides of houses, and road edges. For comparing lengths of shoreline two to three position control points were located on a transparent overlay of the large scale photography (1:8,000). The other (smaller scale) photograph was then enlarged and projected onto the overlay using a Grant Projector so that the sets of position control points for the two photos coincided exactly. Shoreline features could then be traced with a hard, fine pencil line and then compared to the larger scale photo. All measurements were made with a set of dividers and then read off a ruler graduated in millimetres.

In addition, observations were made of other coastal features such as the dune vegetative cover and the hard rock part of the coast. In this last respect, good light penetration through clear water in many

photos revealed the spatial extent of submerged reef/sediment interfaces out to depths of about 5m, and a comparison of these boundaries was made where possible.

5.6.4 Estimate of Errors

Errors in the measurement of coastal changes from air photographs arise from a number of sources. First, the scale of the photo determines the definition of features and resolution of measurements. In this study the smallest useful measureable distance was taken to be 0.2 mm which represents 1.6 m at a scale of 1:8,000 (1 mm = 8 m). To calculate a difference between photographs requires two measurements, so that the margin of error becomes 3.2 m. With additional sources of error controlled, such as variable scale over the surface of the photograph, the total margin of error should be a maximum of 5 m. Therefore, in the following descriptions of coastal changes, measurements less than or equal to 5 m have been considered as too small to be significant.

5.6.5 Results of Analysis

The following results describe changes at large beaches and groupings of smaller beaches from south to north (Fig. 1.2 and 6.1).

Ocean Beach

For most of the length of Ocean Beach changes in the position of the face of the foredunes between 1942 and 1971 have been in the order of the measurement error of 5 m. Exceptions to this include progradation of over 100 m in the most northern portion of the coast

where land immediately south of the present stream outlet was a washover/lagoon area in 1942, but now consists of low (<2 m) sparsely vegetated dunes. As well, immediately north of the stream outlet in the vicinity of beach profile 04, there has been erosion of the dune by 10-20 m. Other areas of instability include the two stream outlets at the southern end of the beach where foredunes are completely absent. In the case of the most southern stream there was an erosional change of 10-15 m in the position of the berm between 1950 and 1971. Also of note for the whole Ocean Beach system are the vast areas of unvegetated, transgressive sand dunes which existed behind the beach in 1942. Although many large blowouts still existed in 1971, there has been a large increase in the area of vegetative cover and stabilised dunes.

McGregor's and Taiharuru Beaches

Both of these pocket beaches (profiles 05, 06) have shown slight erosion (5-10 m) between 1942 and 1961. At McGregor's the erosion has been confined to the southern half, while at Taiharuru 10 m of erosion has occurred along the whole of the face of the dune. Reef/sediment contacts on the seabed of McGregor's Bay were only slightly changed. Some reef areas which were visible in 1942, were not visible in 1961, indicating some sedimentation of the bay floor.

Pataua and Kaoiti Beaches

Changes in the position of the foredune have only been in the order of the measurement error, except for the northern end of Pataua Beach where the foredune has prograded from 5-10 m between 1942 and 1961. Present observations (1977) show that this is still an area of foredune development. The area of presently cliffed dunes at the southern end of Pataua Beach did not show any significant change between 1942 and 1961.

Matapouri, Woolleys Bay

No measureable changes were found in foredune fronts and berm positions on these beaches, except for the extreme northern end of Matapouri Beach. This area had receded south about 10-20 m between 1942 and 1966. As well, there is evidence of pedestrian traffic on the 1966 photographs, which was absent in the earlier photography. This has probably contributed to a decrease in foredune vegetative cover at the northern end of Matapouri Beach.

Mimiwhangata

Air photos taken in 1950 and 1977 were compared. The earlier photography was extremely overexposed and limited the delineation of the dune/beach boundary, but it was clear on the later photograph that the seaward edge of vegetated, low foredunes had moved 30-40 m seaward. Whether or not all of this was actual beach progradation is not clear since some could have simply been due to an increase in the extent of vegetation cover in low foredune areas.

Helena, Oakura, Bland Bay.

Helena Bay showed about 5-10 m of erosion along its whole length between 1950 and 1968. But in the bay, reef/sediment boundaries were entirely unchanged over large areas of the seabed to depths of 5 m. The change at Oakura is generally too small to be significant, with the exception of the extreme southern end which showed progradation associated with the construction of a small groin. In a small bay just north of Oakura, and further up Whangaruru Harbour, a predominantly gravelly shelly beach appears to have prograded about 10 m. Coastal changes at Bland Bay between 1953 and 1976 can only be well defined for the eastern portion. This was because the central and western portions of the beach are low, unvegetated dune areas with

poorly defined features. The eastern portion showed slight erosion at one end with slight accretion toward the more central part, but both of these changes are in the order of only 5-10 m. In addition, reef/sediment boundaries on the seabed of the bay were unchanged.

Akau Bay, Wiwiki Beach

The shallow bay beaches along Akau Bay, south of the Whangamumu Peninsula, commonly lack well defined foredune areas, but a comparison of one area immediately north of beach profile site (18) showed erosion of a backshore scarp by about 10 m between 1951 and 1972. In the later 1976 photography, a storm washover area replaced the scarp. Comparisons of Wiwiki Beach were made on 1951 and 1970 photos, but since clear berm and foredune features were not apparent, no measurements were attempted.

5.6.6 Summary and Discussion

Changes for the last 35 years for most beaches along the coast of the study area are usually less than 10 m with most areas showing stability (≤5 m change) or a slight tendency to erosion (5-10 m) in some parts. Within these predominantly stable areas may be smaller areas of instability associated with stream outlets. It may also be that two beaches within the area are prograding. The first, at Mimiwhangata, may have experienced 30-40 m of progradation over most of its length in a 27 year period to 1977. The second, a small beach in Whangaruru Harbour, has prograded about 10 m. It may be significant that both of these beaches are composed predominantly of biogenic sediment. Thus, biogenic contributions to these beaches may presently be large enough to be causing progradation.

The magnitudes of change found in this study, mostly between 5-10 m, are much less than those which have been observed for the same period at other locations around the New Zealand coast. Along the Bay of Plenty coast erosion/accretion changes have been in the order of 40-80 m over large distances (Healy et al., 1977). On the mixed sand and gravel beaches around the Kaikoura Peninsula of the South Island, many locations show coastal changes greater than 20 m (Kirk, 1975a). Other examples are provided in McLean (1976b). In both of the above cases, the large changes have been due to sediment inputs from rivers, and higher rates of longshore transport on long exposed beaches. Conversely, for the study area low fluvial sediment inputs, confined sediment compartments with negligible longshore movement, and partly sheltered locations, probably account for the relative coastal stability found in this study.

5.7 BEACH MORPHOLOGY AND DYNAMICS

5.7.1 Introduction

There are abundant examples from throughout the world which demonstrate that beaches are very dynamic geomorphic features (King, 1972, pp. 334-360). Beaches usually display natural sequences of erosion and deposition which are related to variations in winds, waves, sea levels, and beach water tables. In the case of sandy beaches, which are the predominant type in the study area, erosion usually occurs under conditions of onshore winds with stormy seas. Erosive effects are also aided by higher than normal sea levels and full beach water tables. In

contrast, beach deposition usually occurs under conditions of low swell waves, and is aided by offshore winds and low beach water tables.

This section presents the results of a survey of the characteristics of beach morphology and dynamics in the study area. The purpose of the survey is to provide information on the following beach features:

(i) characteristic beach morphology, and spatial variations in morphology;

(ii) morpho-dynamics in terms of profile response to temporal variations in physical environment conditions;

(iii) the magnitude of erosion and deposition which is found under present natural conditions on beaches adjacent to proposed inner shelf dredging areas.

5.7.2 Selection of Beaches and Field Survey Methods

To provide the required information, sixteen beach cross-sections were profiled seven times over a period of almost two years (December, 1975 - October, 1977). In addition, four beaches were profiled for part of this period, and one beach once (profile 21). Thus, a total of 20 beaches were studied for their morpho-dynamic characteristics.

The location of the surveyed beach profiles is shown in Fig. 5.1 and 6.1. These locations were selected for a number of reasons. First, they are adjacent, or as close as possible, to Landsea Minerals' six inner shelf prospecting areas. Second, the beaches vary in sediment type and exposure to wave energy and are

thus intended to be representative of the range of beaches along the coast. Third, the beaches are relatively accessible, on a coast where many areas are inaccessible.

Semi-permanent bench marks were established using either existing features such as trees, sign posts, power poles, and buildings, or by installing 2 m long, steel stakes. Profiles were surveyed using a level and stadia rod along survey lines normal to the shoreline. Measurement resolution was typically 0.01 m in the vertical and 0.1 m in the horizontal.

An attempt was made to survey beaches during times of low spring tides so that more of the lower foreshore profile could be surveyed. Sometimes surveys also took place as soon as possible after major storm events in the hope that periods of maximum beach erosion could be recorded to compare with periods of deposition. No attempt was made to allow for the presence of cusp horns or bays on the survey lines. Cusps were simply considered as contributions to the natural amount of cut and fill which could be present at a profile site. In most cases, cusp morphology produced only minor profile change in comparison to that from major erosional and depositional events.

5.7.3 Description of Survey Results

Field survey data was reduced to horizontal and vertical readings and plotted so that the comparison of changes could be made between successive survey times, as shown in Figs 5.5, 5.6, and 5.7. Six sequential survey periods (I-VI) are shown for each profile location. These periods represent phases of beach profile change which are discussed for all of the beaches in Section 5.7.4. The profiles in

Figs 5.5, 5.6 and 5.7 have been chosen as being representative of the two main types of beaches present in the study, namely (i) exposed sandy beaches; and (ii) partly sheltered sand, and mixed sand and gravel beaches. The profiles extend vertically from the upper limit of effective wave action (about 1-2 m above high tide) to slightly below low water spring tide level. Reference will be made to the beach terminology defined in Fig. 5.4, which is applicable to most of the profiles in the study area.

(i) Exposed sandy beaches

Ocean Beach (profile 02, Fig. 5.5) has been taken as representative of the other Ocean Beach profiles (01, 03, 04, Plate 5.1, 5.2), and other exposed sandy beach profiles which include Kaoiti and Pataua Beach (08-11, Plate 4.2), Woolleys Bay (13), Akau Bay (18), Tauranga Bay (19), Taupo Bay (20), and Wiwiki Beach (21, Plate 3.2).

These beaches have common profile features. Wide berms with steep upper foreshore slopes were present at times of beach fill, while slightly concave profiles occurred during initial cut periods. Flat lower foreshores appeared in a prolonged cut phase, and lower foreshore and inner nearshore ridges and runnels formed during initial beach recovery phases. All of these features can be seen from the time sequence of profiles in Fig. 5.5.

This sequence also shows the amount and type of change that exposed sandy beaches experienced during erosional and depositional periods. With respect to the magnitude of beach change, exposed sandy beaches showed greater changes than any other beaches in the study area (Fig. 5.8 and 5.8b). Thus, beach changes seem to be a function of wave energy exposure with the more exposed beaches

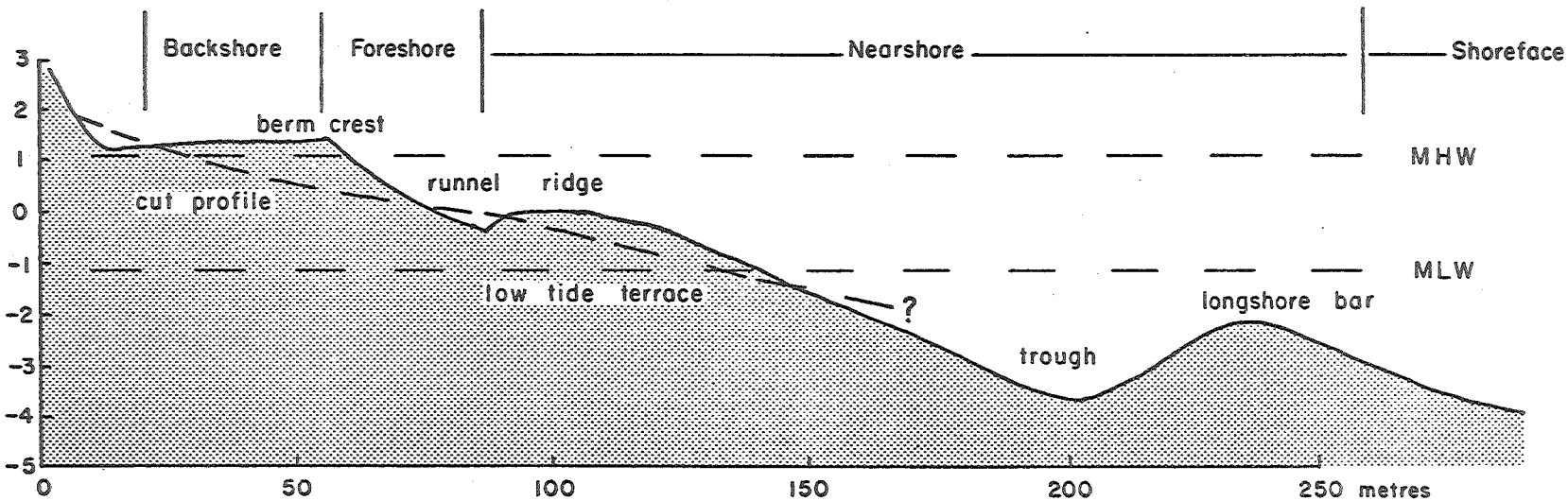

Fig. 5.4 - Beach morphology terminology.

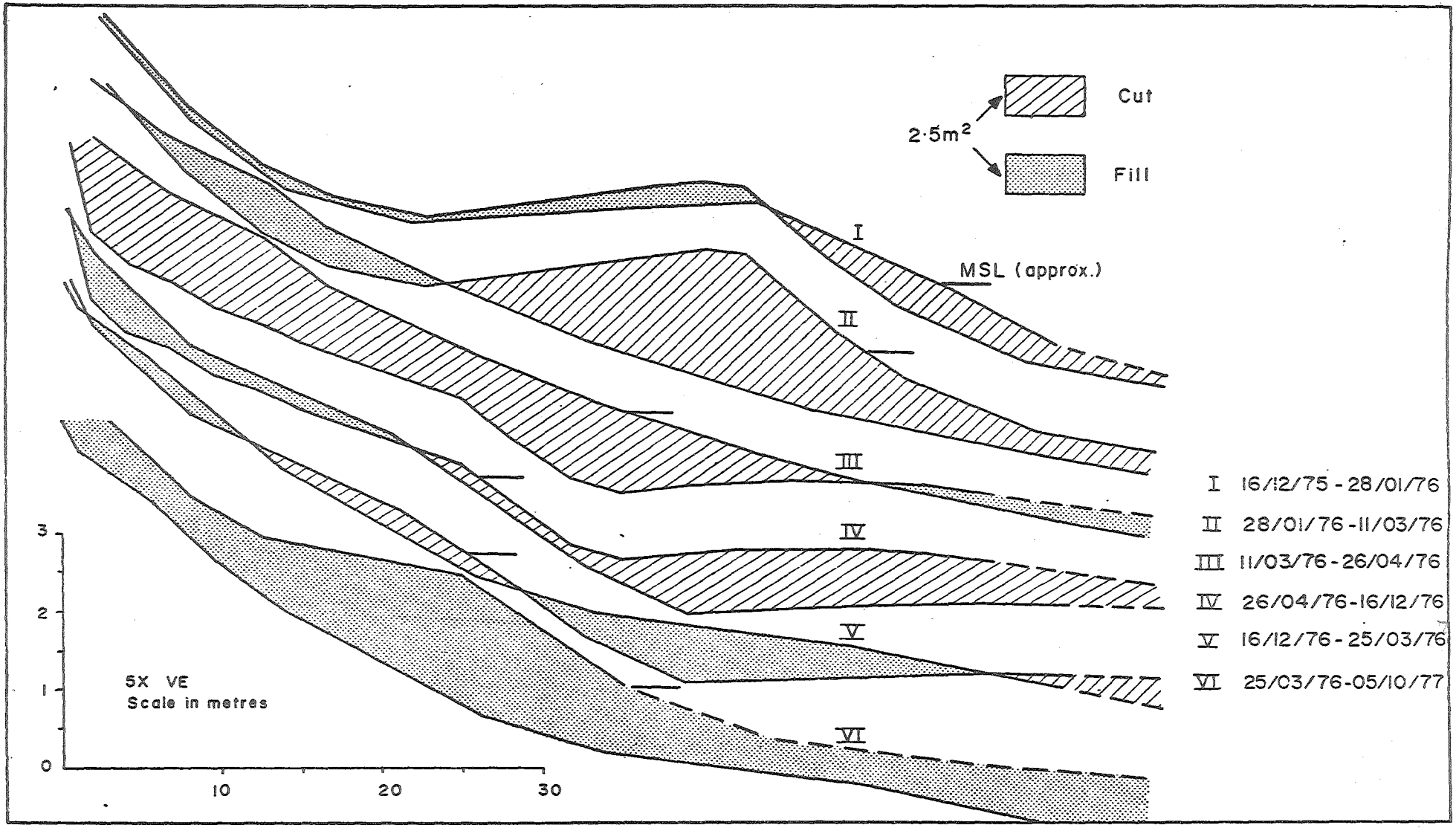

Fig. 5.5 - Time sequence of beach profile changes for the six survey periods at Ocean Beach (profile 02).

Plate 5. 1 - A portion of the southern end of Ocean Beach, December, 1975, before beach erosion. Sand covers most of the intertidal rock (see below). Awarua Rock prospecting area lies off the rocky shoreline to the north.

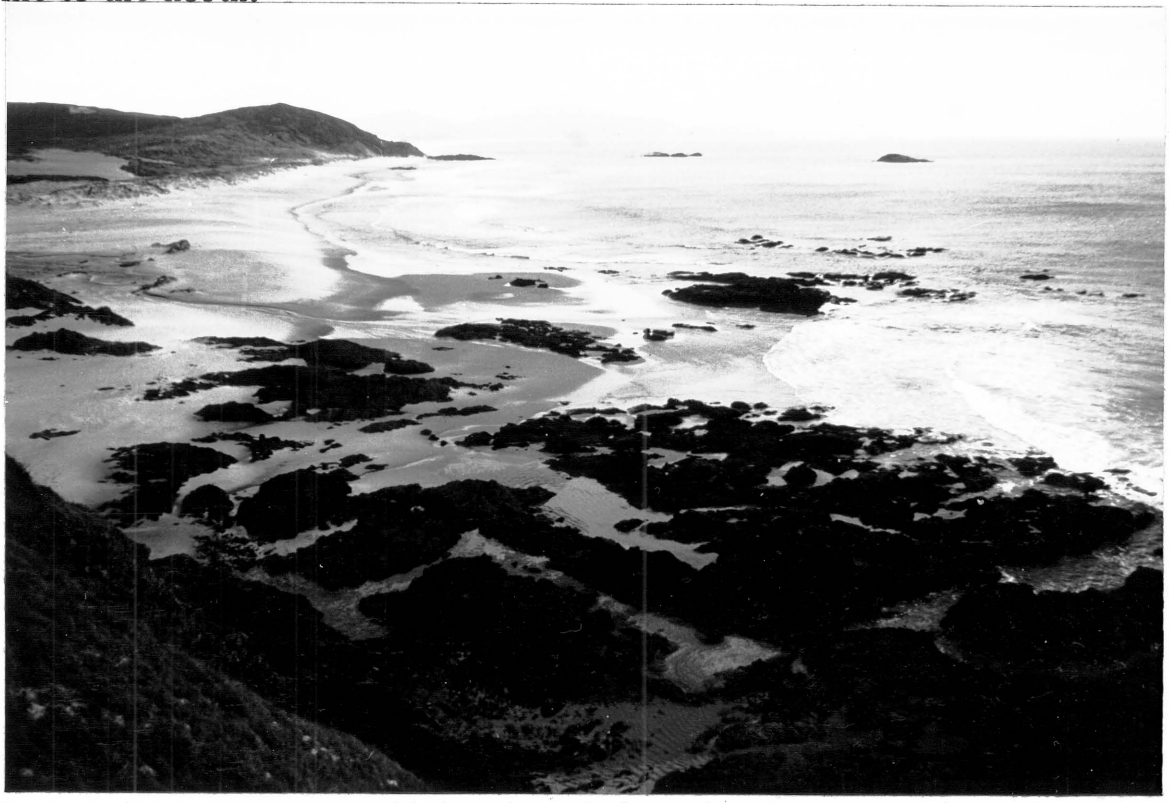

Plate 5. 2 - Ocean Beach, April, 1976. After a period of beach erosion by easterly quarter winds and waves which have exposed the underlying bedrock and narrowed the width of the beach. Tide level is slightly lower than in Plate 5. 1.

experiencing a greater amount of change. This conclusion was also reached by Schofield (1975) in a study of beaches immediately south of the study area.

With respect to the type of changes that occurred, the sequence in Fig. 5.5 illustrates some characteristic features. The berm was slightly built up by the apparent transfer of foreshore sand in period I. Erosion in period II was large and consisted of the removal of the entire berm with some deposition of sediment at the upper limit of wave action at the back of the foreshore. Prolonged erosion, as in periods III and IV, produced cliffed foredunes and flat or slightly shoreward inclined lower foreshore features. These periods also illustrate the initial development of ridge and runnel features. Periods V and VI showed a depositional phase, especially with berm development in phase VI. However, the location of this final berm crest is still about 20 m landward of that at the beginning of period I. This indicates that there has been a net retrogradation of the berm at this site during the study period. This is also shown quantitatively by the net loss of sediment for profile 02 in Fig. 5.8a.

(ii) Partly sheltered sandy, and mixed sand and gravel beaches

These beaches are usually located at the heads of bays and consist predominantly of sand with variable amounts of gravel. Taiharuru Bay (profile 06, Fig. 5.6, Plates 5.3, 5.4) is one of the less sheltered beaches of this type. Other beaches of this type include McGregor's Bay (05), Matapouri Bay (profile 12, Fig. 5.7, Plate 5.6), Helena Bay (15), Oakura (16), and Bland Bay (profile 17, Plate 5.5).

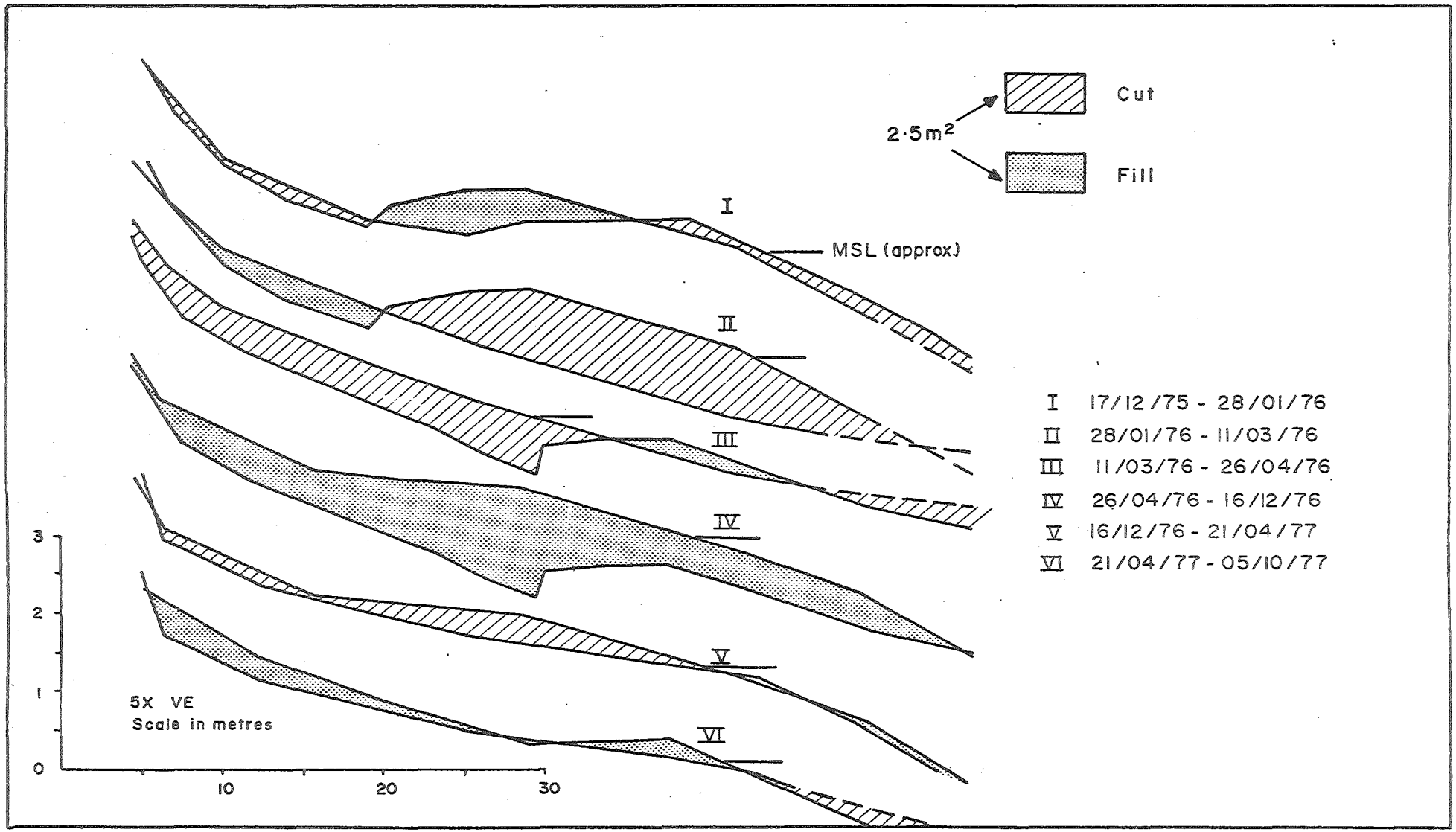

Fig. 5.6 - Time sequence of beach profile changes for the six survey periods at Taiharuru Bay (profile 06).

Plate 5.3 - Taiharuru Beach, a partly sheltered pocket beach in December, 1975. Note predominantly sandy sediments with a minor proportion of gravel, presence of berm crest and wide backshore, and state of dune face in front of houses.

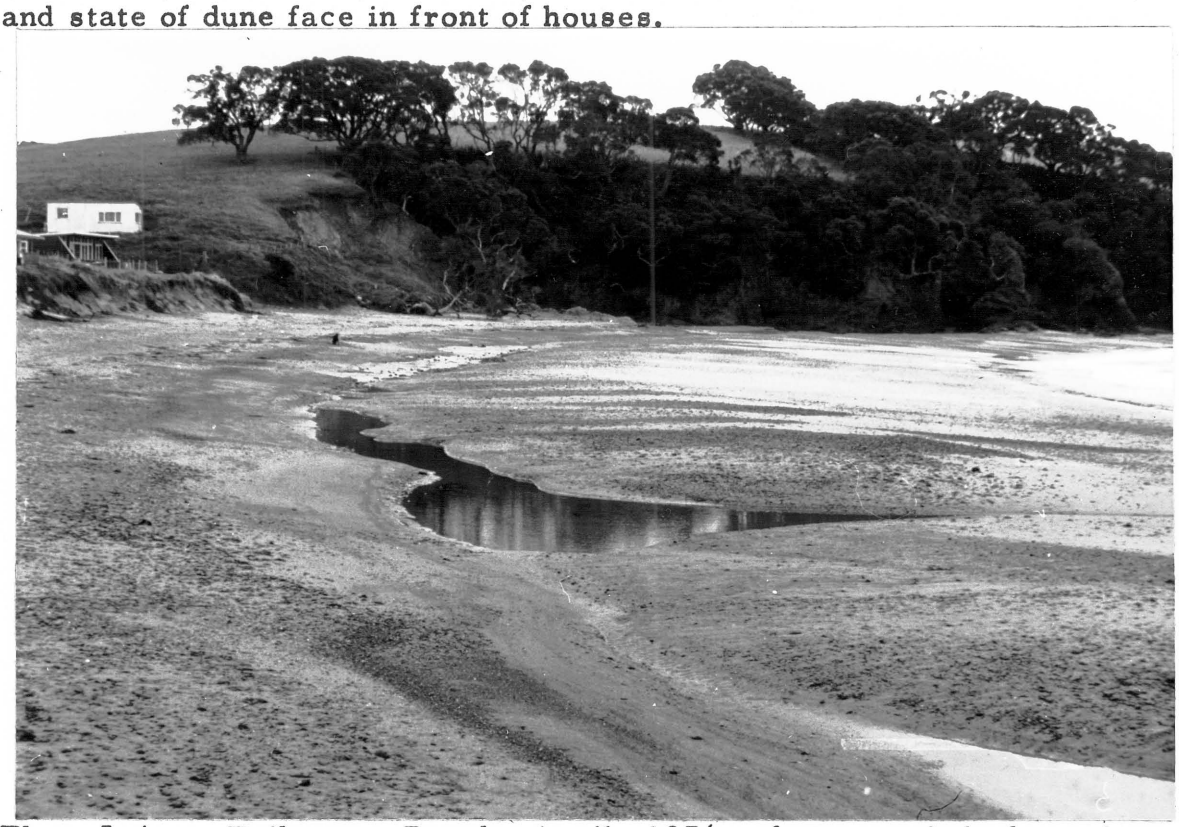

Plate 5.4 - Taiharuru Beach, April, 1976, after a period of erosion. Note larger proportion of gravel, exposed runnel with ridge migrating up the foreshore, and cliffed dunes. Basal clay and organic beds are also exposed on the backshore.

A morphologic feature of some of these beaches, which is not present on the exposed sandy beaches, is a backshore gravel cusp sequence constructed by storm waves (Plate 5. 5). Nearshore and foreshore mixed sand and gravel ridges are also conspicuous on some beaches. They form after major storms and advance rapidly up the beach (Plate 5. 4, Fig. 5. 6 period III). These beaches also exhibited sandy berms during constructional phases (Plate 5. 3, Fig. 5. 6 period IV). The succession of beach changes in Fig. 5. 6 shows the removal of a wide ridge-berm feature in period II. This feature was further cut in period III which also shows a new ridge which has formed rapidly in only a few days after the Easter storm of April, 1976. Period IV represents a large fill phase, while periods V and VI represent more stable periods with minor cut and fill features.

The sequence of changes at Matapouri Bay (Fig. 5. 7) illustrates profile variations occurring on a partly sheltered, sandy beach (Plate 5. 6). Beach change in survey periods I and II took the form of backshore and upper foreshore cut with accompanying lower foreshore fill. In period III the backshore was strongly cut and lowered, and the dune face cliffed. Thus, periods I-III showed a flattening of the backshore and upper foreshore profile. In contrast, beach recovery occurred in period IV, with backshore and upper foreshore fill, and lower foreshore cut, resulting in an overall steeper profile. Finally, in periods V and VI, fill occurred over the complete profile width. This fill took the form of berm crest progradation and lower foreshore fill. It is also apparent that this material must have been derived from either further offshore or alongshore within the confines of the bay.

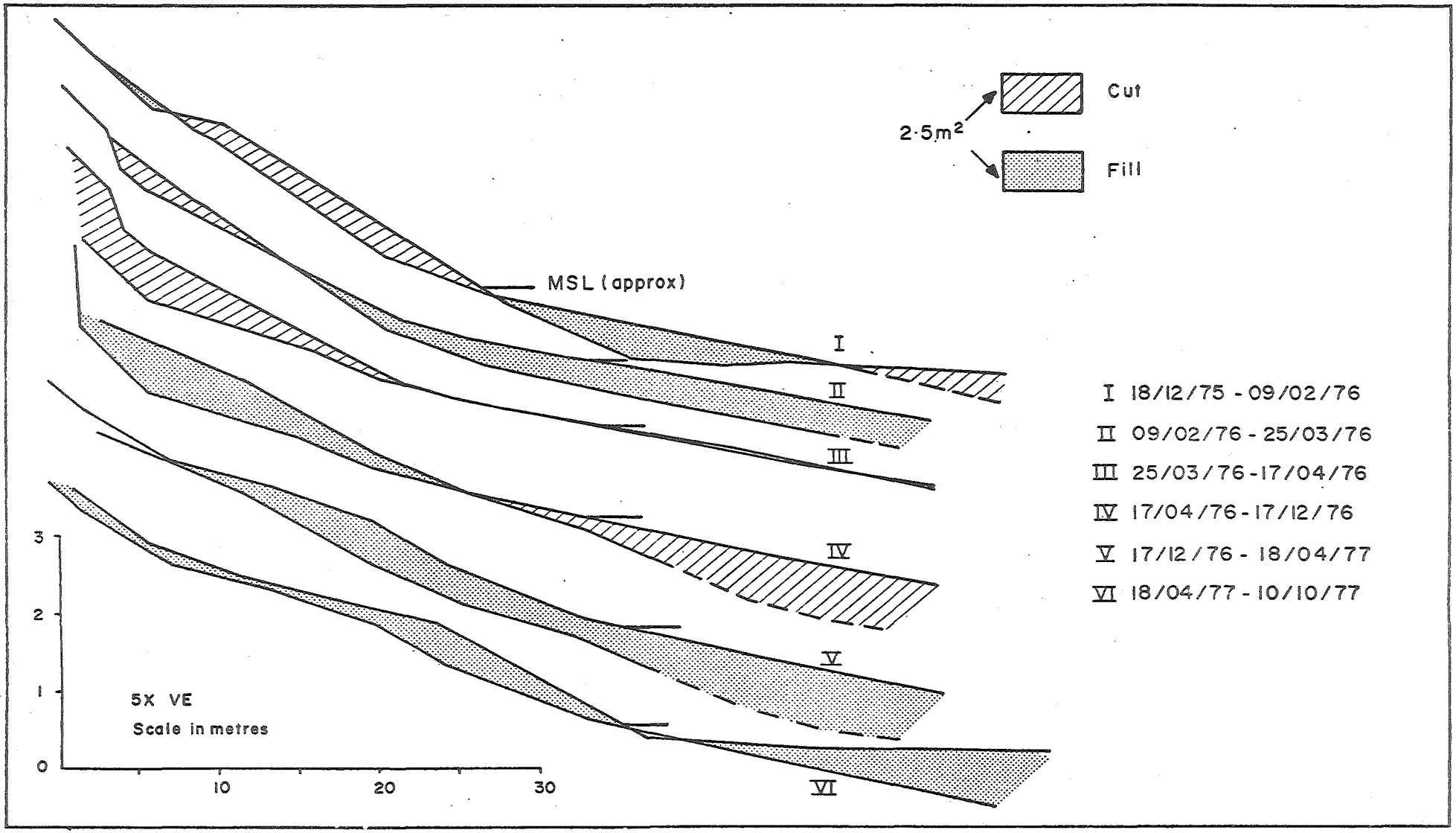

Fig. 5.7 - Time sequence of beach profile changes for the six survey periods at Matapouri Bay (profile 12).

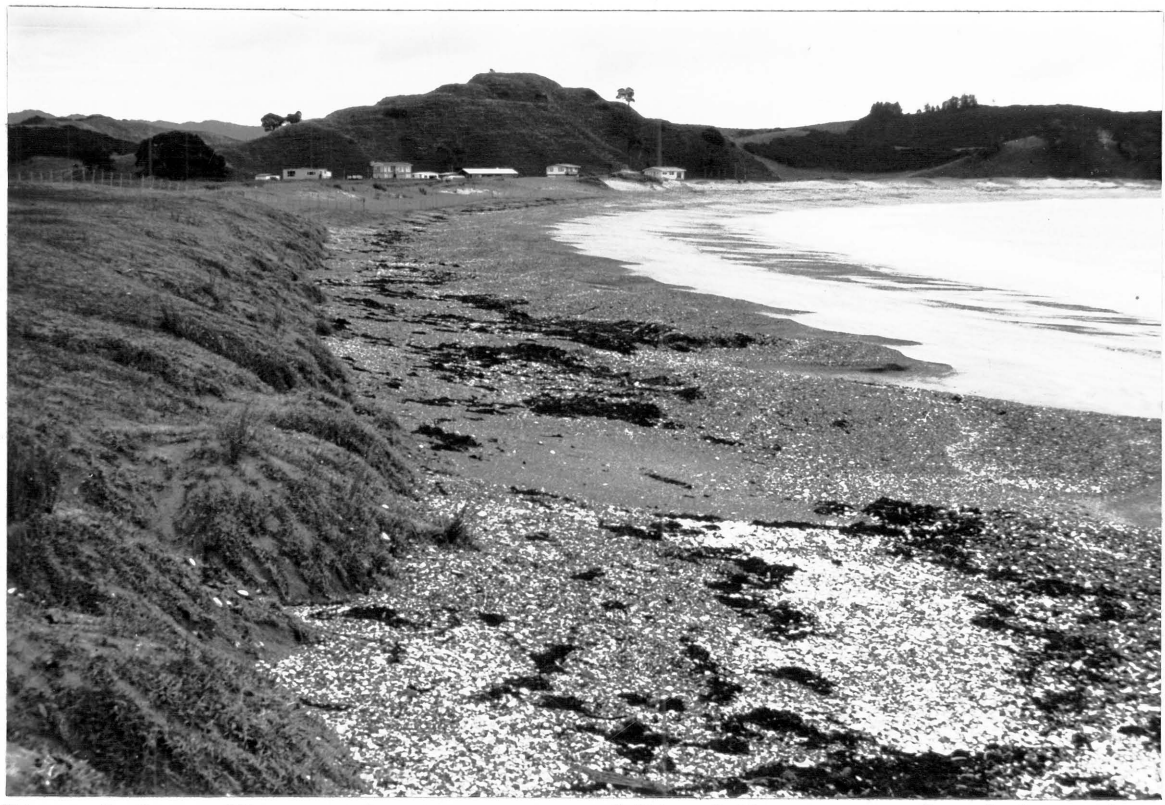

Plate 5. 5 - The southwest corner of Bland Bay, a partly sheltered beach near Home Point. Note storm generated mixed shell and gravel cusps on the backshore and sandy foreshore sediments.

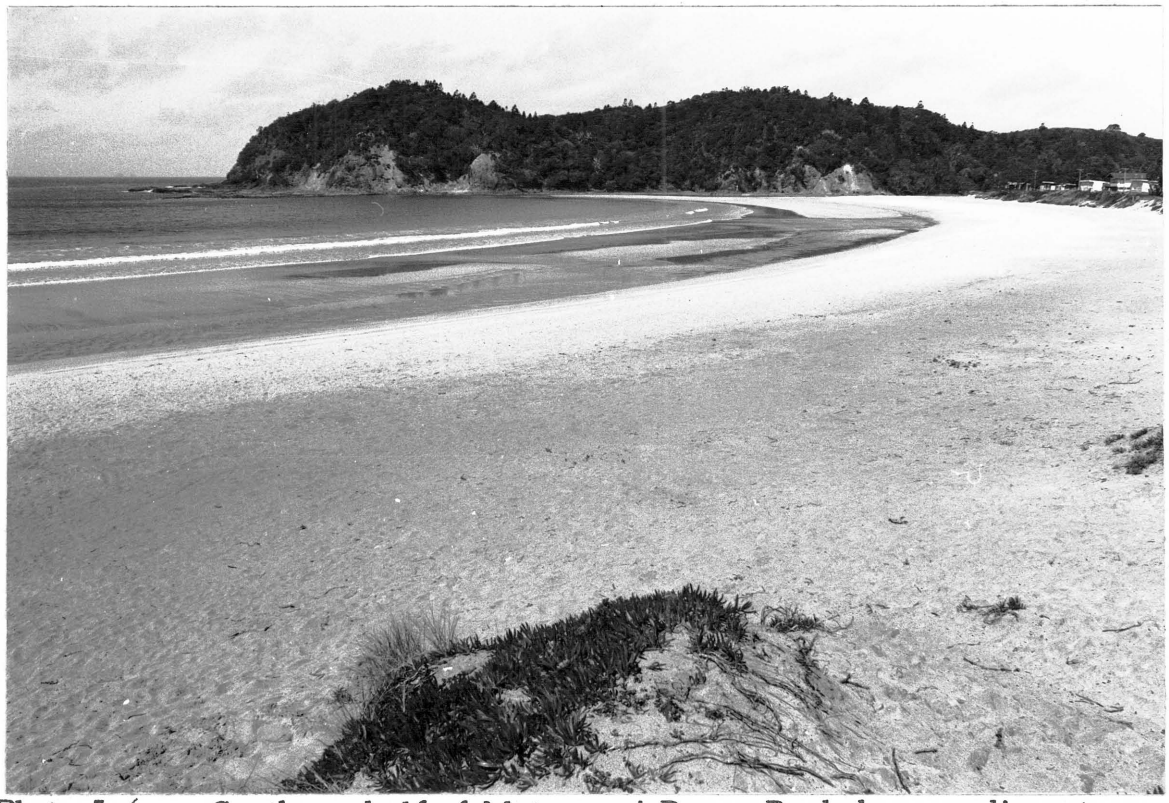

Plate 5. 6 - Southern half of Matapouri Bay. Backshore sediments are mixed shell and greywacke sands, while foreshore sediments are shell sands. Also note the low tide terrace with low relief ridge and runnel morphology.

Cumulative changes at Matapouri Bay (profile 12, Fig. 5.8b) show little change in cross-sectional area until the fill in periods V and VI. Thus, although earlier periods (I-IV) were dynamic in terms of backshore and foreshore changes, the net effect of these changes amounted only to a redistribution of sediment within the profile cross-section. In this regard, the mid-foreshore portion of the profile changed little. This area would appear to behave as a "hinge", about which the profile oscillates vertically due to shore normal sediment transfer between the upper and lower portions of the beach.

Maximum Amounts of Cut and Fill

It was mentioned above that the greatest amount of profile change occurred in exposed sandy beaches. This is shown by the movement of berm crest positions. For Ocean Beach this has amounted to greater than 40 m, with the berm being partly destroyed as shown by the cliffed dune face in period III (Fig. 5.5). By comparison, the berm crest on Matapouri Beach may move horizontally about 10-15 m and can also be destroyed during maximum erosional periods (period III, Fig. 5.7). Thus, although the magnitude of beach change may vary with exposure to wave energy, most beaches in the study area can experience dune cliffing during major erosional events. In addition, the magnitude of these surveyed shorter term horizontal changes is as great or greater than those determined from air photos for 30-40 year periods (Section 5.6). Therefore, seasonal and annual beach changes can be as great as historical changes, but should not be used to extrapolate historical changes.

As regards the amount of cross-sectional profile change, for exposed sandy beaches this can reach a maximum cut of about 90 m^2.

For sheltered beaches a maximum of about half this amount, or 50 m^2, can be expected (Fig. 5.8a; 5.8b).

5.7.4 Periods of Beach Profile Change

From the seven survey times, six intervals of beach profile change have been defined, as referred to above and shown in Table 5.4 and Fig. 5.8a; 5.8b.. Beach profile changes for three of the beaches as shown in Fig. 5.5, 5.6, and 5.7, and for all of the other beaches have been measured and presented as cumulative changes through time in Fig. 5.8a and 5.8b. The beach changes for each period were determined by measuring the cut and/or fill between the upper limit of effective wave action and the low tide level. These changes were measured as cross-sectional areas in m^2 to the nearest 0.1 m^2. The areas were measured with an electronic digitizer which gave a repeatability of about 5%. Although this is an objective means of determining net cut or fill for the whole profile, it does not show the distribution of cut and fill within the profile.

As can be seen from Fig. 5.8a and 5.8b, the nature of beach profile change varied considerably between beaches. However, when all of the beaches are considered together there is an apparent trend over the study period. The general trend was for an initial period of stability (period I) which was followed by two marked erosional periods (II and III), with many of the beaches reaching their maximum cut at the end of period III. This was followed by a stable/depositional phase in period IV during the winter of 1976. In turn this was followed by two marked depositional periods (V, VI) during summer and winter 1977. A summary of these changes is presented in Table 5.4. At the end

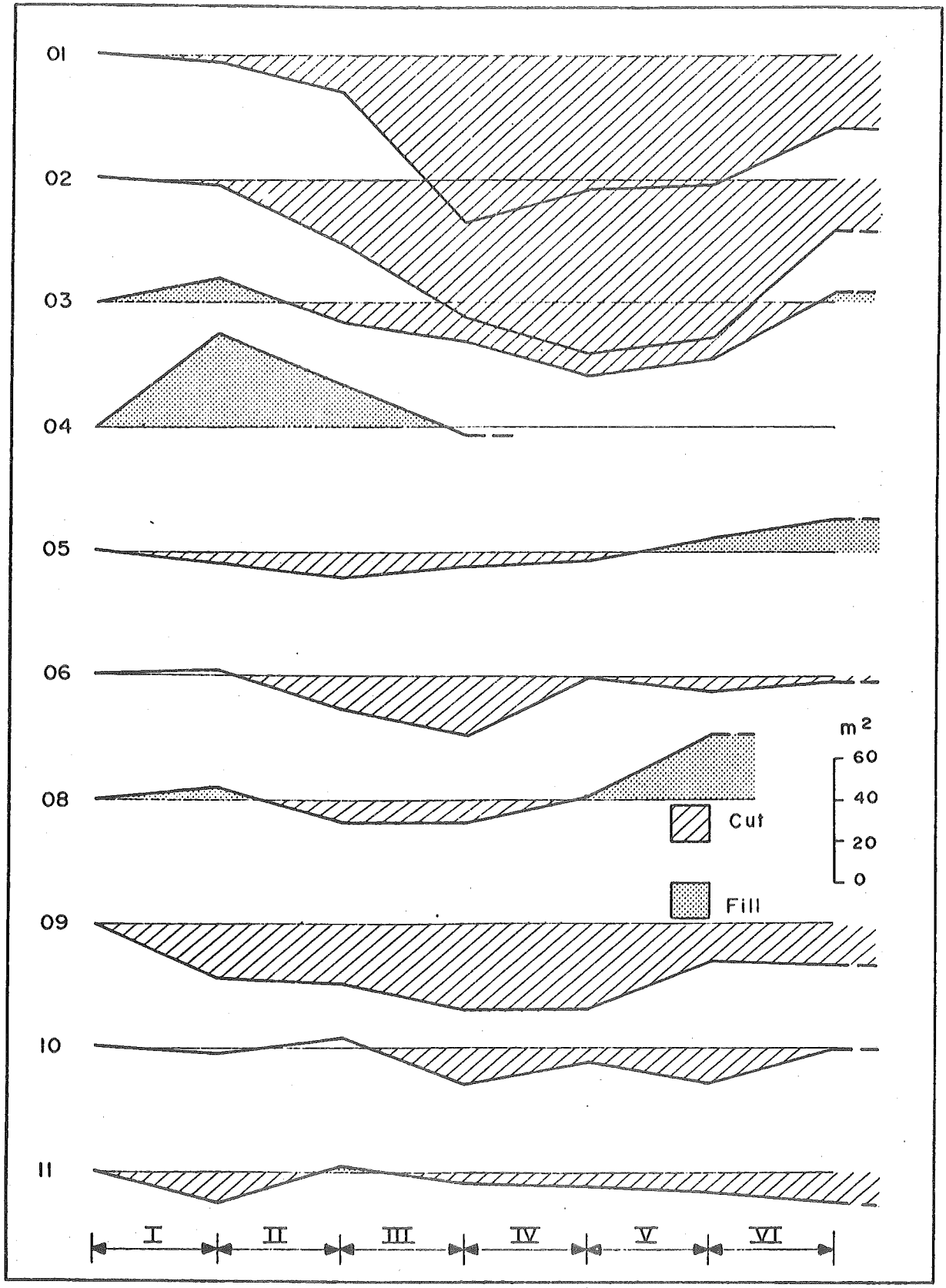

Fig. 5.8a - Cumulative change in beach profile cross-sectional area for six survey periods (I-VI). Horizontal reference lines represent the state of the beach at the beginning of the survey. See Fig. 5.1 for beach profile locations. The six survey periods are as defined in Table 5.4.

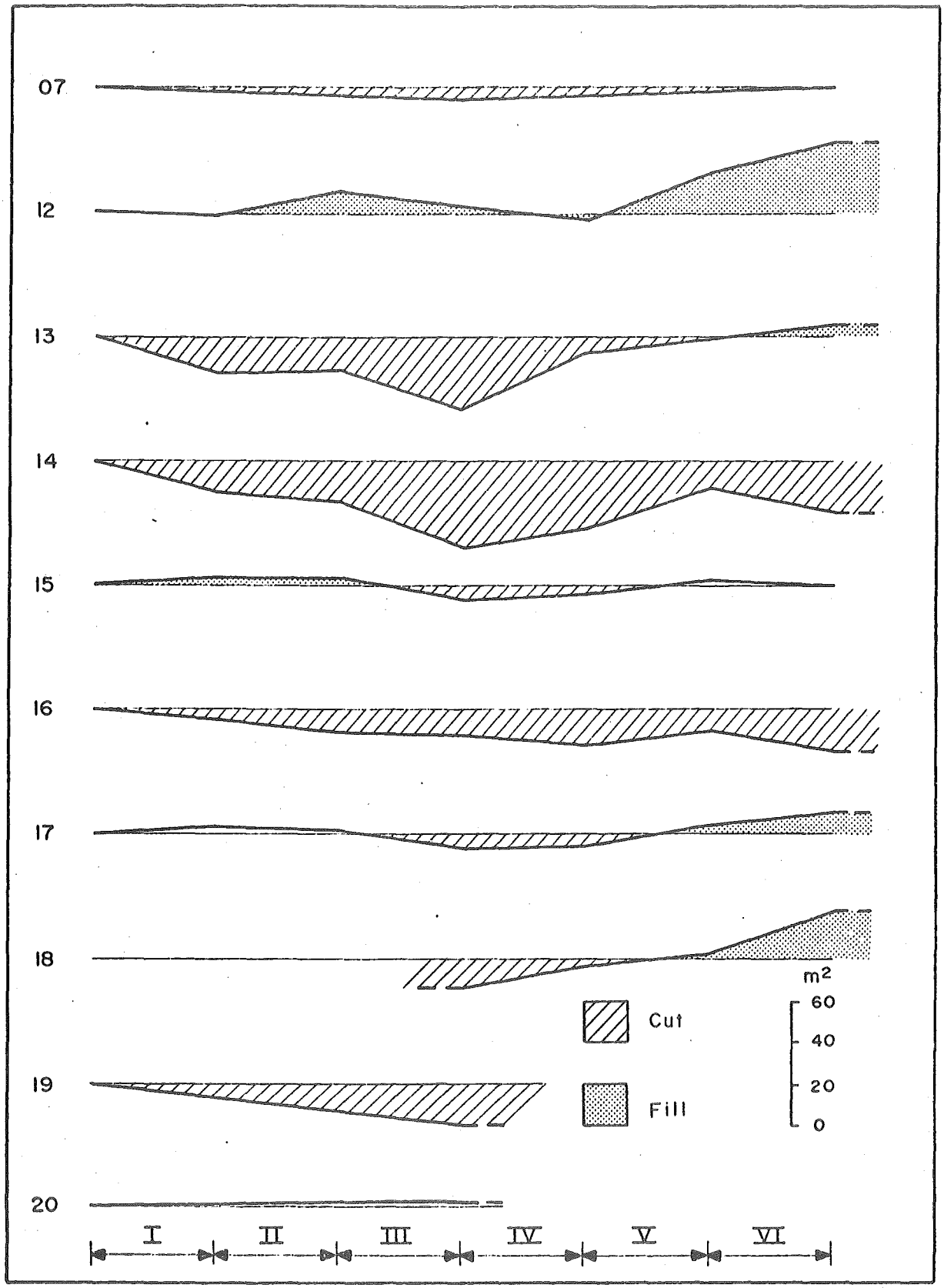

Fig. 5.8b - Cumulative change in beach profile cross-sectional area for six survey periods (I-VI). Horizontal reference lines represent the state of the beach at the beginning of the survey. See Fig. 5.1 for beach profile locations. The six survey periods are as defined in Table 5.4.

Table 5.4 - Summary of beach profile dynamics showing the frequency of types of changes (either cut, stable, or fill) and the dominant change for each survey period. Stable is defined as a change of $\leq 5\ m^2$. Source data from Fig. 5.8a; b.

Survey Period	Frequency of Profile Change Type			Dominant Change Type
	Cut	Stable	Fill	
I Summer, 1976 (15 Dec, 1975- 14 Feb, 1976)	4/19	12/19	3/19	Stable
II Late Summer, 1976 (15 Feb, 1976- 25 Mar, 1976)	10/19	6/19	3/19	Cut
III Autumn, 1976 (26 Mar, 1976- 27 Apr, 1976)	14/19	4/19	1/19	Strongly Cut
IV Winter, Spring, 1976 (28 Apr, 1976- 21 Dec, 1976)	3/17	7/17	7/17	Stable/Fill
V Summer, 1977 (22 Dec, 1976- 21 Apr, 1977)	3/17	3/17	11/17	Fill
VI Winter, Spring, 1977 (22 Apr, 1977- 10 Oct, 1977)	3/17	4/17	10/17	Fill
Total Period (15 Dec, 1975- 10 Oct, 1977)	6/16	6/16	4/16	Stable/Cut

of the survey period it was found that of the sixteen beaches which had been surveyed for the whole period, six had less sediment than at the start, six had essentially the same amount, and there were four with more sediment (Fig. 5.8a; 5.8b; Table 5.4). Thus, the erosional periods of II and III which were created in two months, took about 18 months to re-establish the beach cross-sections which existed prior to the erosion.

In addition, the periods of erosion and deposition are correlated with the occurrence of onshore wind and wave conditions as shown in Fig. 5.9. In this respect, Schofield (1975) has also shown that beach changes in the Hauraki Gulf are related in part to the occurrence of onshore winds. In the absence of detailed wave observations, this record of wind observations has been used. The wind observations are made daily by staff of the Leigh Marine Laboratory and include an estimate of the Beaufort Force, which is based on sea state conditions (Appendix 1). This data has been summarised for the six beach survey periods in the form of wind roses, using Beaufort Forces ≥ 4 for onshore conditions (Fig. 5.9). The percentage of days during each period with Beaufort values ≥ 4 has also been calculated.

It can be seen that profile periods II and III(Fig. 5.9, Table 5.4) had the highest percentage frequency of onshore winds. The coincidence of the Easter 1976 storm event with high spring tides was also a significant factor in determining beach erosion. In contrast, periods V and VI, which were depositional, had lower percentages of onshore wind and sea conditions.

It is also noteworthy in Table 5.4 that the first summer-autumn period (II and III) was erosional, but that the following summer (period V) was largely depositional. In addition, the first winter

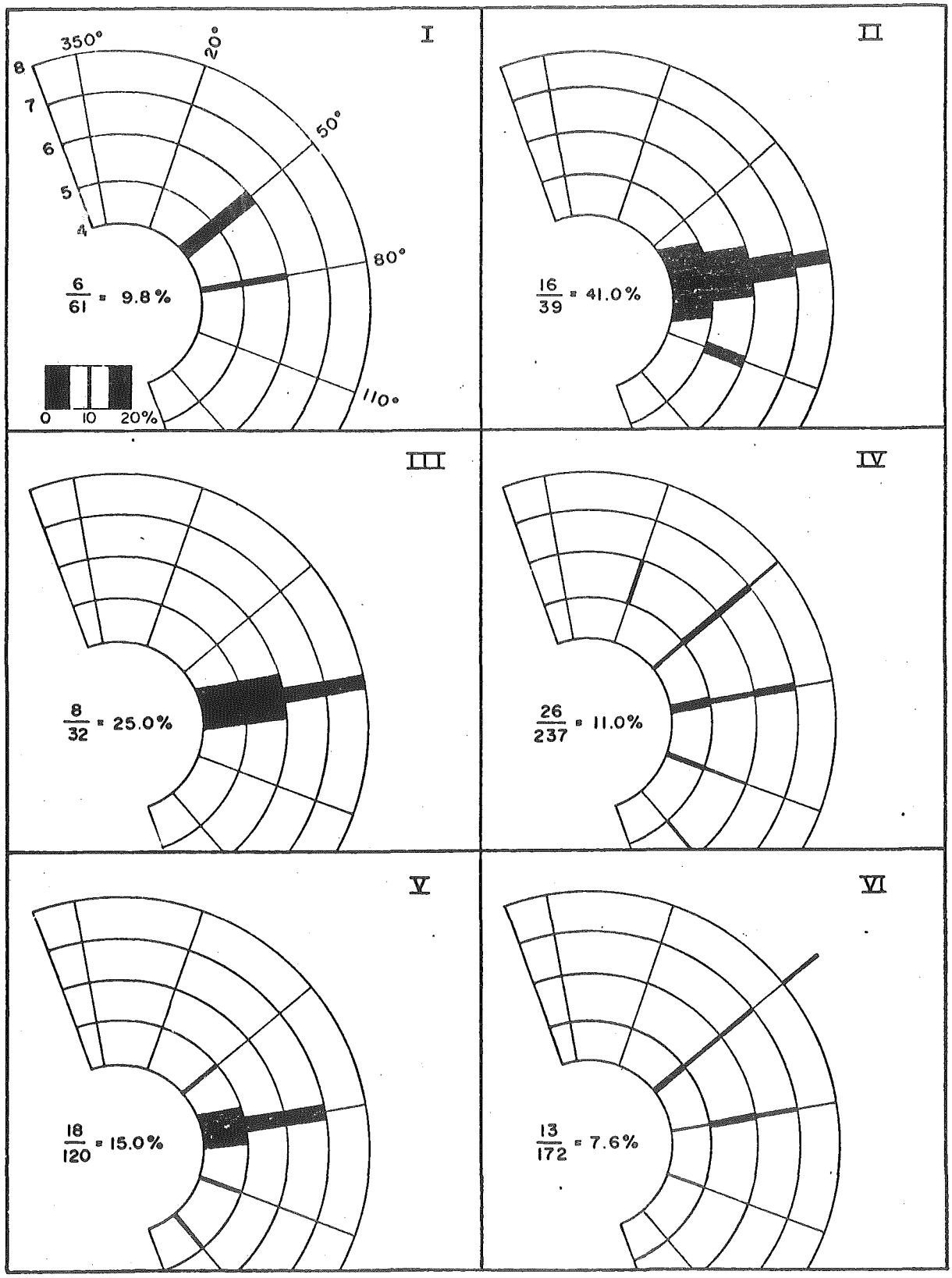

Fig. 5.9 - Percentage of onshore wind conditions of Beaufort force 4-8 in each of the beach survey periods. Based on daily observations at the Leigh Marine Laboratory. The six survey periods (I-VI) are as defined in Table 5.4.

(period VI) was depositional. This illustrates, to some degree, the variability (from one year to the next) in beach processes and responses which is likely to occur along this coast. This supports the temporal pattern of beach changes postulated in Chapter Four.

5.8 SUBMARINE PROFILES

5.8.1 Introduction

Submarine profiles were surveyed off almost all of the locations at which land based beach profiles had been established (Fig. 5.1). The only profiles omitted were 19 and 20, around Whangaroa Harbour. The submarine profiles were done to extend the land-based backshore and foreshore beach profiles into the submerged nearshore portion of the beach, and further out to the deeper shoreface region. At Pataua Beach (the only area with gravel deposits immediately offshore of the beach and shoreface) the submarine profiles also extend into inner shelf regions.

The surveying of submarine profiles was necessary in order to determine the nature of seabed morphology and the presence of rock reef areas and/or sediment cover in offshore regions. This information has been used to further identify the extent of any relationships that may exist between beach, shoreface, and inner shelf deposits. In this respect, it is probably only at profiles 09-11 off Pataua Beach that contemporary relationships may exist between beach and inner shelf sediments.

At the other profile locations a number of factors suggest that contemporary relationships are unlikely. These factors include large distances between some of the beaches and inner shelf deposits, the depth at which most of the inner shelf deposits occur (usually from 30-50 m), and the fact that inner shelf gravel sediments are not likely sources for sandy beach sediments. Furthermore, in many areas rocky reefs and headlands intervene between beach and inner shelf deposit areas.

5.8.2 Procedures of Sounding and Positioning

The profiles were sounded with a Furuno FG-200, Mark-3, Type A echo sounder which was fitted to a 5.5 m boat. The recording unit has an effective paper width of 90 mm which corresponds to a depth of 22 m full scale range. This gives a satisfactory depth resolution of less than 0.25 m. However, the amount of information which could be interpreted from the chart recording concerning the nature of the sea-bed and sediment cover was more limited by the high transducer frequency (200 kHz). As well, the recordings were also limited by their circular arc shape which gives distorted slope angles.

The positioning method used consisted of three marker bouys which were spaced out along a survey track running perpendicular to the alignment of the shore. The positions of the three bouys were fixed by taking repeated sextant angles to features on the shore which were recognisable from either 1:15,840 scale maps or large scale (1:10,000) vertical air photos. This method was free of any need for shore based personnel and allowed the complete profiling operation to be conducted from the boat.

Profiles were run beginning from off the seaward end of the line of three position fixing bouys and continued past the shoreward end until the combination of bottom, tide, and surf conditions prevented safe further approach to the shore. Profiles were attempted during periods of relatively low swell to calm conditions, with calm to light offshore winds aiding the running of the profile. Sounding was also conducted around high tides so that the boat could come closer to shore. The times of the start and finish of sounding runs were also noted so that if necessary depths could be corrected for state of the tide and reduced to local chart datum.

5.8.3 Results of the Survey

The echo sounding records which are shown in Figs 5.10a to 5.10d, were obtained during two periods. Profiles 01-11 were run in early February 1977, while profiles 12-18 and 21 were run in mid-October, 1977. The sounding records have not been corrected for state of the tide at the time of sounding so that depths are approximate. In addition, distances along the sounding record are shown as approximate, but are comparable to within $\pm$ 10% for most of the profiles. All profiles have a vertical exaggeration of about 33 times. The apparent wavy bottom on most of the profiles is produced by surface waves with wave heights of less than 0.5 m.

The profiles extend offshore from 500 to over 2,000 m from the shoreline and reach maximum depths of slightly greater than 20 m. Bottom slopes, between 2 and 22 m depths, vary between 1:30 (1.6^{o}) and 1:160 (0.4^{o}). As can be seen the profiles are quite varied between

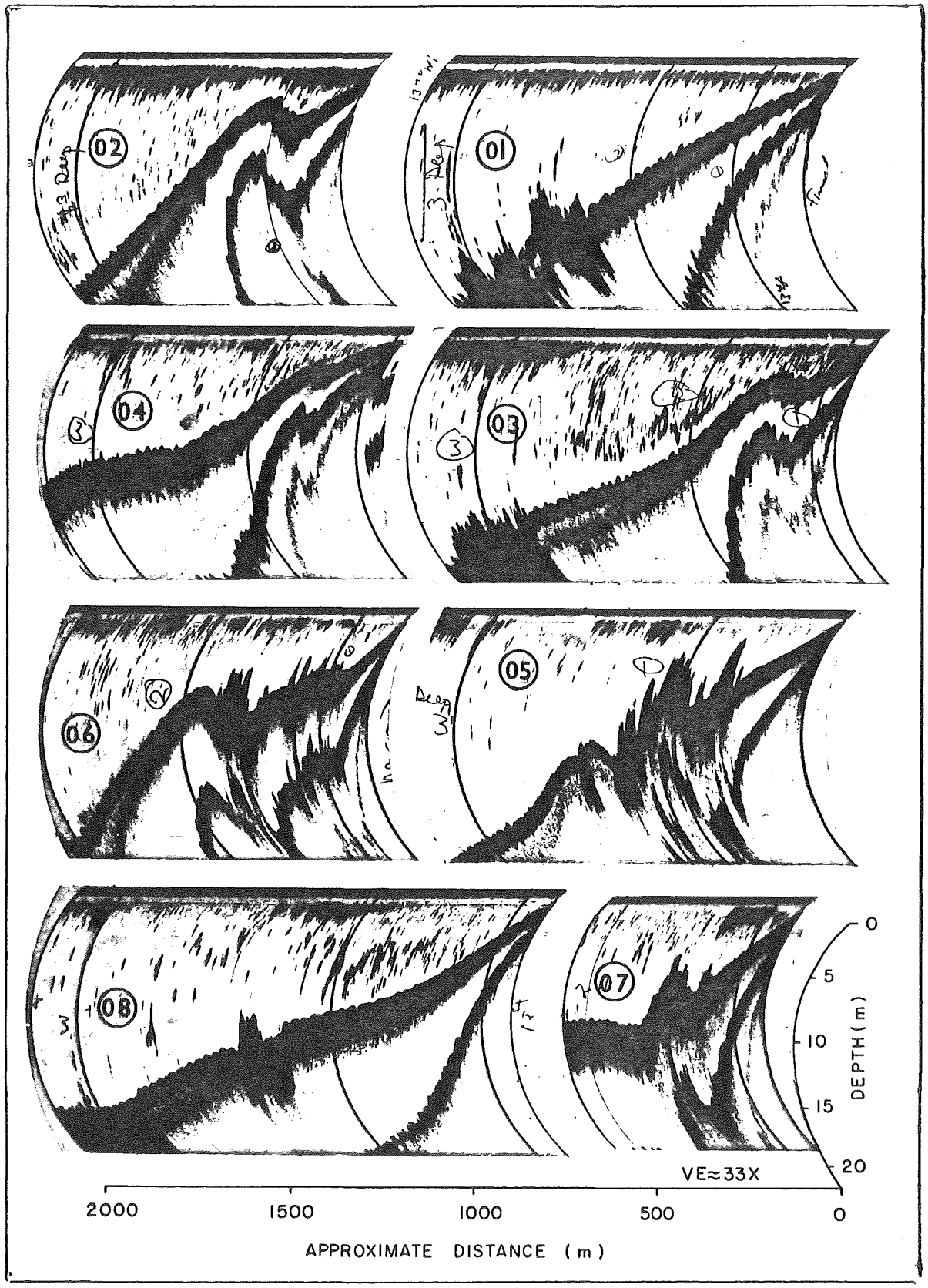

Fig. 5.10a - Submarine profiles. Ocean Beach (01-04), McGregors (05), Taiharuru (06), Fishers (07), Kaoiti Beach (08).

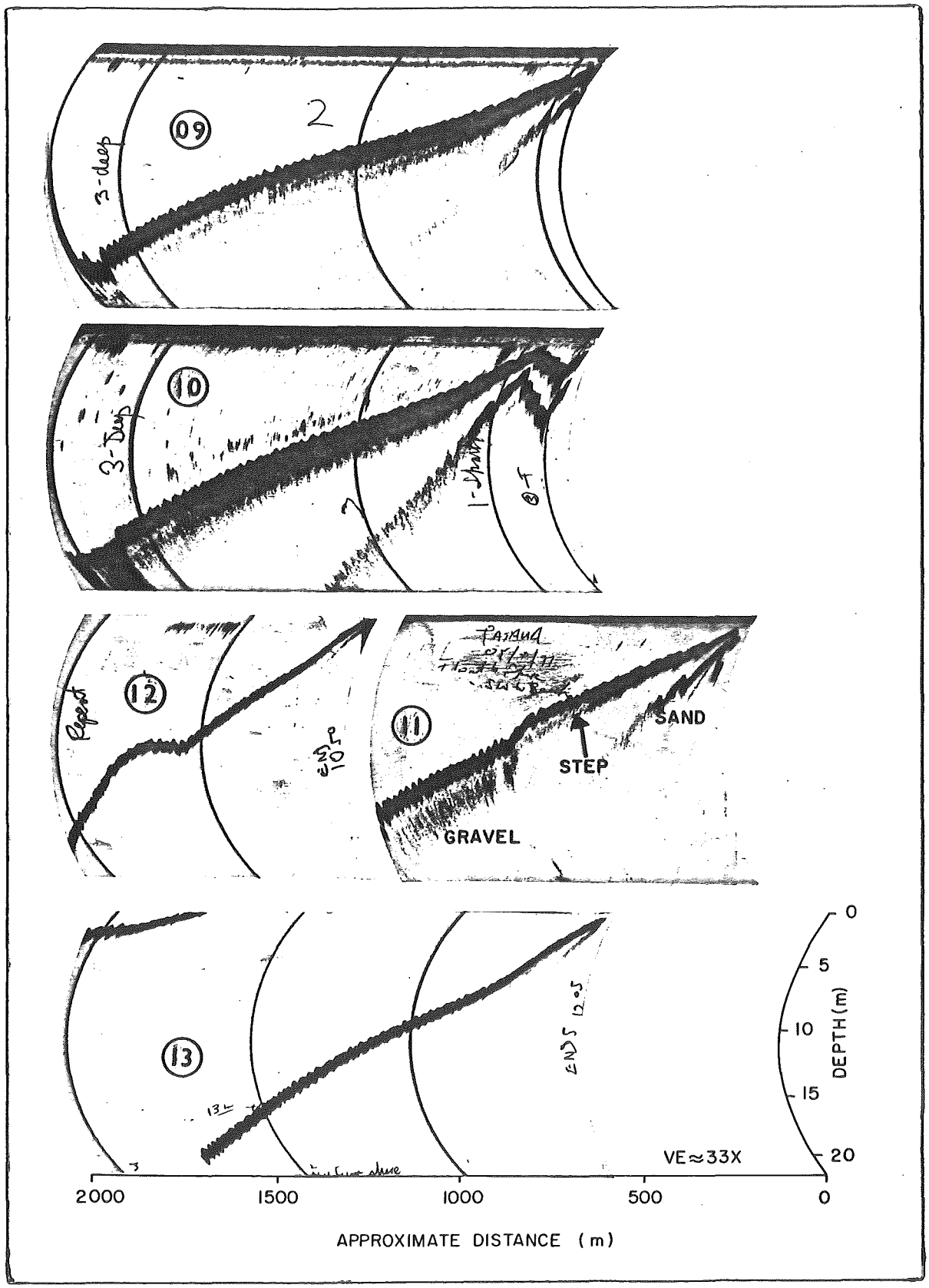

Fig. 5.10b - Submarine profiles. Pataua Beach (09-11), Matapouri (12), Woolleys Bay (13).

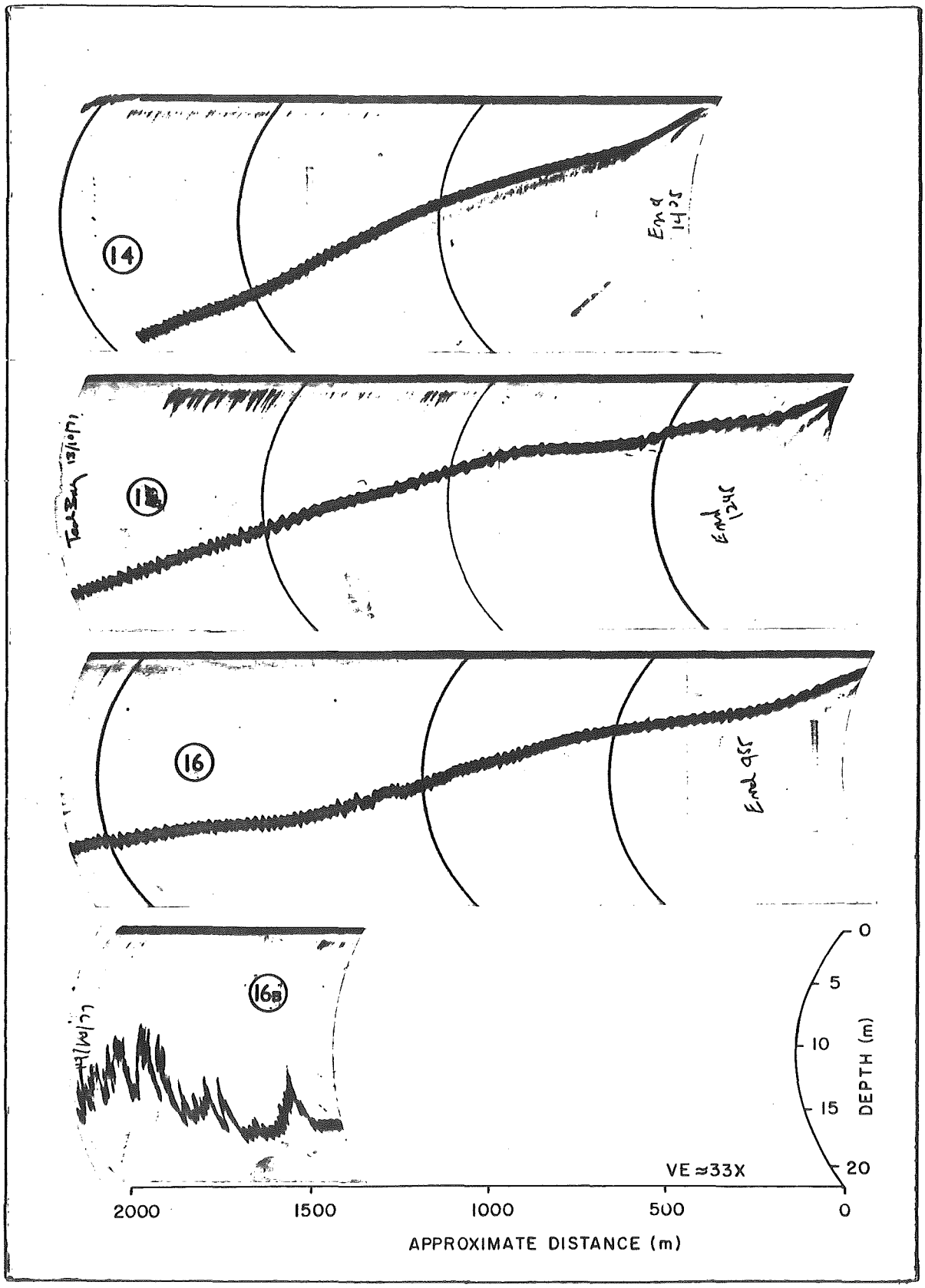

Fig. 5.10c - Submarine profiles. Mimiwhangata (14), Helena Bay (15), Oakura Bay (16, 16B).

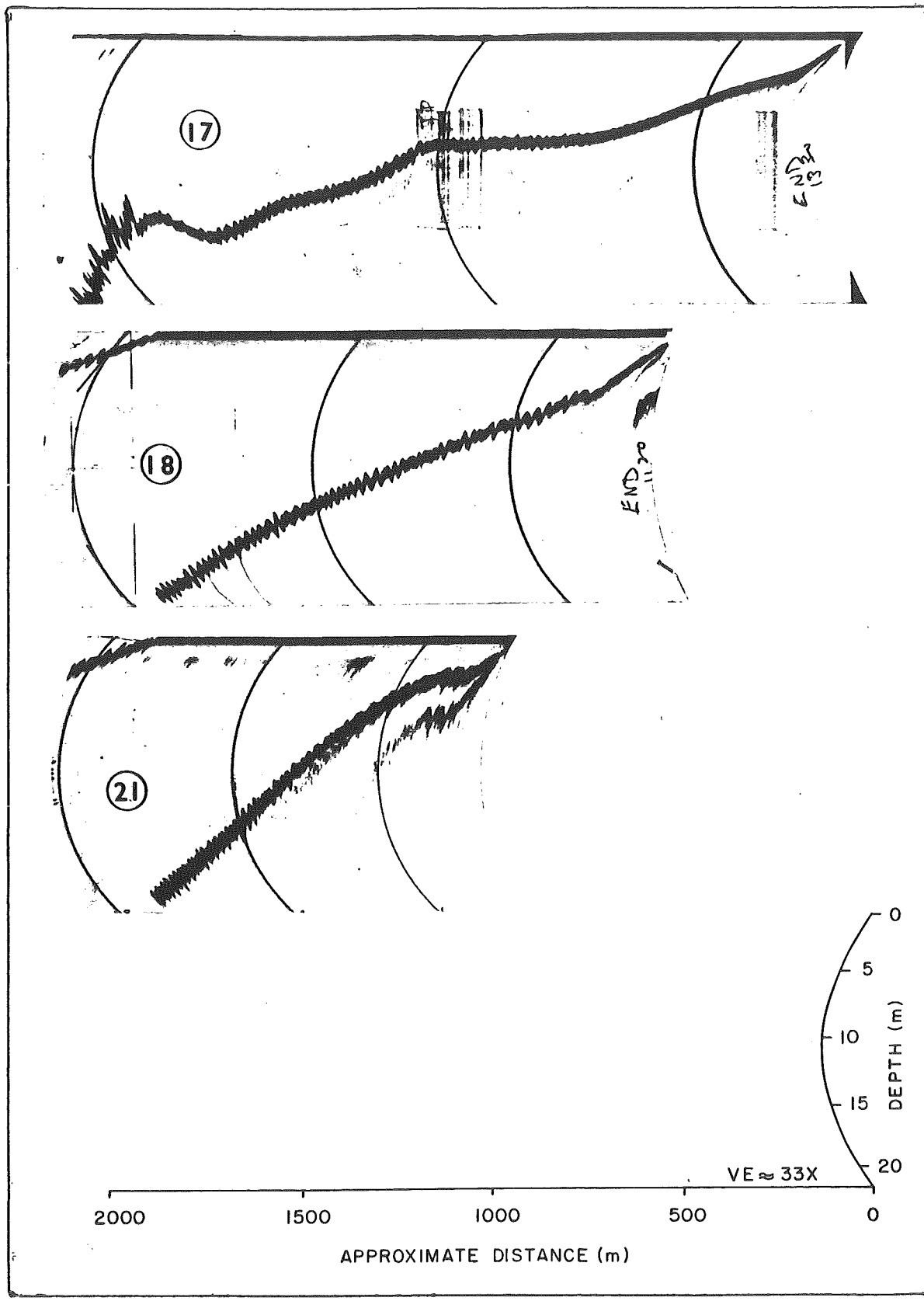

Fig. 5.10d - Submarine profiles. Bland Bay (17), Akau Bay (18), Wiwiki Beach (21).

sites. Four main types of features have been identified, with some profiles having more than one type of feature.

(i) Rocky reef features are present on 9 of 19 profiles. In most cases these reefs are probably not completely continuous along the coast, but their presence does indicate a partial discontinuity in the sediment cover between the beach and inner shelf areas. The reefs may thus form barriers to sediment transport and they may be acting as beach sediment dams at some sites (profiles 01 and 03).

(ii) A single submerged longshore bar is present on six of the profiles. The occurrence of this feature is confined to Ocean and Pataua Beaches (profiles 01, 02, 03, 04, 10, 11). Both of these beaches have substantial nearshore deposits of sand fully exposed to waves from the open ocean. Healy et al. (1977) also recorded prominent bars on Bay of Plenty beaches, and it has been noted by Zenkovich (1967) that longshore bars are common on beaches throughout the world which have a low tidal range, with sediment ranging from fine to medium sand, and with nearshore slopes varying between 1:200 and 1:50. However, longshore bars are not necessarily permanent features of nearshore morphology. The absence of bars on other profiles may simply be due to different wave conditions existing prior to their survey.

(iii) Smooth profiles, with or without longshore bars in the nearshore zone, are present on seven of the recordings. If these profiles represent the surface of a moderate thickness of beach and shoreface sediment, then they may be interpreted as "marine profiles of equilibrium" (Dietz and Fairbridge, 1968), which have developed in response to sediment supply, wave exposure, and the present sea level. This is expected to be the case for Pataua and Ocean beaches and other beaches where there are substantial beach and shoreface deposits.

(iv) Profiles with abrupt changes in slope angle not due to reefs, total six and are prominent in bay sites such as Matapouri Bay (12), Helena Bay (15), Oakura (16), and Bland Bay (17). These changes in slope may be due to the control of shallow underlying bedrock or other subaerially produced surfaces not in equilibrium with the present marine environment.

At profile 11, the northernmost of Pataua Beach, there is a prominent 1-2 m step in the submarine profile at a depth of approximately 10 m. This step is also present on profile 10 at a depth of 18 m. Reconnaisance diving on this feature revealed that it coincided with an abrupt boundary between inner shelf mixed sand and gravel sediments, and shoreface sands. The nature of the boundary is also illustrated in Plate 7.3 and its spatial extent is shown in Fig. 7.5. The occurrence of this lower shoreface step, and the associated sediment change indicates a boundary of sedimentary dynamics which is modern (rather than relict) and is probably maintained by wave induced, seabed sediment sorting processes. A possible sediment sorting mechanism is discussed in Chapter Eight.

The occurrence of reef-free, continuous sediment cover on profiles at other sites may be only apparent, due to the inability of the echo sounder to delimit bottom types or to penetrate beneath the surface. In this respect a dive along the shallow (<10 m) portion of profile 15 revealed only a patchy sediment cover of sand and silt lying on a flat, stiff clay surface which probably represented a residual, subaerially weathered bedrock surface. This type of stiff clay surface was also found off Pataua Beach at a few localities (Plate 7.4). This information, along with the sub-bottom profiler

records presented in Chapter Six, demonstrates the thin, patchy nature of the shoreface sediment cover along parts of this coast.

5.9 SUMMARY

The investigation of coastal deposits in the study area has provided information on two areas of interest: first, the extent of contemporary relationships between coastal and inner shelf deposits; and second, a baseline description of variations in coastal sediments, morphology, and naturally occurring beach dynamics.

With respect to the first area of interest, it is unlikely that contemporary relationships exist between beach and inner shelf deposits in the vicinity of the prospecting areas shown in Fig. 1.1, with the possible exception of the Pataua deposit. Contemporary beach-inner shelf relationships are unlikely because prospecting areas are located off cliffed, rocky coasts, with either no beach deposits on the adjacent coast or no connection to beach deposits further along the coast. In this respect, submarine profiles surveyed off beaches also show areas of rocky reef which intervene between beach and inner shelf areas, and where sediment is present in shoreface regions it is typically a thin and patchy cover over the underlying basement.

Off Pataua Beach investigations have revealed conflicting evidence about contemporary relationships. Coarse to very coarse sand fractions are appreciable in both beach and adjacent inner shelf sediments (Fig. 8.3), but as will be shown in Chapter Seven shoreface fine sands intervene between these two coarse sand facies, and there is a very abrupt change at the shoreface-inner shelf sediment interface.

Contemporary relationships between beach, shoreface, and inner shelf sediments are also a possibility at other locations in the study area which are not associated with prospecting areas. In this respect, the regionally high percentage (mean 39.7 wt%) of calcium carbonate material in sandy beach sediments and the occurrence of appreciable quantities of offshore species in beach drift shell indicate that shoreface and inner shelf regions may be significant sources of beach sediments. However, this relationship varies geographically within the study area depending upon the contribution of sediment from other sources.

The baseline investigation of beach sediments and morphodynamics has indicated the nature of spatial and temporal variations in these characteristics within the study area. The Bay of Islands Sand Facies has been studied in greater detail than was originally done by Schofield (1970). In particular the variable contribution of calcium carbonate and rock fragment material has been further defined. Calcium carbonate material in sandy beach sediments ranges from 2.3-82 wt% with a mean of 39.7 wt%. Differences between beaches are probably due to the combination of three factors: shell production, transport and deposition, and dilution by other sediment sources.

Beach and coastal morphological changes have been considered on a variety of time scales from short term to long term (Table 5.3). Historical changes determined from air photos have been less than 10 m with most areas showing stability (<5 m change) or a slight tendency to erosion (5-10 m). In contrast, two beaches showed progradation with high biogenic contributions being the possible cause. However, beaches in the study area can be regarded as stable when compared to other locations around the New Zealand coast.

Seasonal and annual beach changes were as great or greater than changes determined from air photos for periods of 30-40 years. In particular, exposed sandy beaches experienced horizontal movements in the berm crest of up to 40 m in a few months. Comparison of periods of beach profile change with the occurrence of onshore wind and wave conditions showed that erosion coincided with periods of higher frequencies of onshore winds. In addition, the quasi-seasonal and annual pattern of beach changes postulated in Chapter Four was supported by the two year study.

CHAPTER SIX

INNER SHELF DEPOSITS

6.1 INTRODUCTION

This chapter describes the inner shelf sand and gravel deposits contained within the prospecting areas shown in Fig. 1.1, concentrating study on the aspects of sediment characteristics (Section 6.2) and geomorphic characteristics (Section 6.3). An attempt is also made to interpret the origin of the deposits and the role played by contemporary inner shelf processes in determining deposit characteristics.

Almost all of the data contained in the section on sediment characteristics has been taken from preliminary studies which were made for Landsea Minerals Ltd. prior to the present investigation (Bioresearches, 1974; Ritchie and Saul, 1974; 1975). It is necessary to use data collected by others because seabed sediment samples were collected by the author only at the Pataua deposit. The Pataua area has been studied in greater detail than the other areas in this investigation, and its sediment characteristics have been included with other studies specific to Pataua in Chapter Seven. In the following, both between and within deposit sediment variations are discussed for all of the prospecting areas. The role of carbonate material is emphasised particularly because of the significance of contributions from contemporary inner shelf molluscan communities.

The data contained in the second part of this chapter on the geomorphology of the deposits was collected by the author from an extensive echo sounder and seismic profiler survey. Deposit characteristics revealed by this survey included the spatial extent and depth of the deposits, and the nature of the underlying bedrock surface. This information, along with inferences from the sediment data, has been used to interpret the probable origin of the deposits.

Seabed Sediment Maps

Maps of seabed sediment types and percentage areas of cover are presented in Table 6.1 and Fig. 6.1 in the back map pocket. The data used to prepare these maps has been taken from original surveys in the reports of Ritchie and Saul (1974; 1975). Data collected in their surveys included dredged sediment samples, diver observations at selected seabed sites, and echo sounder profiles. The seabed type boundaries are considered to be only approximate because of the limited nature of the survey. Moreover, in some of the areas which have been designated as "Gravel" the gravel occurs as isolated patches in reef areas, or as areas of gravel with protruding reef. Note also that the "Gravel" designation is usually a mixture of gravel and sand, whereas "Sand" refers to pure sand.

It should also be emphasised that previous studies and the present one have examined only selected portions of the inner shelf along the coast. Thus, as referred to in Chapter Four, mixed sand and gravel deposits may also be present at other locations not shown in Fig. 6.1. In addition, gravel deposits are also likely to be buried under the extensive blanket of sand which is present in inner shelf areas (Fig. 3.2). Other possible areas of gravel have not been investigated, so that the following discussion applies solely to the prospecting areas.

6.2 SEDIMENT CHARACTERISTICS

6.2.1 Introduction

The preliminary sediment studies referred to above were carried out primarily to assess the biological value of the deposits and the potential biological impact of prospecting and mining them. Data on sediment contained in the studies included general comments on gravel lithology, particle shape, and surface bedforms. In addition, more detailed data was included on sediment particle size analyses and visual estimates of shell content. Sediment samples were normally collected from the seabed surface by divers, or by using a bucket dredge hauled from a boat. In addition, three shallow depth (1.0-1.5 m) sub-bottom core samples were taken. Particle size analyses were made using three different sets of coarse mesh sieves, so that results from the sieve analyses are only comparable on the following size class basis:

$\geq$ 5 mm	gravel, $\geq$ small pebbles
1-5 mm	very coarse sand and granules
$<$1 mm	$<$ coarse sand

The fraction $\geq$5 mm includes sediment retained on sieves up to a 40 mm mesh, but usually only the 10 and 20 mm sieves contained sediment. The fraction $<$1 mm also contained any silt and clay which was present, and which was usually less than 1% of the total sample. In addition, shell material was included in the sieve analyses of the total sample.

6.2.2 Results of the Preliminary Sediment Studies

The lithology of the inner shelf gravel was found to be greywacke which is not unexpected considering the ubiquitous exposure of greywacke bedrock in adjacent coastal and hinterland areas (Fig. 3.1). Shape characteristics of gravel size sediment were described as angular to well-rounded, with a much greater frequency of rounded than angular particles. The fact that most of the gravel is rounded does not clearly distinguish its origin. Although no studies have been done on possible in situ rounding of inner shelf gravel, it is likely that the predominantly rounded shapes were produced in a previous environment. Likely possibilities are either fluvial, beach, or shallow (<5 m) marine environments. In this respect, it has been found from laboratory studies of gravel rounding under simulated surf conditions that the attainment of a rounded shape requires only the equivalent of tens of years (Kuenen, 1964). Therefore, it is concluded that it would take a relatively short period of time for greywacke gravel eroded from coastal exposures to become rounded in a beach or shallow marine environment.

Sediment surface bedforms, which were present as large areas of symmetrical "wave-ridged" surfaces in mixed sand and gravel sediments (Plate 7.1), were found down to depths of 50 m. At this depth wave-formed bedforms were well developed, with estimates of ridge heights of 0.3 m and wavelengths of 1.5 m. This gives some indication of the depth and degree to which the complete extent of the inner shelf deposits are affected by wave-induced bottom currents. This feature of the deposits has been investigated in detail for the Pataua Area (see Chapter Eight).

Sediment Particle Size-Sorting Characteristics

Size analyses for 64 sediment samples from five of the six prospecting areas are presented in Fig. 6.2, in which relative proportions of the three previously defined size classes have been plotted. When considered with respect to conventional Folk terms (Folk, 1974, p. 28) the 64 samples are classified as follows: sand (7), slightly gravelly sand (3), gravelly sand (8), sandy gravel (17), and gravel (29).

Fig. 6.2 shows a relatively uniform spatial distribution of samples within the diagram, i.e. the samples are not markedly clustered on the basis of size and sorting. Minor exceptions to this trend are the seven samples clustered in the sand corner of the diagram. These are samples from the Pataua and Awarua Rock prospecting areas which are areas with significantly higher percentages of sand than the others (Table 6.1, Fig. 6.1). Higher sand quantities in these two most southern areas probably reflects the influence of the northern extremity of the inner shelf Hauraki (A) sand facies referred to in Chapter Three. In contrast, most of the samples along the $\geq$5 mm to 1-5 mm side of the triangular diagram (Fig. 6.2), which are from the Stephenson Island deposit, have negligible amounts of sandy sediments $<$1 mm. In addition, there is a lack of samples along the $\geq$5 mm to $<$1 mm side. This is a common feature of triangular diagrams (Folk et al., 1970, p. 953), because any samples along this side would be uncharacteristically strongly bi-modal and poorly to extremely poorly sorted.

As well as an unclustered distribution of mixed sand and gravel samples on the basis of size characteristics, there is also about as much variation within prospecting areas as there is between

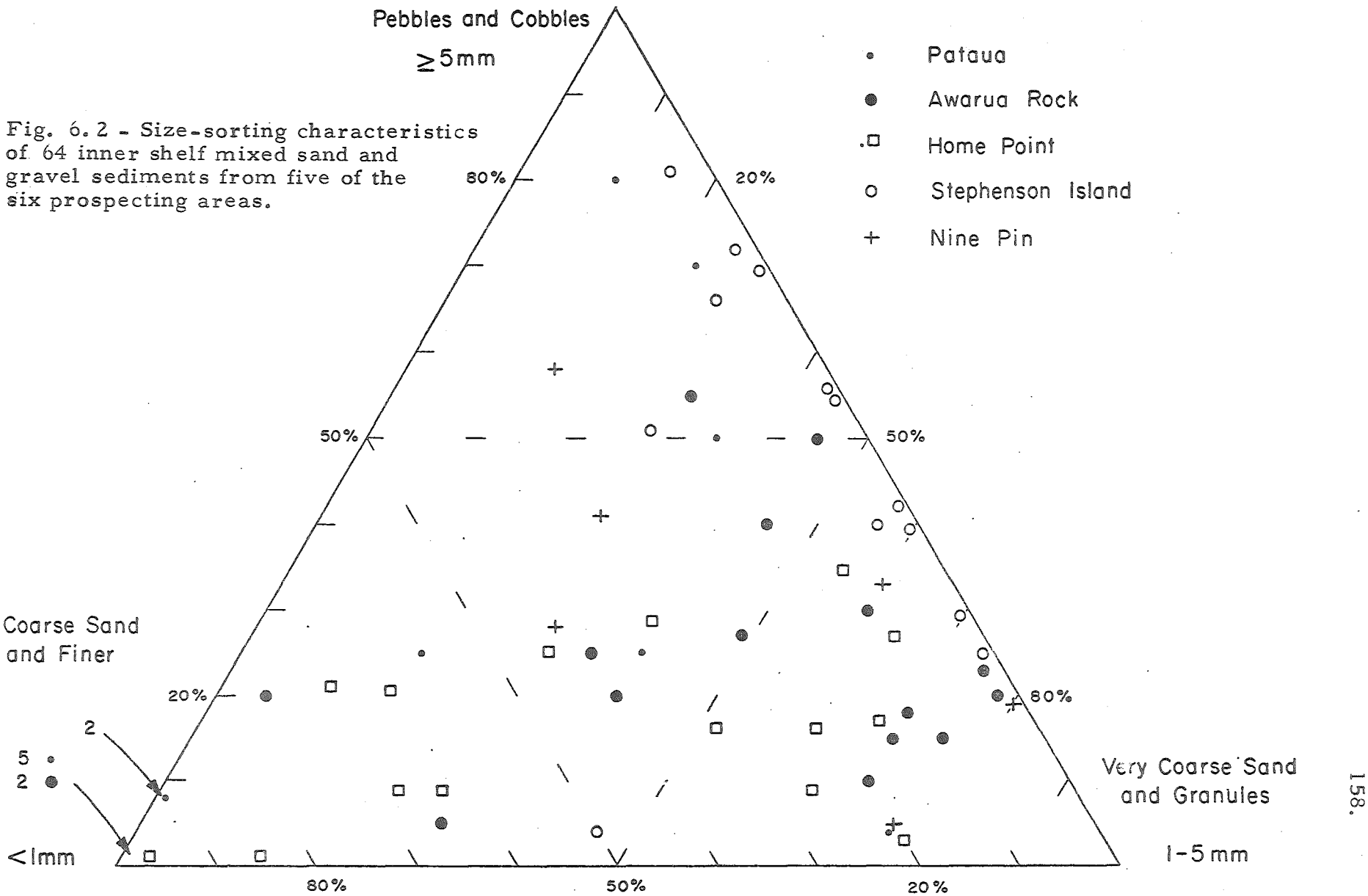

Fig. 6.2 - Size-sorting characteristics of 64 inner shelf mixed sand and gravel sediments from five of the six prospecting areas.

areas, i.e. the samples are not strongly clustered on the basis of geographic location. Two minor exceptions to this are the previously mentioned Stephenson Island samples which have little sand, and the Home Point samples which uniformly have less than 40% of ≥ 5 mm material.

The fact that the triangular diagram shows neither much size-sorting clustering nor geographic clustering suggests that the deposits have similar, varied size-sorting characteristics and therefore may also have a similar origin. In particular, three possible hypotheses may be proposed for the origin of the characteristics of the sediment samples, as follows:

(i) Hypothesis One: The original source area characteristics and environment of deposition of the sediments are the same, i.e. they are either all originally fluvial, beach, or shallow marine deposits, and are therefore now relict.

(ii) Hypothesis Two: The original source areas and environments of deposition are not the same, but because of the possibility of poor definition of sedimentary environments within the study area the environmental factor is not discernable. Thus, the deposits may again be relict, but from different sources.

(iii) Hypothesis Three: Modifications of the inner shelf deposits have occurred to such an extent that any original distinguishing characteristics have been greatly changed. Possible modifications might include either the addition or removal of a sand fraction, or mixing into the sediment of shell material. Thus, the sediment may be palimpsest to a lesser or greater degree, and possibly may be more correctly termed modern if present-day processes are determining much of the sediment characteristics.

Information is presented in the following sections of this chapter, and in Chapter Seven for the Pataua deposits, which indicates that Hypothesis Three is most likely.

6. 2. 3 Carbonate Material

According to Ritchie and Saul (1975, p. 14) shell content was visually estimated as a percentage in each size class. Although this method of estimating shell content is probably at best only accurate to 10%, the difference in means shown in Table 6. 2 is considered to be valid.

Table 6. 2 - Mean shell content (% visual estimate). Computed from raw data in Ritchie and Saul (1974; 1975).

Prospecting Area and Number of Samples	Size Fraction	
	Fine Gravel (1-5 mm)	Coarse Gravel ($\geq$ 5 mm)
Stephenson Island (13)	50	15
Nine Pin (6)	45	20
Home Point (15)	35	25
Awarua Rock (16)	85	50
Pataua (13)	no data	60
Mean (50, 63)	56	36

Three features can be seen in Table 6. 2. First, there are significant quantities of shell in both size classes of all areas. Thus, marine biogenic agencies have contributed to and altered the original non-biogenic particle size distribution characteristic of all of the

inner shelf samples. Second, this contribution has not been uniform between areas. Awarua Rock and Pataua areas have shell contents in the $\geq$ 5 mm size range which are two-four times greater than coarse gravel contents in the other areas. Third, shell content in the fine gravel fraction of each deposit is greater than the coarse gravel fraction by up to two-three times. Thus, comminuted shell is also present in large quantities. The significance of these features of shell material is examined in the following.

6. 2. 4 The Significance of Inner Shelf, Molluscan Communities

It has been shown (Table 6. 2) that all of the inner shelf sand and gravel deposits contain significant amounts of biogenic calcareous sediment which is mostly composed of molluscan shell and shell fragments. About 20 species of bivalves were identified in the sediment samples with the four most frequently occurring being Tawera spissa, Glycymeris laticostata, Glycymeris modesta, and Venericardia purpurata. This association of bivalve species has been studied at a number of locations along the Northland coast and has been termed a "Venus" shell community (Powell, 1936; Grace, 1966; 1972; McKnight, 1969; Ballantine et al., 1973). Venus communites and variations described by McKnight are widespread around the New Zealand continental shelf on gravelly to sandy substrates at depths of 10-70 m. These substrate areas are also generally free of extensive silty conditions which would clog the siphons of suspension feeders relying on a planktonic food supply.

Although there are significant amounts of dead shell material from Venus communities in sediment samples, the survey of Ritchie and Saul (1974, p. 24) did not reveal substantial populations of live molluscs in the sand and gravel deposits of the North Gable area. However, a number of species were found to exist both peripherally and scattered through the deposit. In addition, Bioresearches (1974) obtained a number of dredge samples from the North Gable, Pataua, and Awarua Rock deposits in which the number of mollusc individuals was estimated as 20-100 / m^2 of the seabed. The production of shell material from Venus communities can also be very large under favourable conditions as shown by the dense concentrations of 2,000 to 7,000 / m^2 of 2 cm diameter Tawera spissa individuals on the seabed off Mimiwhangata (Ballantine et al., 1973).

The predominance of shell material derived from contemporary inner shelf species is also shown by the fact that of the 118 dive stations and bottom dredge samples taken from all of the six prospecting areas, at only three sites was the presence of a harbour species (Chione stutchburyi) and a sandy beach species (Amphidesma subtriangulatum) noted. Thus, shell material which is contained in samples from surface layers of the deposits is overwhelmingly modern, because the contributing mollusc species are from contemporary inner shelf environments. Furthermore, this is also the case for three samples taken from sub-bottom depths of 1.0-1.5 m. The sub-bottom samples are from three different prospecting areas (Stephenson Island, Home Point, and Pataua) in water depths respectively of (40, 21, and 18 m) (Ritchie and Saul, 1975). The presence of this inner shelf shell, which has been incorporated into the sediments, indicates a level of gravel mobility

which has been great enough to mix surface derived shell to a depth of at least 1.5 m.

In summary the following evidence suggests that Hypothesis Three is the most likely:

(i) there is from 36-56% shell in the gravel fraction of inner shelf mixed sand and gravel sediments;

(ii) the shell is overwhelmingly derived from contemporary inner shelf molluscan communities; and

(iii) the shell is mixed with the deposits to a depth of at least 1.5 m.

Therefore, it is suggested that modifications of the original source characteristics of gravel in the deposits has occurred to such an extent that the original size distributions have been significantly changed. The deposits are thus considered to be at least palimpsest, and may be more correctly termed modern, because of the degree to which contemporary inner shelf processes are determining sediment characteristics. The modern nature of the deposits is illustrated further in Chapters Seven and Eight for the Pataua area.

6.2.5 Silt and Clay

One of the environmental concerns about dredging inner shelf deposits is that mud might be stirred up and suspended by any dredging operation, and then would settle out on adjacent flora covered rock areas. The significance of mud suspension because of dredging will depend upon the type of dredging used, the amount of mud which is available for suspension from the deposits, and the ultimate site of deposition of the suspended mud. Also of consideration is the amount of naturally occurring fine sediments presently settling out in an area.

In most of the gravel deposits silt and clay size sediment proved to be absent, or present in only very small amounts (Bioresarches, 1974; Ritchie and Saul, 1974; 1975). Silt and clay were found as distinct deposits only in the North Gable area where they occupy about 2% of the prospecting area, and are confined to isolated pockets in the deepest (50 m) portions (Fig. 6.1, Table 6.1). In the Pataua deposit, core sample mud contents reached a maximum of only 2.2% and were usually less than 1% (Fig. 7.7).

Potential sources of mud in inner shelf deposits would include relict fluvial or estuarine deposits, or modern mud passed onto the shelf by rivers in flood. In the latter case it has been noted that coastal waters can be discoloured for three-six days after major floods (Section 4.3). There can also be considerable temporal variations in mud occurrence in certain areas of the deposits. For example, observations have shown that a thin (5-10 mm) veneer of silt occurred from time to time over the deeper rock, gravel, and sand areas of the North Gable deposit. In this area on four successive dives extending over a two month period, a normally wave-ridged gravel bottom at 41 m showed the temporally variable presence of a silt veneer. The occurrence of the silt veneer was correlated with locally heavy rains and discharge from the adjacent coast of flood waters heavily laden with fine sediment. After a period of rainless weather silt was not found in this area and had probably been re-suspended and transported away by wave action and other currents, In another study the temporary presence of mud on the seabed off the Puerto Rican shelf at depths of less than 70 m was also found to be related to large river discharge events (Pilkey et al., 1978). In this example mud was initially deposited as a thin blanket across the shelf after heavy floods, and

was subsequently moved seaward by small, storm wave events in an episodic manner by a sediment bypassing mechanism termed "mud hopping". Here mud sediments were episodically moved during storms to the outer shelf. A similar process probably also operates in the study area. Therefore, although mud may temporarily cover deposits after floods, and small amounts (1-2%) may be incorporated into the deposits, it would seem that inner shelf deposits in the study area do not form a final depositional site for mud sized sediments.

6.3 GEOMORPHIC CHARACTERISTICS

6.3.1 Introduction

In Chapter Three it was postulated that the formation of gravel deposits within all of the prospecting areas (with the exception of Pataua) was strongly related to the supply of gravel from the erosion of adjacent coastal cliffs, and that this gravel had been deposited on a relict, planed, bedrock surface at inner shelf depths of 30-50 m. The existence of the planed surface was inferred from the smooth, gently seaward sloping nature of inner shelf profiles at depths greater than about 30 m (Fig. 3.2, 3.3), while the cause of the planed surface was postulated as being due to marine planation processes in equilibrium with sea level highs of 20-40 m below present during most of the last glaciation (Fig. 3.4). The purpose of this section is to present more detailed geomorphic data which has been obtained in a field survey of inner shelf areas using echo sounder and seismic profiling equipment. The survey has provided data on the nature of seabed bathymetry, and

the sub-bottom bedrock surface beneath the deposits. In addition, the survey has shown the spatial extent and depth of the deposits, and the relationship of deposit sediments to underlying and adjacent rock areas. As will be shown in the following, this data has also been interpreted as supporting the postulated origin of the deposits described above.

The survey was conducted in four of the six prospecting areas. The four areas surveyed were Nine Pin, the northern arm of Home Point, Pataua, and Awarua Rock (Fig. 1.1, 6.1). A preliminary seabed sediment and echo sounder survey (described in the previous section) had already been made of these four, and the other two deposits. Existing bathymetric data was also available from various hydrographic charts (H.O., RNZN, 1973; 1977a; 1977b) as shown in Fig. 6.1.

6.3.2 Field Work, Equipment, and Methods

The field work for this survey began in early February, 1976 and was intended to be completed in about one month. But technical problems with the sub-bottom profiler in late February and continuously bad sea conditions through the month of March prevented work being completed until April, 1976. Over this period the survey had to be confined (because of financial and logistic constraints) to completely within or immediately adjacent to the prospecting license areas. Thus, there were no opportunities to run surveys into some of the large bays, and off beaches and other interesting depositional features, such as Ngunguru and Whananaki Spits. Therefore the description to follow considers only the seabed contained within the prospecting areas.

The vessel used in the survey was the "Anne Maree", an 11 m fishing boat which was owned and skippered by Mr Fred Stewardson of

Waitangi, Bay of Islands. As can be seen in Plate 6. 1, the boat had some enclosed cabin space as well as covered deck space over the stern. The boat had its own 12 volt DC circuit and an echo sounder, a Furuno FG-II, Mk 3. This sounder is similar to the one described in Section 5. 8 except for two important differences. First, a lower transducer frequency of 50 kHz (as opposed to 200 kHz) gave a better definition of seabed sediment types (i. e. gravel/sand/mud). Second, the first chart depth range of 75 m full scale, over an effective paper width of 90 mm, reduced resolution to about 0. 75 m, but the greater 75 m depth range also prevented the problem of range scale changes, since all of the seabed studied was at water depths less than 75 m.

The sub-bottom profiler and its recorder unit required their own power supplies. Thus, two additional portable generator units had to be carried on board. The sub-bottom profiler was of the "boomer" type and in general operation is similar to profilers described by Sargent (1966; 1970) and Barnes (1970). The boomer source had a maximum 2 kJ power output with a 400-800 Hz peak signal range. The signal was fired for a 0. 25 millisecond pulse length every 0. 5 seconds. The transducer plate was towed on the surface about 15 m astern, with the reflected seabed and sub-bottom signals being received by a 5 m "eel" containing a string of ten hydrophones (Plate 6. 2). The received signal was then filtered and recorded on an EPC 4600 recorder. The complete profiler system was hired through Professor G. Sargent, Department of Geology, University of Queensland, Brisbane.

When the profiler system was operating properly a sub-bottom penetration into gravel sediments of at least 10 m was possible with a resolution of better than 1 m. But these were optimum conditions and many records of less than satisfactory quality were obtained.

Plate 6.1 - The "Anne Maree", the vessel used for the sub-bottom profiler survey. At Paihia Dock, Bay of Islands, February, 1976.

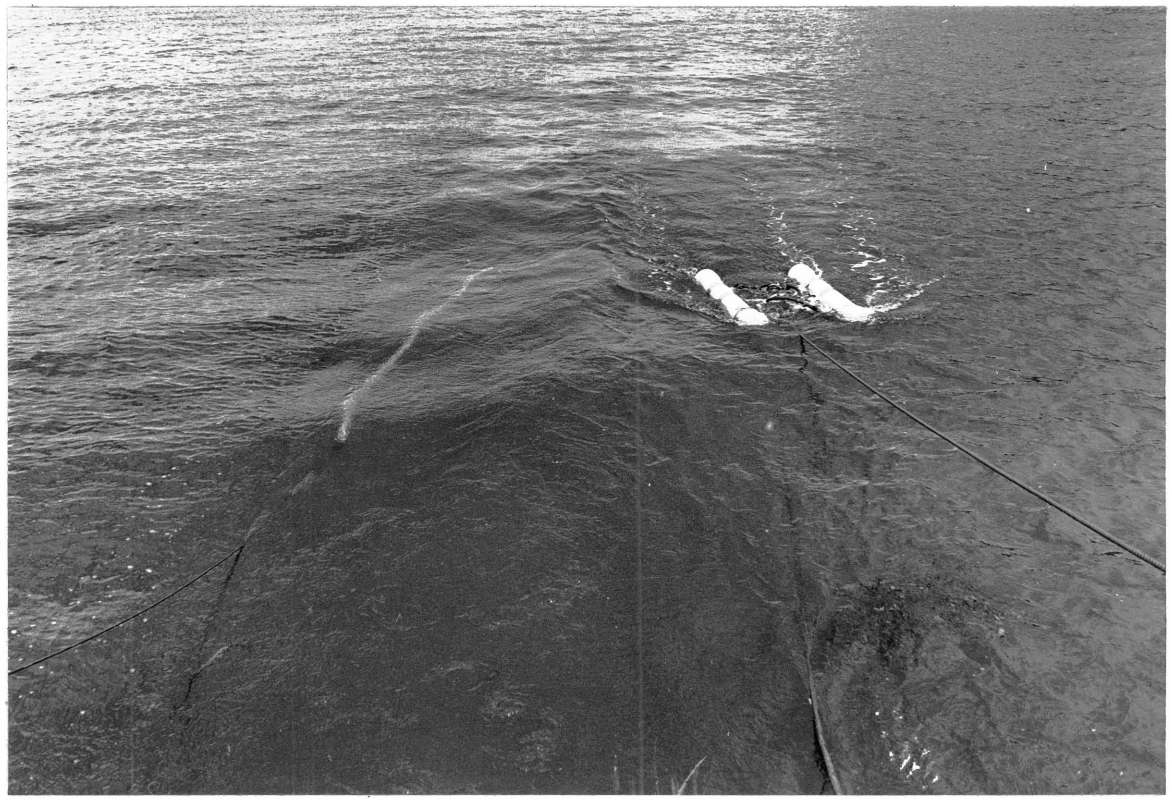

Plate 6.2 - Sub-bottom profiler equipment in tow. Boomer source on right with hydrophone eel on left.

Usually, record quality was impaired by the relatively high 500 Hz frequency which had to be used as a lower filter cut-off to reduce noise from waves and turbulence. This had the effect of limiting the depth of penetration into sands and gravels. In addition, a resonance pattern in the chart recording frequently obscured reflections at sub-bottom depths of 2-10 m. Lastly, wind and sea conditions, as well as boat speed, also strongly affected the quality of the record. Thus, operating conditions were usually limited to swell wave heights less than 2 m, sea chop from winds less than 10 m/sec, and boat speeds less than 2 m/sec.

Positioning control of the boat during the survey was achieved with two shore-based theodolite stations with operators in radio transceiver communication with each other and the boat for position fix commands. The accuracy of this system is $\pm$ 5 m over a 10 km distance.

6.3.3 Results, Interpretations, and Discussion

Initial survey analyses consisted of plotting the boat's position from the theodolite fixes on either 1:9,000 or 1:12,000 scale working charts similar to the reduction shown in Fig. 7.2 for the Pataua area. From the charts the total length of survey lines completed was found to measure 261 km, being distributed between the areas as follows: Nine Pin (62 km), Home Point (93 km), Pataua (62 km), and Awarua Rock (44 km). Over the 261 km of survey line there were 501 position fixes giving a fix density of about one for each 0.5 km of line surveyed.

A selection of 12 lengths of survey line are presented in Figs. 6.3a, 6.3b, 6.4a, and 6.4b. These survey lines have been

chosen primarily to illustrate the nature of sand and gravel deposits and their relationship to underlying and adjacent rock areas. Figs. 6.3a and 6.3b are photographic reductions of portions of sub-bottom profiler records. The location of these and the composite echo sounder sub-bottom recordings (Figs. 6.4a, 6.4b), are shown on maps of each area (Fig. 6.1). For all of the recordings, depths are represented in metres, and it has been assumed that the sound travelled at 1.5 km/sec in both seawater and sediment.

The profile J-J' in Fig. 6.3a runs across the northern half of the mouth of the Bay of Islands. This profile is exceptional among the sub-bottom records collected in a number of ways. It is unusually clear and shows a deep sub-bottom penetration of about 30 m. The bedrock reef area near J can be followed beneath the overlying sedimentary layers to two, large, buried river channels. These buried channels probably represent the course of the ancestral Kerikeri River and its tributaries which presently flow into the head of Kerikeri Inlet some 13 km to the west of this location. The channel fill is characterised by acoustically transparent sediments in the deep portion of the channels, with more acoustically opaque sediments having numerours reflecting layers in the shallower portions. Some of these more prominent reflecting layers have the appearance of river terraces. At a sub-bottom depth of about 3 m a very sharp, horizontally extensive reflector forms an unconformity over the underlying channel fill material. The sediment above this reflector is probably similar to the seabed surface sediment which is designated as fine sand and mud on the local chart (H.O., RNZN, 1977a). This extensive reflector probably represents a shallow, nearshore, wave planed surface in sediments, which would have been created by the late Holocene sea level

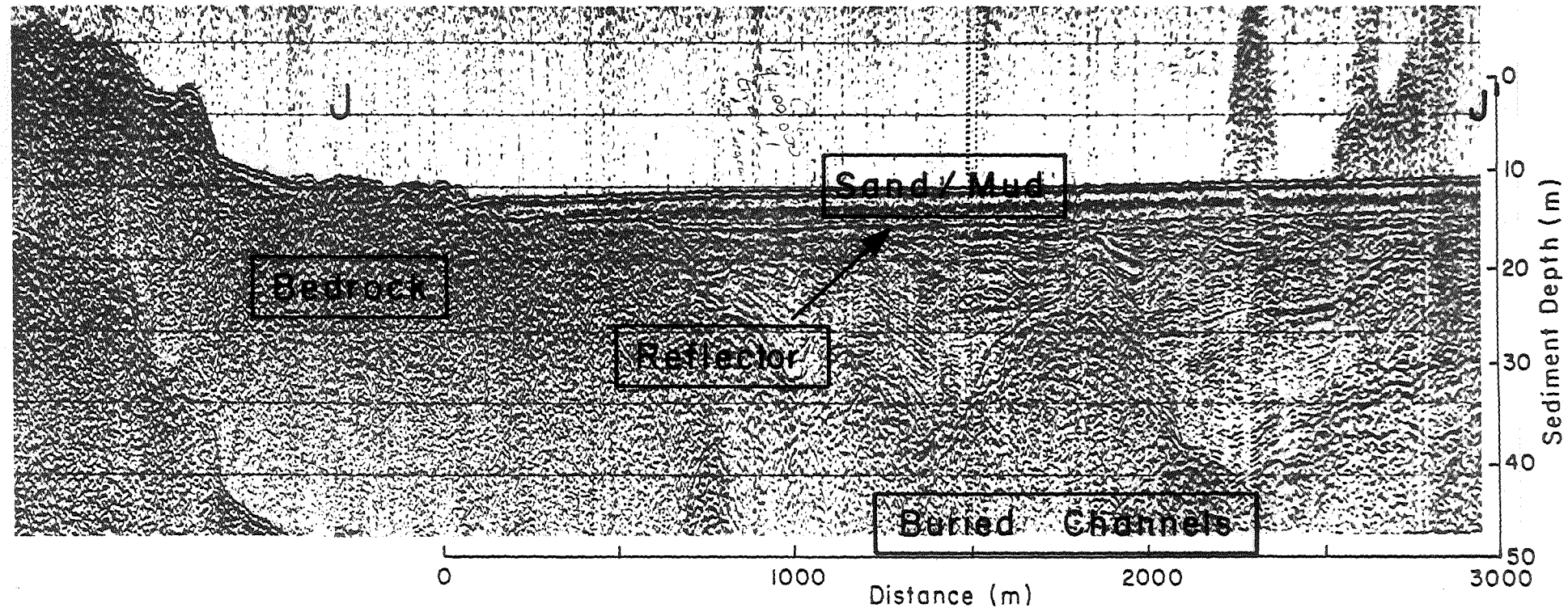

Fig. 6.3 a - Sub-bottom profiler recording, Bay of Islands (J-J'). For location see Fig. 6.1 (map pocket).

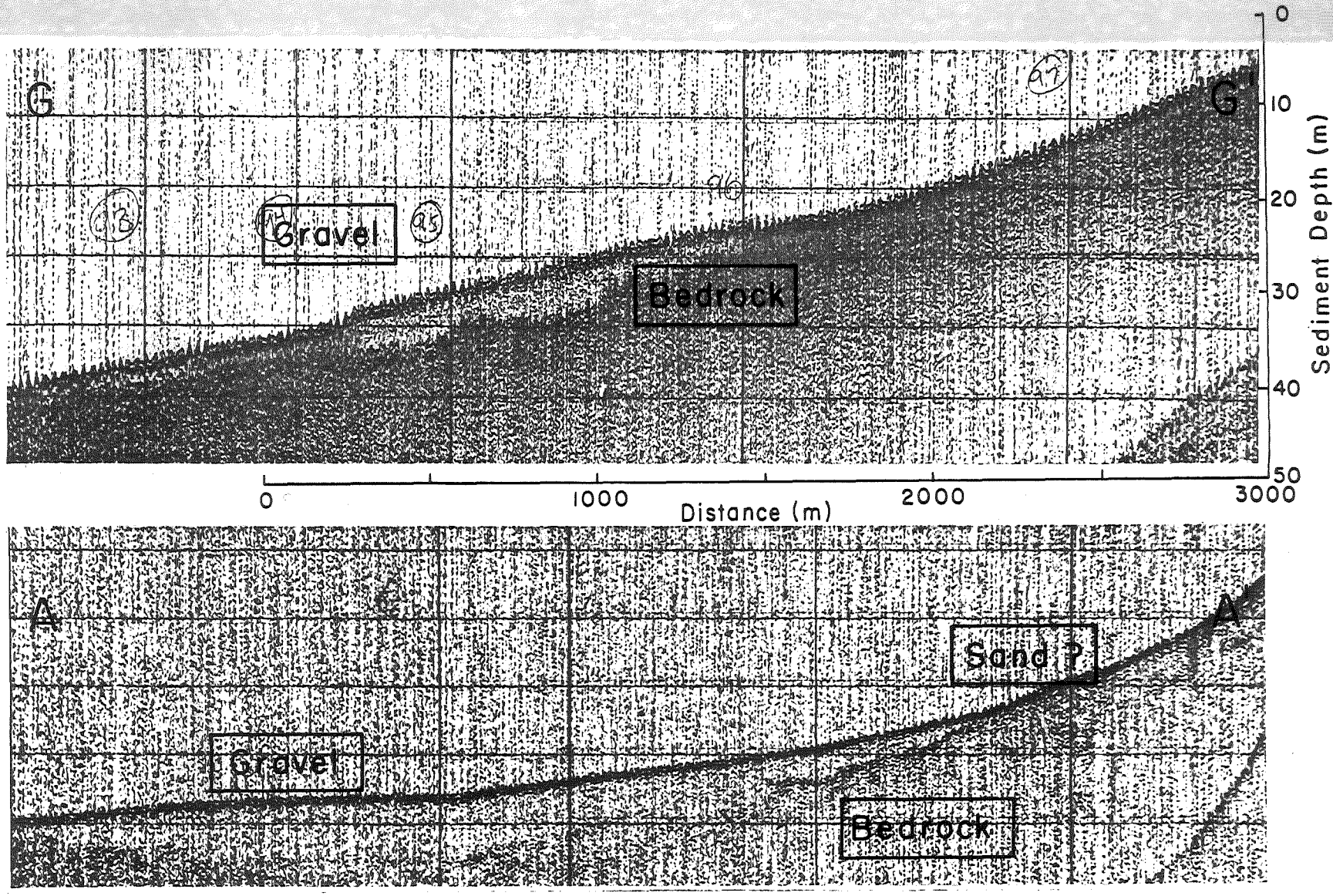

Fig. 6.3 b - Sub-bottom profiler recording, Home Point (G-G') and Awarua Rock (A-A'). For location of profiles see Fig. 6.1 (map pocket).

rise and transgression into the Bay of Islands. The reflector occurs at a depth of about 37 m below present sea level. Therefore, using the sea level rise curve of Fig. 3.4, this would place its age of formation at about 10,000 - 9,000 yr BP. The overlying sediment thickness of 3 m has accumulated since then, giving an average rate of sedimentation of about 0.3 m/1,000 yr. In comparison, Lewis (1973b) found higher deposition rates of 1-3 m/1,000 yr for sediments of a similar age on the inner shelf south of Hawke Bay.

Fig. 6.3b shows two sub-bottom profiles of seabed areas which are known to be covered by gravel (Fig. 6.1). Profile A-A' at the southern end of the Awarua Rock area shows a 5-10 m thick layer of sediment for a distance of 2.5 km along the profile line. The sediment is most probably gravel near A and sand near A'. The underlying reflector, which is probably bedrock, is relatively smooth. It rises just to the seabed surface at the shoreward end (A') of the profile.

Profile G-G' from the Home Point area, shows a gravel layer with a maximum thickness of 5 m which is underlain and thins out to bedrock at both ends of the profile. The shallow end of this profile is gently sloping without any apparent sub-bottom reflectors. This area probably represents a thin gravel deposit covering a low relief, reef area.

The profiles presented in Figs.6.4a, and 6.4b are reduced echo sounder recordings, with additional overlay tracings from sub-bottom recordings. Using the procedures described by King (1967) for interpreting sediment types from echo soundings, and some knowledge of seabed sediment (Fig. 6.1), the echo sounder records can be differentiated into two different types of bottoms. Bedrock areas are characterised by thick, dense, topographically irregular traces.

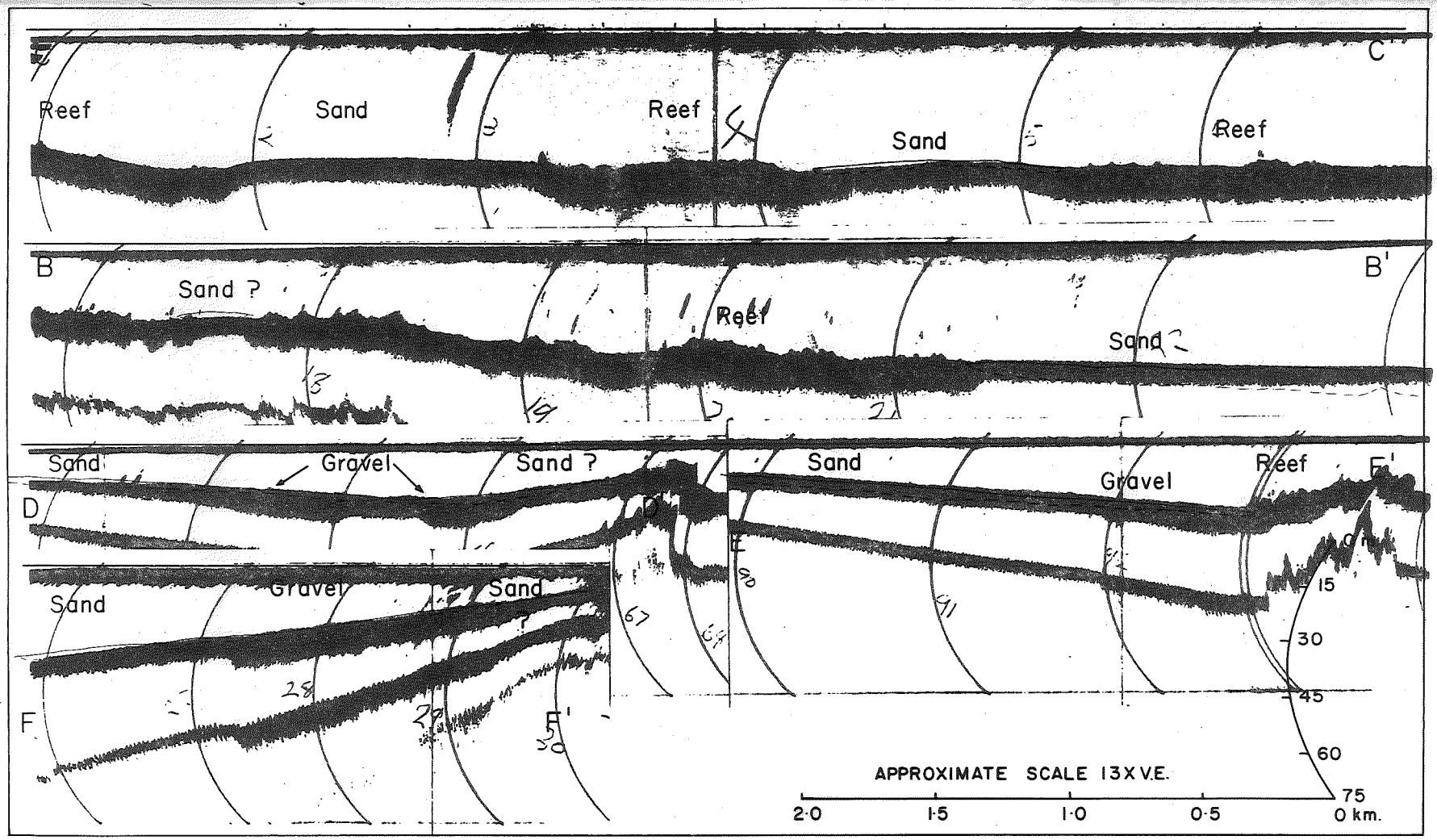

Fig. 6.4 a - Sub-bottom profiles (C-C', B-B', D-D', E-E', F-F'). For location of profiles see Fig. 6.1 (map pocket).

Areas with sediment thick enough to mask the underlying bedrock appear as thinner, smooth traces with differences between sand and gravel sometimes being apparent.

Profiles C-C', and B-B' in Fig. 6.4a each show about 5 km lengths of seabed over a predominantly rocky bottom with a relatively thin cover of sand and gravel. As can be seen from the map of the Awarua Rock seabed types in Fig. 6.1, the two areas which have been identified as sand on line C-C' lie off adjacent coastal embayments. The deeper end of profile B-B' has a similar thickness (5-10 m) of sediment overlying bedrock, as shown in the deeper end of profile A-A' (Fig. 6.3a).

Profiles from the Pataua prospecting area (Fig. 6.4a: D-D', E-E', F-F') show an extensive, but thin, cover of sand and gravel deposits. Of particular note is the way in which the echo sounder record has clearly differentiated sand from gravel seabed types. Because of the thinness of the surfical deposits, the sub-bottom profiler did not define the depth of these. Therefore, additional seabed observations and coring information has been used. This is discussed more fully in the next chapter which examines the Pataua deposits separately. Finally, no evidence of buried river channels was found in the survey of the Pataua deposit, although the present Pataua River enters the sea at the southern end of the prospecting area. Moreover, no evidence for buried river channels was found beneath the sand and gravel deposits of any of the prospecting areas. But, as shown in Fig. 6.3a, buried river channels do exist in other areas.

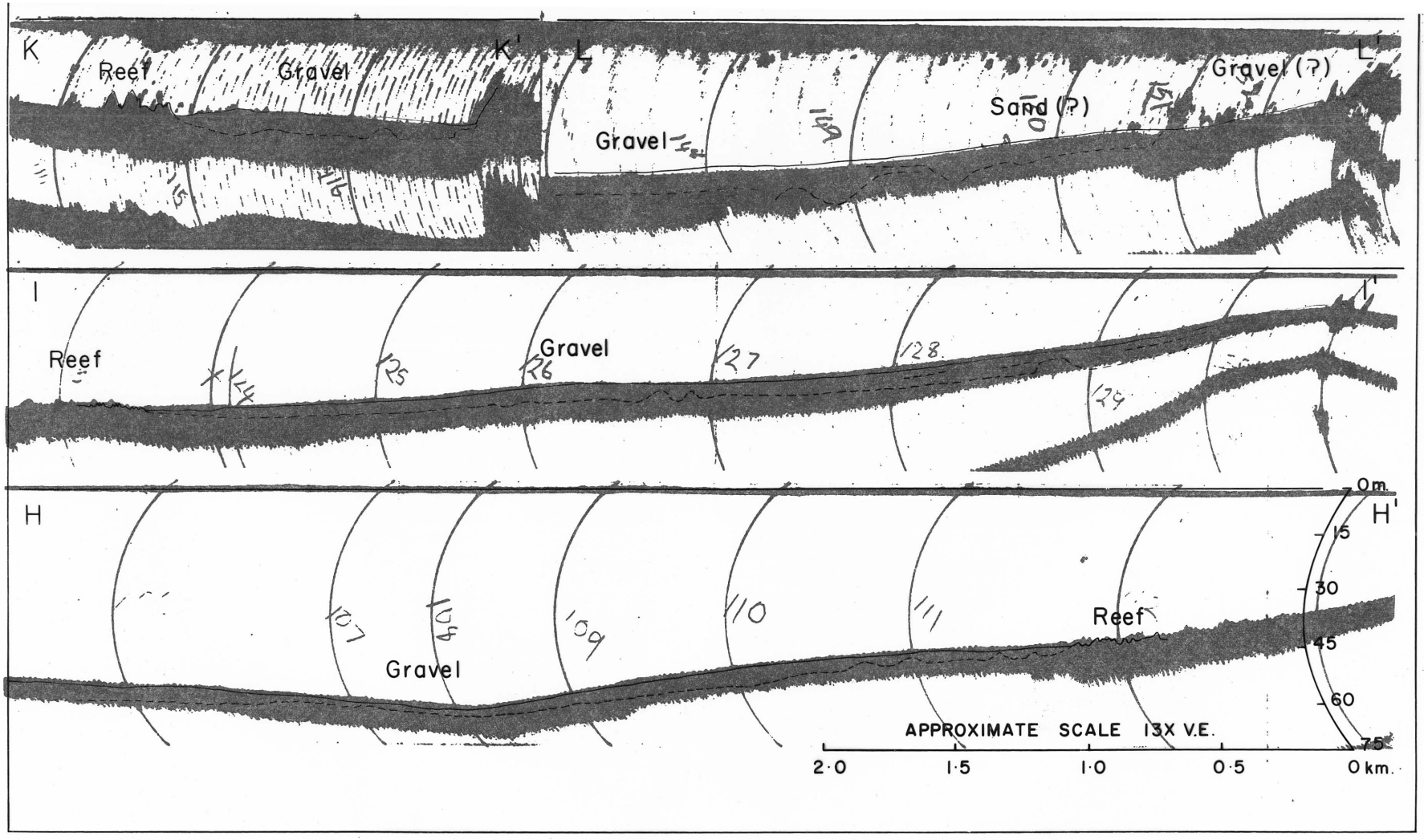

Fig. 6.4b - Sub-bottom profiles (K-K', L-L', I-I', H-H'). For location of profiles see Fig. 6.1 (map pocket).

Profiles I-I' and H-H' (Fig. 6.4b) from the Home Point deposit, show generally more extensive and thicker (3-10 m) deposits of gravel. But here, as was also the case for Awarua Rock, the gravel deposits occur as sheets over smooth bedrock surfaces rather than deeper infillings of channel-like features. Furthermore, the topographic smoothness of the underlying bedrock surfaces at depths of 30-50 m below present sea level contrasts with the high relief topography of adjacent shoreward, shallower, and gravel deficient reef areas.

Profiles K-K' and L-L' from the Nine Pin prospecting area show relatively deeper (10 m) deposits of gravel lying in a topographically more irregular bedrock situation than those of Home Point.

6.4 SUMMARY

With the exception of the Pataua area, all of the inner shelf mixed sand and gravel deposits studied in this investigation (Figs. 1.1, 6.1) are located off rocky cliffed coasts, at water depths of 30-50 m, and in association with underlying, planed bedrock surfaces. Gravel sediments within the deposits consist predominantly of rounded, greywacke particles. A comparison of sediment samples, both between and within prospecting areas, does not show either marked size-sorting clustering or sample clustering due to geographic location. This suggests that the deposit areas have similarly varied sediment characteristics and thus, perhaps similar origins. In addition, shell is present in substantial quantities (36-56%) in coarse and fine gravel size fractions (Table 6.2) and has been mixed within the deposits to a

depth of at least 1.5 m. Because of this mixing, and the fact that the shell is from contemporary inner shelf molluscan communities, it has been suggested that the deposits are definitely palimpsest, and perhaps even modern because of the degree to which contemporary biogenic and physical inner shelf processes are determining sediment characteristics. This aspect is investigated further in the next two chapters on the Pataua area.

Fine sediments (silt and clay) may occur in deep (50 m) inner shelf areas as a veneer immediately after major floods. However, this mud veneer appears to be temporary and, although small amounts (1-2%) may be incorporated, coarse inner shelf deposits in the study area are not ultimate sites of deposition for mud sized sediments. But, in other areas fine sediment deposition has occurred with an inferred average rate of 0.3 m/1,000 yr for a site at a 37 m depth near the mouth of the Bay of Islands.

Except for the Pataua area, where very thin deposits are found, within most of the other prospecting areas sand and gravel deposits occur as 3-10 m thick pockets and sheets. Buried river channels were not found beneath the deposits of the prospecting areas, although they do exist in other areas (Fig. 6.3a). Moreover, it has now been shown that in addition to the deposits occurring off rocky coasts, they also rest upon planed, bedrock sub-surfaces. These observations militate against a predominantly fluvial origin for the deposits as has been previously suggested by Gibb (1974). Such a fluvial origin would also require the redistribution of gravel along the shelf from possible source areas.

A hypothesis more consistent with the data and observations presented in this chapter is that the gravels were derived directly from erosion of adjacent coastal rock exposures. This would have occurred both throughout a series of sea level highs 20-40 m below present in the last glaciation (Fig. 3.4), and since that time during the last post-glacial transgression. This hypothesis more adequately explains the localised nature of the deposits and their relationships both to the underlying surfaces and adjacent coastal geology.

The importance of episodes of coastal erosion in generating gravel deposits during the Quaternary probably varied along the coast. Accordingly, this explanation may not apply to other gravel deposits of the Northland inner shelf. However, it is the most probable one for the gravel deposits in prospecting areas off rocky sections of the coast.

CHAPTER SEVEN

PATAUA INNER SHELF DEPOSITS

7.1 INTRODUCTION

The Pataua deposit is the only one of the six prospecting areas shown in Fig. 6.1 which is located immediately seaward of a long section of sandy beach. Thus, the possibility of coastal erosion from inner shelf dredging is more likely at Pataua than at other areas. Consequently, much fieldwork has been concentrated in this area. Pataua is also the smallest and shallowest of the prospecting areas and is thus easier to study. The mixed sand and gravel deposits (at depths of 10-20 m) make SCUBA diving work more practical in comparison to the 30-50 m depths in other areas. Furthermore, the area is relatively accessible both in terms of travel from Whangarei, and for working out of the Pataua Inlet in a small boat under favourable sea and tide conditions.

It was for these reasons that the Pataua area was selected for detailed study. However, in many ways it is not representative of the five other deposits. In addition to its relatively small size and shallow depth, the Pataua deposits are thin (Fig. 6.4a) and have a high carbonate content (Table 6.2). There is also a large amount of sand of Hauraki (B) Facies type in beach and shoreface areas (Section 5.3). A stronger tidal current influence is also likely because of the proximity of the inner shelf deposits to the Pataua Inlet. Finally, seabed sedi-

ment movement probably occurs more frequently and with a greater magnitude because of the shallower depths. This last characteristic is described in detail in Chapter Eight and will be shown to provide a valuable insight into contemporary inner shelf sediment transport processes.

Detailed investigations of the Pataua deposit have included echo sounder and sub-bottom profiler surveys, some results of which have been referred to previously (Section 6.3). For this chapter seabed sediment distribution has been mapped in detail, with comparisons between two years being made to demonstrate seabed changes. The distribution of shell material in seabed sediments has also been used to illustrate sediment variability and mobility within the deposit. Finally, information obtained from the sediments and stratigraphy of five sub-bottom cores is combined with other sources of data to interpret the sedimentary history of the deposit.

7.2 BATHYMETRY

The construction of the bathymetric map shown in Fig. 7.1 was based upon results from a detailed echo sounder survey which was conducted over the Pataua deposit on 1 and 31 March, 1976. The lines of the field survey (Fig. 7.2) were run both parallel and perpendicular to the shoreline so that depths could be checked where survey lines crossed. The techniques and equipment used in the survey have been described in Section 6.3. Although the survey lines had a close spacing of about 200 m, this was not sufficient to define the complex bathymetry in the area of rock reefs on the eastern side of the map.

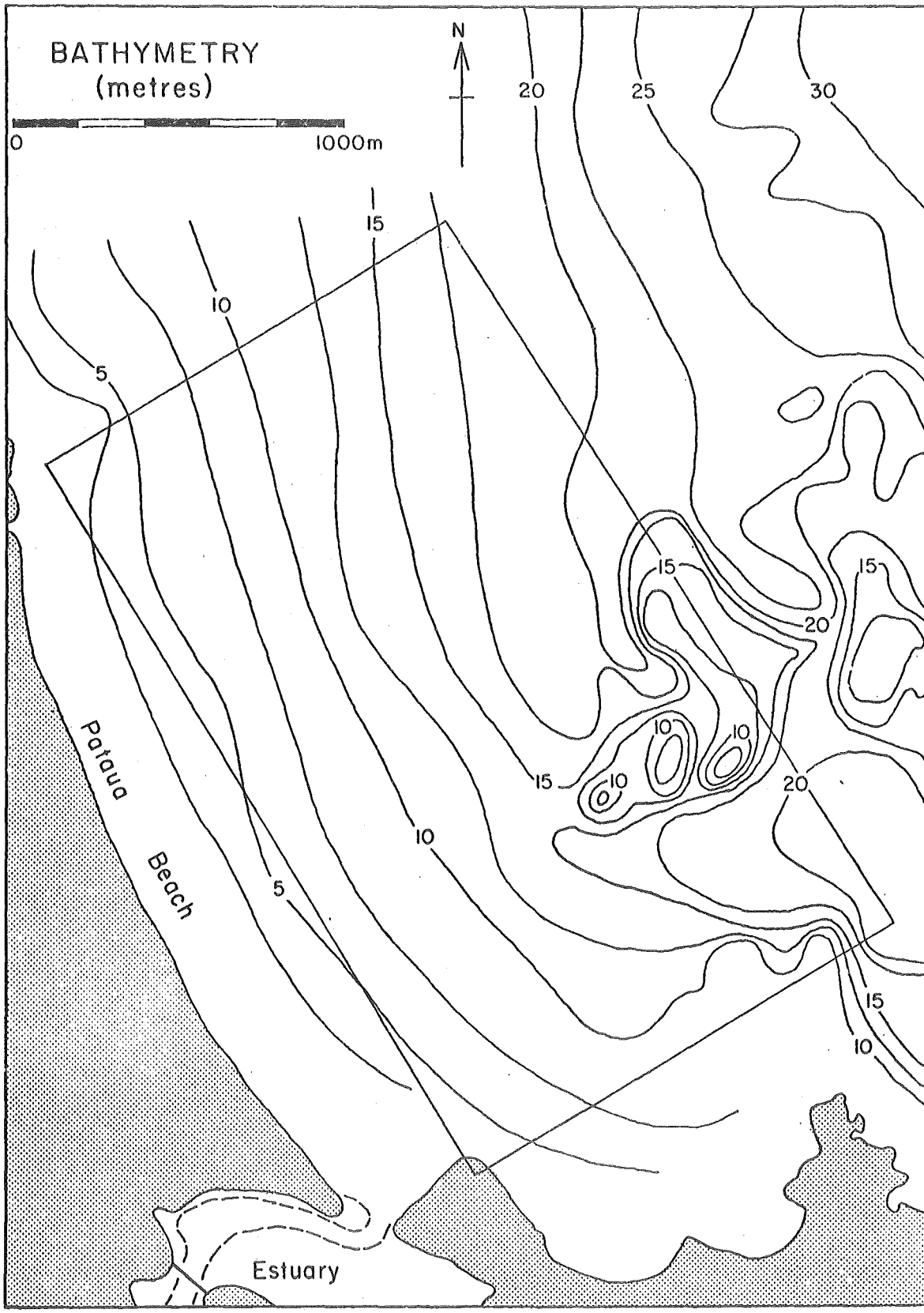

Fig. 7.1 - Pataua bathymetry. Depths in metres below chart datum (lowest astronomical tide). Isobath interval equals 2.5 m. Depths less than 10 m not shown for rocky shoreline. Drawn from echo sounder field survey (Fig. 7.2) and supplemented with survey of the Hydrographic Branch, RNZN, Chart 521/10.

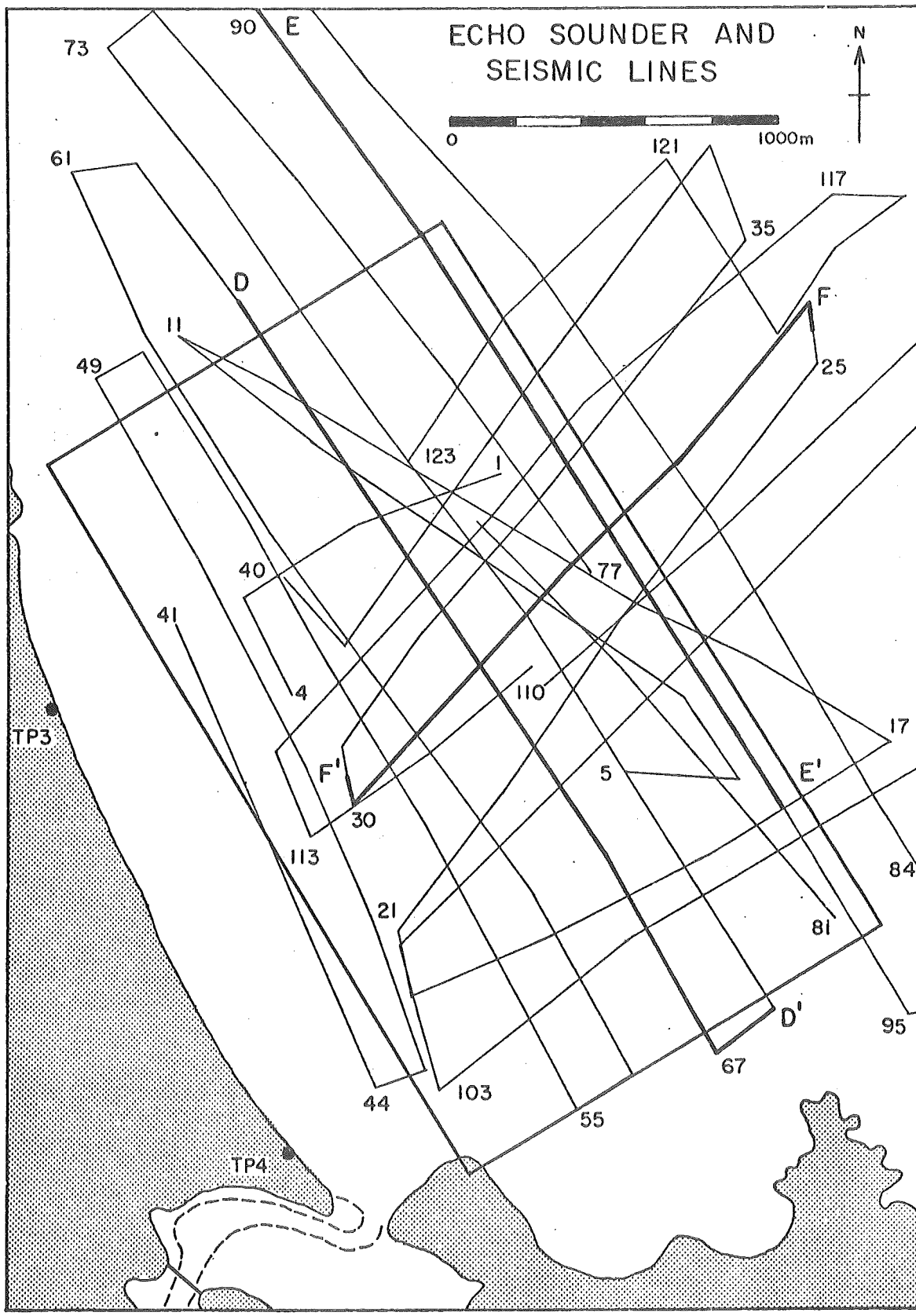

Fig. 7.2 - Pataua echo sounder and seismic survey lines. TP3 and TP4 refer to shore based theodolite stations. Thick lines (D-D', E-E', F-F') refer to sub-bottom profiles shown in Fig. 6.4a.

Therefore, in these rocky reef areas use was also made of additional sounding data from the 1:36,000 scale, field chart 521/10 available from the Hydrographic Branch, RNZN.

The bathymetry shown in Fig. 7.1 refers to local chart datum which is approximately equivalent to lowest astronomical tide. The isobath interval of 2.5 m is adequate in describing broad seabed features at this scale. However, it is not possible, for example, to show the topographic step at the boundary between shoreface sands and inner shelf gravel deposits (Plate 7.3, Fig. 5.10b).

Over the shoreward and northern side of the prospecting area the bathymetric contours can be seen to be regular in plan and parallel tc the shoreline, with a smooth seaward slope of 0.7°. In the mid-eastern portion of the map the irregular bathymetry is produced by an area of rocky reefs. Here the seabed rises abruptly from 20 m to less than 7.5 m, and with locally steep slopes in excess of 30°. Seaward of this reef area, at depths below 25 m, seabed topography is smoother. Nearshore beach bathymetry at depths less than 5 m is more complex than in shoreface regions, but this complexity cannot be illustrated at this scale and isobath interval. An indication of the complexity of nearshore bathymetry is shown by the longshore bars on some of the submarine profiles (Fig. 5.10b).

The bathymetry shown in Fig. 7.1 is also of relevance to wave refraction and wave breaking processes within the area. For example, the smooth shoreface topography causes wave fronts to approach nearly parallel at the shoreline, and this should reduce the potential for longshore beach drift. However, as will be shown in Section 8.3, wave approach angles in inner shelf areas at the northern, seaward edge of the deposit can vary by 10-15° depending upon the source of waves.

Some indication of possible wave heights during storms was also shown by the presence of breaking waves over the reef area. The reef at its shallowest is only 5.5 m below chart datum. During large sea and swell wave events, waves have been observed to sometimes break over the reef at lower stages of the tide. Assuming a breaker height/water depth ratio of 0.75, then breaker wave heights during these times were about 4 m. This inferred wave height has been of relevance in the interpretation of seabed sediment movements as discussed in Chapter Eight.

7.3 SEABED SEDIMENTS

7.3.1 Introduction

A total of 87 seabed surface sediment samples were collected within and adjacent to the Pataua prospecting area (Fig. 7.3). In addition, 14 sediment samples from 4 core sites have also been analysed separately in Section 7.5.

The first 53 seabed samples were collected in 1976, in three working days between 22 and 25 February. In 1977, 34 samples were collected on three days between 3 February and 2 March. All of the samples were taken with a small cone-shaped, dredge sampler which was hand-hauled from a 5.5 m boat. The cone dredge had a 15 cm diameter mouth with an attached, leather collection bag.

Sample positioning was achieved in 1976 using two shore-based theodolites, and in 1977 a sextant was used from the boat. Position fixing with the theodolites and sextant were accurate to

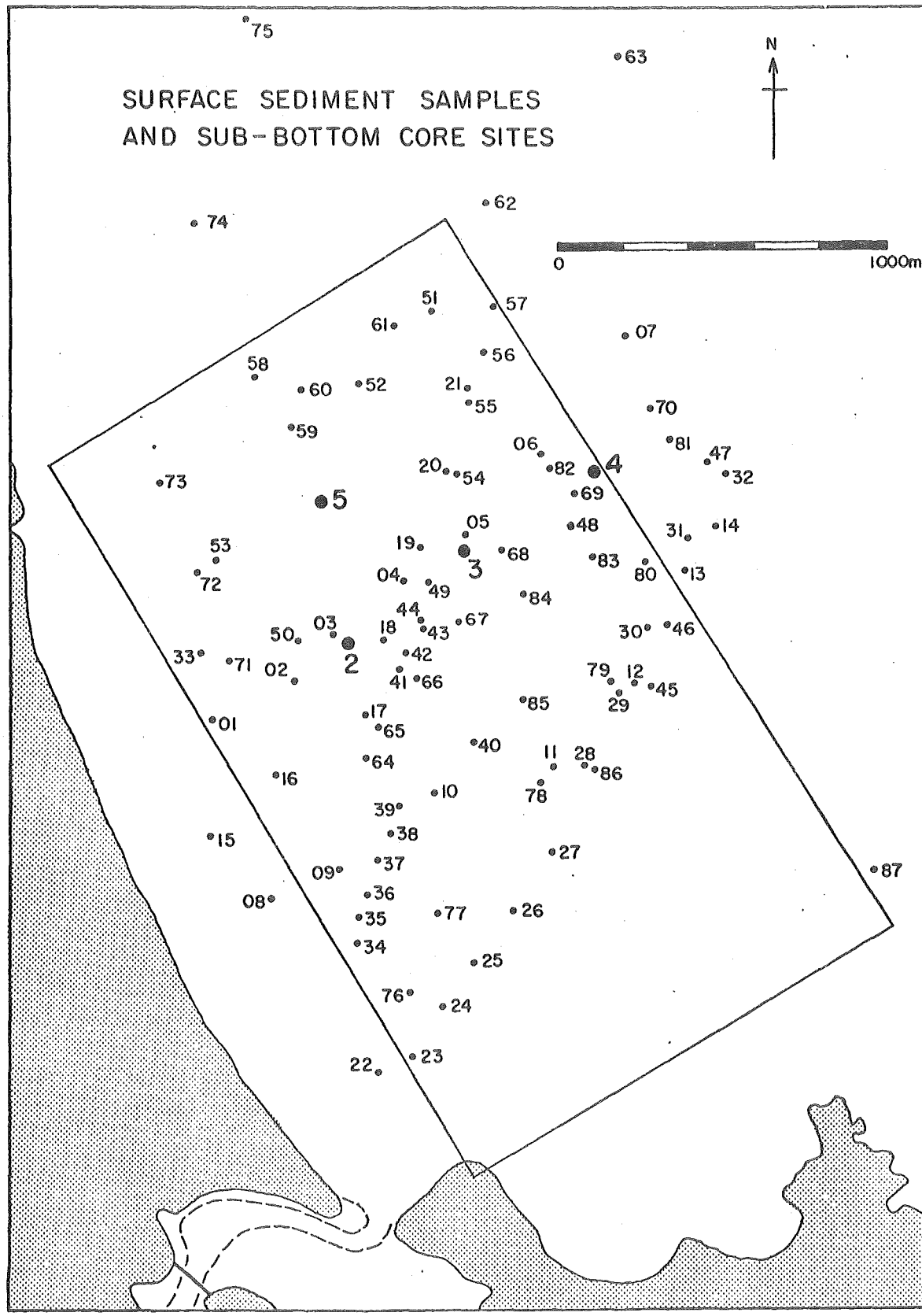

Fig. 7.3 - Pataua surface sediment samples (01-87) and sub-bottom core sites (2, 3, 4, 5). Samples were not taken in the southeast corner of the deposit because this is predominantly an area of rock reefs (Fig. 6.1).

respectively, 5 m and 20 m. Owing to variations in the direction in which the dredge was hauled (e.g. alongshore as opposed to shore-normal), seabed sediment may not have been uniformly sampled. This is because of variations in sediment types over short distances (<1 m) between ripple troughs and crests (Plate 7.2). There was also the possibility of mixing ripple trough and crest sediments during sampling. Therefore, only the broad characteristics of the collected samples are discussed in the following.

The particle size analysis of seabed samples was identical to that outlined for beach samples in Section 5.3. Sieving was used for sediment coarser than 0.0 ϕ, and a settling tube was used for sediment finer than 0.0 ϕ. Shell material contained in the samples was included in both size analyses.

7.3.2 Sediment Characteristics

Results of the particle size analyses have been presented in Table 7.1 and Fig. 7.4. Table 7.1 lists the statistical parameters of mean size and standard deviation (as defined in Appendix 2), and three size fraction proportions. These Folk parameters are of value in making comparisons between samples which have uniform size characteristics, i.e. either all sand or all gravel. However, differences in mixed sand and gravel samples can be discerned more readily by comparing proportions of size fractions. Therefore, all of the samples have been plotted in Fig. 7.4 in terms of the three size fractions listed in Table 7.1.

As can be seen from Fig. 7.4, the seabed samples can be assigned to two main sediment types. These are (i) pure sands

Plate 7. 1 - View seaward over the duned seabed on mixed sand and gravel inner shelf deposits. Taken at 18 m depth at Pataua. Diving knife is 30 cm long.

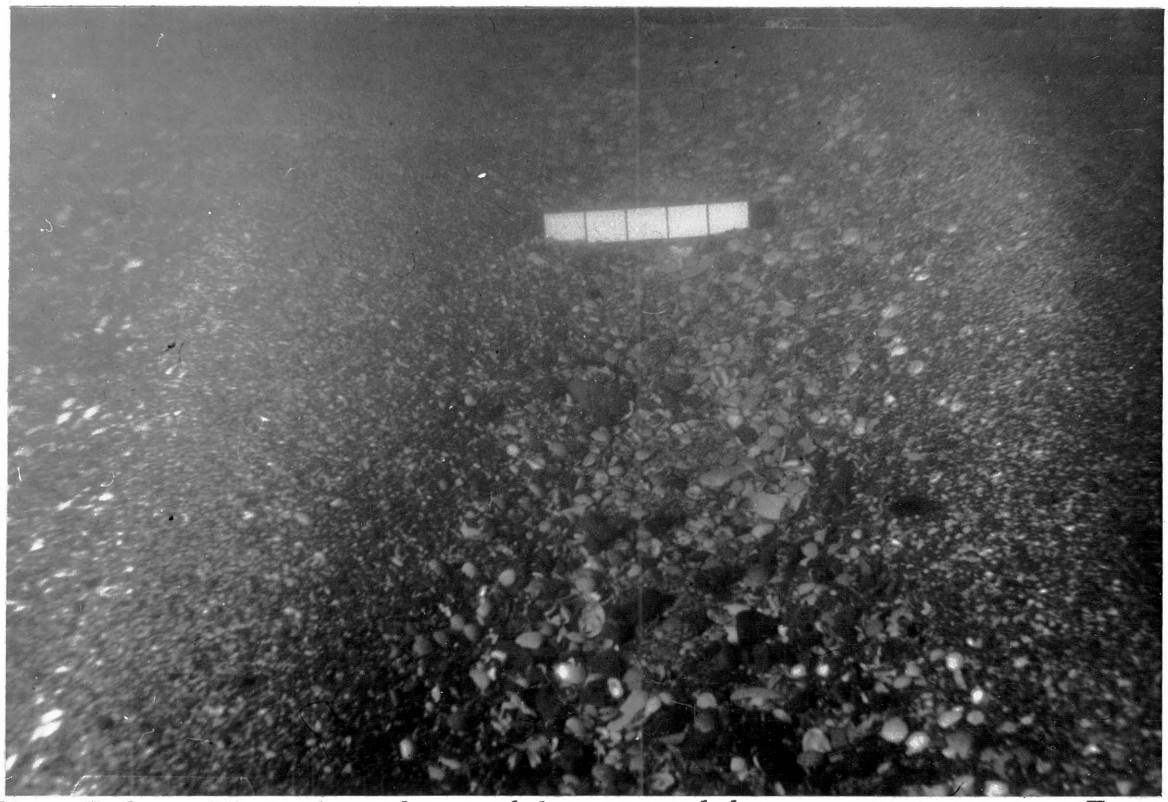

Plate 7. 2 - View alongshore of dune trough between two crests. Trough sediments are poorly sorted, sandy gravels; crest sediments are moderately well sorted, slightly gravelly sands. Dune wavelength = 90 cm, height = 15 cm. Scale is 25 cm long.

Table 7.1 - Size characteristics of Pataua seabed sediment samples. Folk parameters in Ø units.

Sample No.	M_z	σ_I	Size Fractions (%) >-2.0Ø	0.0 to -2.0Ø	<0.0Ø	Sample No.	M_z	σ_I	Size Fractions (%) >-2.0Ø	0.0 to -2.0Ø	<0.0Ø	Sample No.	M_z	σ_I	Size Fractions (%) >-2.0Ø	0.0 to -2.0Ø	<0.0Ø
01	2.56	0.26	0	0	100	30	-0.89	1.68	22	52	26	59	2.83	0.21	0	0	100
02	0.12	1.51	10	38	52	31	2.76	0.45	0	1	99	60	2.79	0.22	0	1	99
03	-0.81	1.92	26	34	40	32	2.74	0.34	0	0	100	61	2.80	0.18	0	1	99
04	-0.30	1.72	15	32	53	33	2.60	0.34	0	1	99	62	2.82	0.18	0	0	100
05	-0.00	1.26	10	40	50	34	2.55	0.25	0	0	100	63	2.71	0.21	0	0	100
06	0.43	0.81	3	31	66	35	2.63	0.21	0	0	100	64	2.70	0.21	0	0	100
07	2.75	0.29	0	0	100	36	2.73	0.22	0	0	100	65	-1.51	1.52	37	51	22
08	2.39	0.30	0	1	99	37	2.78	0.21	0	0	100	66	-0.73	1.55	23	44	33
09	2.73	0.27	0	1	99	38	2.77	0.21	0	0	100	67	-1.91	1.63	46	40	24
10	2.80	0.25	0	1	99	39	2.77	0.21	0	0	100	68	-1.81	1.87	40	46	24
11	2.80	0.25	0	0	100	40	2.80	0.21	0	0	100	69	-0.20	1.00	7	62	31
12	-4.84	1.03	93	7	0	41	2.82	0.17	0	0	100	70	2.71	0.23	0	1	99
13	2.75	0.35	0	0	100	42	2.83	0.17	0	0	100	71	2.79	0.22	0	3	97
14	2.60	0.38	0	1	99	43	2.78	0.21	0	1	99	72	2.77	0.19	0	0	100
15	2.41	0.46	0	1	99	44	-0.82	1.66	23	44	33	73	2.84	0.21	0	0	100
16	2.76	0.26	0	0	100	45	Rock Reef					74	2.82	0.21	0	0	100
17	-1.11	1.76	27	51	22	46	Rock Reef					75	2.84	0.22	0	0	100
18	-0.21	1.62	16	31	53	47	2.76	0.20	0	2	98	76	2.72	0.24	0	0	100
19	0.16	1.25	11	30	59	48	-1.35	1.74	25	57	18	77	2.80	0.19	0	0	100
20	0.53	0.70	2	27	71	49	-0.46	1.61	18	33	49	78	2.74	0.20	0	2	98
21	2.86	0.23	0	2	98	50	2.73	0.24	0	0	100	79	Rock Reef				
22	2.48	0.34	0	1	99	51	-1.11	1.91	36	33	31	80	2.71	0.20	0	1	99
23	2.54	0.29	0	0	100	52	-1.40	1.93	39	39	22	81	2.64	0.26	0	0	100
24	2.67	0.26	0	0	100	53	-1.19	1.84	32	42	26	82	-0.05	0.94	6	50	44
25	2.78	0.23	0	0	100	54	0.01	1.19	9	44	47	83	-2.14	1.79	49	40	11
26	2.84	0.23	0	0	100	55	0.45	0.81	2	28	70	84	-2.18	1.64	51	42	7
27	2.74	0.24	0	1	99	56	2.69	0.19	0	0	100	85	2.92	0.23	0	3	97
28	2.87	0.30	0	1	99	57	2.74	0.22	0	0	100	86	-0.30	1.24	10	59	31
29	Rock Reef		83	17	0	58	2.77	0.21	0	0	100	87	2.76	0.23	0	1	99

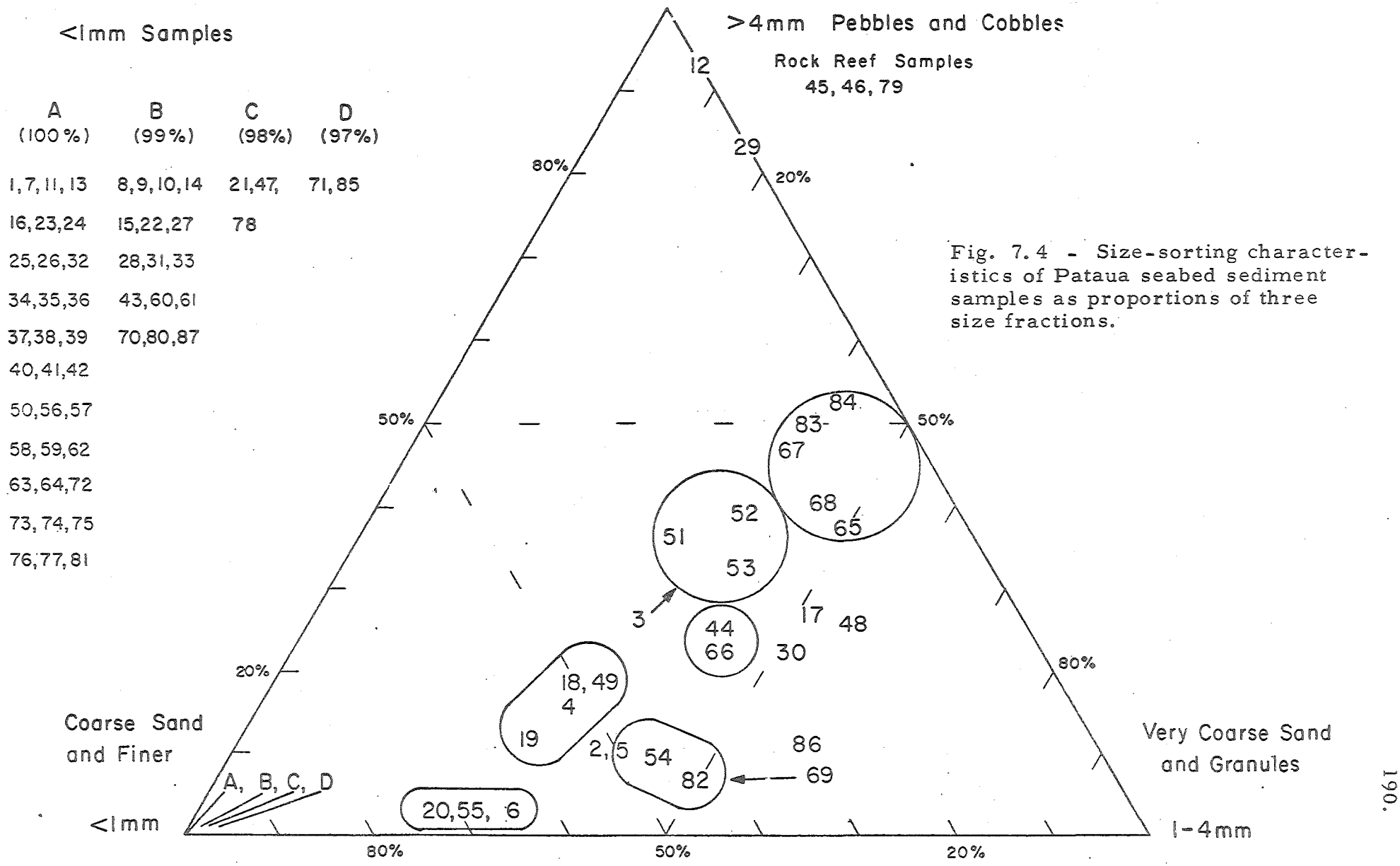

Fig. 7.4 - Size-sorting characteristics of Pataua seabed sediment samples as proportions of three size fractions.

(samples A, B, C, and D), and (ii) "gravels", which predominantly include pure gravels, sandy gravels and gravelly sands, and with a minority of slightly gravelly sands.

Using this sediment classification, the two main types of sediment samples have been mapped on Fig. 7.5 which also includes a separate transparent overlay of 1977 samples to compare with the 1976 map. Included on the 1976 map are seabed sediment types which have been interpreted from echo sounder records following the methods of King (1967). From Fig. 7.5, it can be seen that there are three main sediment facies: (i) shoreface fine sands, (ii) inner shelf mixed sand and gravels (marked "gravel"), and (iii) inner shelf fine sands. There is presently very little mixing of inner shelf gravel sediments with either of the shoreface or inner shelf fine sands. In this respect, the sand in predominantly gravel sediments is not fine sand, but is mostly coarse to very coarse sand (Fig. 7.4, Fig. 8.3). Boundaries are also abrupt between the fine sand, and gravel facies. A complete change from one sediment facies to another occurs over distances less than 50 m, and less than 10 m in the case of the boundary between the inner shelf gravel facies and the shoreface fine sand facies (Fig. 7.5, Plate 7.3). Therefore, it is inferred that the inner shelf hydraulic environment has either maintained or produced the sorting of extremes of sediment size into separate areas.

It is also of interest that many of the Pataua Beach sediment samples (Table 5.1) have moderate amounts (50%) of medium to coarse sands, which are also contained in large amounts in the sand fraction of the inner shelf mixed sand and gravel deposit. However, these similar sand fractions are separated by shoreface fine sands which have negligible coarse sand. Therefore, the coarse sand beach

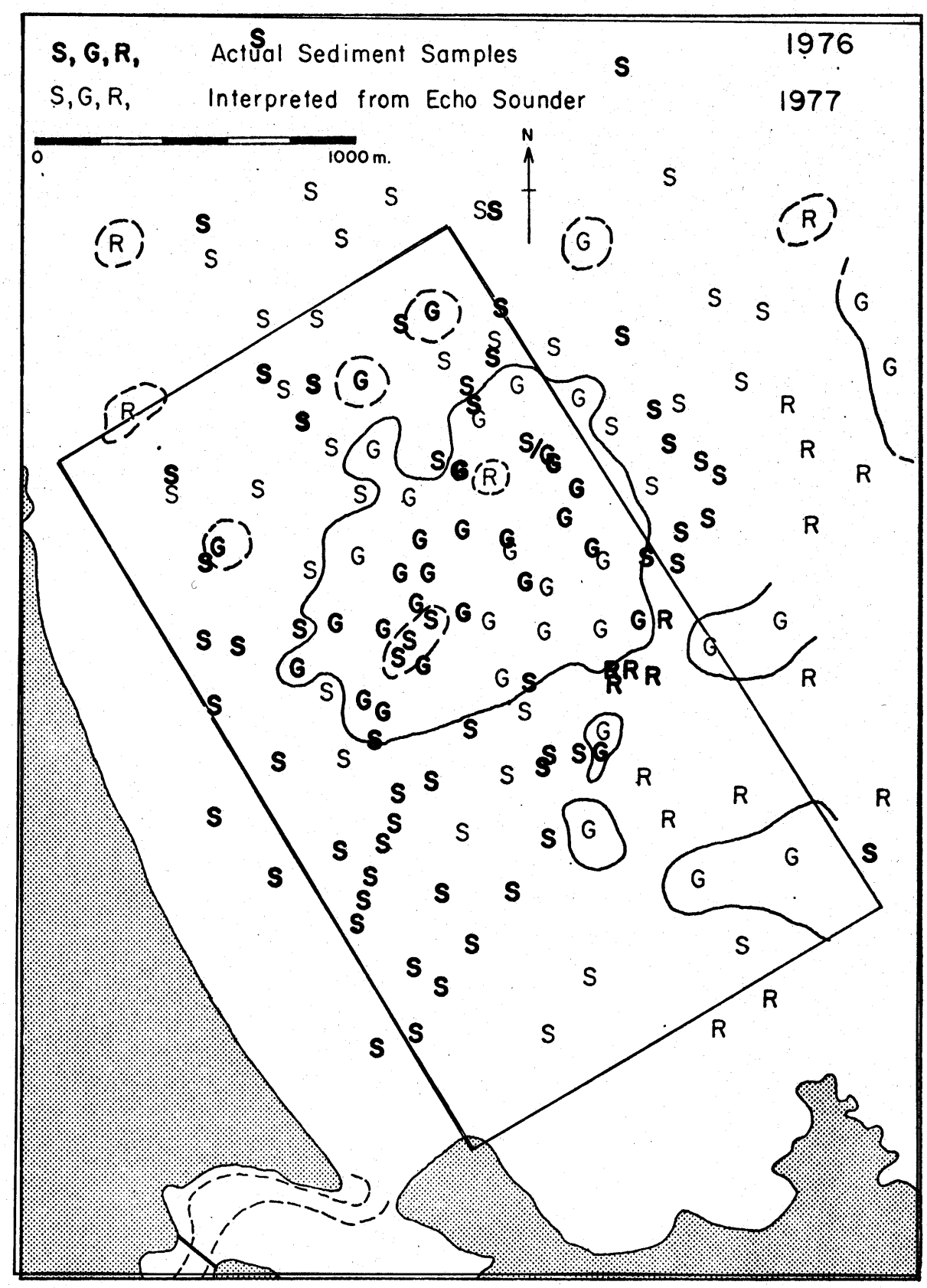

Fig. 7.5 - Comparison of 1976 and 1977 seabed sediment distribution. S refers to fine sands, G to mixed coarse sand and gravel sediments, and R to rock. Boundary of main gravel deposit is also shown.

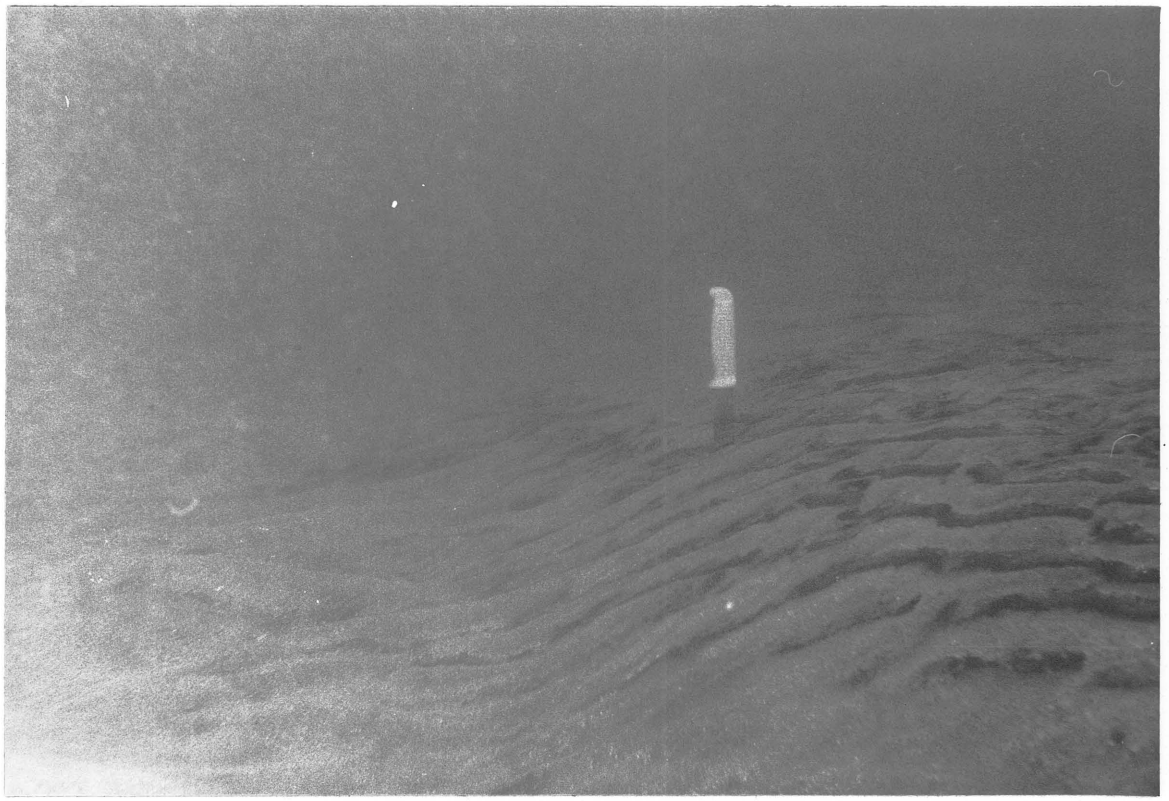

Plate 7.3 - View alongshore at the step at the shoreface-inner shelf boundary. Shoreface sediments are fine sands. Within 10 m to the left are mixed sand and gravel inner shelf sediments similar to those in Plate 7.1. Knife is 30 cm long.

Plate 7.4 - Stiff clay exposed on inner shelf seabed with a thin covering of mixed sand and gravel sediments. Location is shoreward of Core 2 (Fig. 7.3). Knife is 30 cm long.

sediments are probably derived from a source other than the present inner shelf deposits, or have been derived in the past by a sediment transport connection between the inner shelf and the beach. At present there is no apparent connection between these two facies.

Sample Groupings Within the Gravel Deposit

The sample groupings shown in Fig. 7.4 have been based on size-sorting affinities and sample proximities on the seabed (Fig. 7.3). Thus, for example, the grouping of the gravel samples 65, 67, 68, 83, and 84 on Fig. 7.4 also defines an oblong area centrally located within the deposit (Fig. 7.3). Using similar criteria, five other groups of mixed sand and gravel samples have been identified on Fig. 7.4. It should also be noted at this time that the position of samples within the triangular diagram reflects the combined contribution of both terrigenous (greywacke) and biogenic (shell) sediments making up the total size distribution.

The sample group (51, 52, 53, and possibly 3) is located on the northwestern end of the deposit, with three samples occurring separately outside of the main gravel area as shown on the 1976 distribution map (Fig. 7.5). These samples have relatively low coarse fraction shell contents (Table 7.2), so that their coarse size is mainly due to terrigenous sediment.

Sample groups (5, 54, 82, and possibly 69) and (20, 55, and 6) have very low amounts of pebble and cobble size material, with the latter group containing relatively more coarse and finer sand (<1 mm). Both of these groups occupy the north corner of the gravel deposit, with the (20, 55, 6) group being transitional between the pure sand and the area designated as gravel.

Groupings (44, 66) and (4, 18, 19, 49) are not as well defined as the other groups since they occupy a transitional position, both in terms of sediment characteristics and their location between more well defined groups.

Samples adjacent to, and from rocky reef areas (12, 29, 45, 46, 79), exhibit the coarsest particle sizes. The next coarsest group of samples (65, 67, 68, 83, 84) consists of approximately equal proportions of > 4 mm and 1-4 mm size fractions, with less than 10% of the <1 mm fraction. This latter group occupies the eastern portion of the contiguous gravel deposit. The group can also be divided into two sub-groups on the basis of shell content. Samples 83 and 84 have very low shell contents in their coarsest fractions, whereas samples 65, 67, and 68 partly derive their coarse fraction from about a 30% shell content (Table 7.2). The distribution and significance of shell contents is discussed further in Section 7.4.

Silt and Clay

Sediments finer than very fine sand, i.e. silt and clay, appeared to constitute a minor portion of all but a few samples. Three samples which appeared to be "dirty" when washed were analysed specifically for silt and clay and yielded the following results: sample 82 (0.6%), 83 (1.5%), and 84 (0.4%). In comparison, four "clean" samples (77, 78, 80, 81) had only 0.1 - 0.2% silt and clay.

Gravel Particle Roundness

From a brief visual examination of pebble size material in the range (-2 to -4 ϕ) using a Powers (1953) roundness scale, the majority of particles were classed as sub-rounded to rounded. For particles larger than -4 ϕ, and in those samples close to reef areas, particle roundness was less, being only sub-rounded.

7.3.3 Comparison of 1976 and 1977 Sediment Maps

When initially determining the distribution of seabed sediment types only the collected spot samples (totalling 53 for 1976 and 34 for 1977) had been used to determine the position of the sand/gravel boundary as shown in Fig. 7.5. Based on these samples alone, it appeared that there had been a southward shift in the sand/gravel boundary between 1976 and 1977. This shift was about 200 m in the vicinity of samples 41, 42, 43, and 66 (Fig. 7.3). In addition, the location of the 1976 gravel samples 51, 52, and 53 appeared to be anomolous in light of the nine sand samples found in close proximity to these locations in 1977 (Fig. 7.5, overlay). A check on the possibility of inaccurate plotting showed that this source of error was not the cause, and that the apparent changes in distance were ten times greater than could be attributed to positioning system errors alone.

However, when interpretations of seabed sediment types from the 1976 echo sounder records were included in the production of the 1976 map this view changed. With the additional echo sounder information it became possible to more exactly delineate the position of the sand/gravel boundary than was possible from the spot sediment samples alone. As a consequence of this, the sand samples 41, 12, and 43 were re-interpreted as probably representing an isolated patch of sand within a predominantly gravel area. Thus, there is general agreement in the boundary area of contiguous gravel between 1976 and 1977. This finding also demonstrates the value of using continuous echo sounder recordings to supplement spot samples in the positioning of facies boundaries.

However, there are still some areas which do not show agreement between 1976 and 1977, for example the isolated gravel samples 51, 52, and 53. It is also interesting that where these gravel samples (sampled on 25 February) are crossed by echo sounder lines (taken on 31 March) in 1976, the sounding records can be interpreted only as a sand seabed. Since the collection of sediment samples and the echo sounder survey were separated in time by a month of stormy sea conditions (Fig. 5.9), it is possible that sandy sediment covered the area sufficiently during the echo sounder survey to mask the gravel deposits which had been previously exposed and sampled.

Another indication of instability is apparent from a comparison of Fig. 7.5 with the map of Pataua by Ritchie and Saul (1975) shown in Fig. 6.1. The latter map was surveyed in October, 1974 and shows the gravel deposit extending further in a northwesterly direction than is the case in the March, 1976 survey. Significantly, the anomolous samples 51, 52, and 53 were located in the extended area shown on the map of Fig. 6.1. Thus, it is possible that the fine sand facies along the northern end of the deposit exists as a sheet which provides a variable cover over the underlying gravel sediments.

Core 4 (Fig. 7.7) provides additional evidence for the long term mobile nature of the sediment in the northeast corner of the deposit. The core shows a shell gravel layer about 0.25 m thick overlying a fine sand layer. This core is located on the offshore edge of the gravel/sand boundary and suggests that a shell gravel facies has migrated north-northeastward over the more seaward sand facies.

7.3.4 Summary

From the analysis of 87 sediment samples and interpretations from echo sounder records, it has been possible to define the broad scale, spatial and temporal characteristics of the Pataua inner shelf deposits. In particular, three main sediment facies have been defined. These are (i) a shoreface fine sand facies, (ii) an inner shelf "gravel" facies, and (iii) an inner shelf fine sand facies. The fine sand facies and the gravel facies are separated by abrupt boundaries with changes in facies type occurring over distances less than 50 m, and less than 10 m in the case of the inner shelf gravel - shoreface fine sand boundary. The latter boundary is also marked by a topographic step. Moreover, although both beach deposits and inner shelf gravel deposits contain appreciable amounts of similar coarse sand sediments, there is no surficial connection between these two deposits based on contemporary sediment distributions. This can be taken to mean that there is presently little sediment transfer taking place between inner shelf and beach deposits in the Pataua area.

The inner shelf "gravel" (mixed sand and gravel) facies consists of varying proportions of gravel and coarse sands which form distinctive sub-areas within the deposit. Thus, the deposit is not simply an area of uniform sediment characteristics. There is also considerable spatial variation in shell content within the deposit. The significance of this is discussed in the following section.

Changes in inner shelf sand/gravel facies boundaries probably occur from year to year, and also possibly within a year, and may be caused by the shifting nature of a thin cover of fine sand.

It was also inferred that some of the inner shelf gravel deposit sediments are mobile. The extent of this mobility has been investigated and is defined further in Chapter Eight.

7.4 CALCIUM CARBONATE IN SEDIMENTS

7.4.1 Introduction

It was demonstrated in Section 5.4 that large amounts of calcium carbonate were present in the beach sediments of the study area. Furthermore, it was also shown that at least the gravel size fraction of beach sediments consisted of shell material which had been transported to beaches from inner shelf areas under contemporary conditions.

In six Pataua Beach samples the mean calcium carbonate content was 23% (Table 5.1). A potential source of this carbonate material lies in the adjacent, shelly, inner shelf deposits. In addition, characteristics of carbonate variation in inner shelf areas at Pataua are of interest in determining possible contemporary sediment dynamics of the deposits. In order to study these aspects of the Pataua inner shelf deposits, calcium carbonate contents were determined for the "gravel" fraction ($>0.0\ \phi$) of 29 samples and the "sand" fraction ($<0.0\ \phi$) of 30 samples (Table 7.2). In both size fractions, carbonate determinations were made following the methods described in Section 5.4, i.e. gravel sized shell was determined by hand separation after sieving, and sand sized shell was determined by sample weight loss after acid digestion.

Table 7.2 - Percentage calcium carbonate of (i) mixed sand and gravel and (ii) sand samples from Pataua seabed sediments.

(i) Mixed Sand and Gravel Samples

Sample No.	Size Fraction (Ø units) Sand		Gravel					Mean Gravel	Comments
	<0.0	0.0	-1.5	-2.0	-2.6	-3.0	-3.4		
02			34	29	17	16	24	24	fresh shell
03	56.6		15	18	25	26	44	26	"
04	38.3		22	23	31	28	35	28	"
05			49	45	50	55	47	50	worn shell
06	18.1	80	90	82	100	83	100	91	
12			0	0	0	13	0	3	
17			32	34	41	16	20	29	
18		25	20	17	21	18	0	15	worn shell
19			50	40	44	51	25	42	"
20	33.6	90	95	100	100	50	100	90	"
29			0	0	0	7	19	13	
30	63.3	60	53	13	20	6	0	18	bryozoan shell
44	38.9		30	31	27	32	28	30	
48	24.4		49	62	49	71	73	61	
49			60	44	44	34	57	48	
51			18	21	12	12	4	13	
52	35.6		26	17	19	17	5	17	
53	42.2		29	26	33	25	26	28	
54		75	90	80	100	92	100	92	shell hash
55		95	100	100	100	100	100	100	"
65	35.0	25	20	27	25	26	49	30	hinged and live shell
66	31.0	20	10	15	15	21	31	18	hinged and live shell
67	26.2	15	10	10	13	20	52	25	hinged and live shell
68	28.6	20	30	39	37	35	33	35	hinged and live shell
69	15.1	25	60	69	93	87	87	79	worn shell
82		50	70	90	100	78	100	88	"
83		15	10	9	8	5	9	8	
84		15	5	5	5	4	21	8	
86	59.8	85	80	77	38	42	100	61	shell hash

(ii) Sand Samples

(1) <1.0 Ø - Sample 07(16.6), 08(25.5), 13(25.3), 15(18.8), 16(18.1), 31(33.0), 33(22.5), 34(20.2), 60(23.2), 61(17.0).

(2) <2.0 Ø - Sample 78(21.9), 80(22.7), 81(18.1), 85(34.7), 87(24.9).

The data in Table 7.2 has been mapped in Fig. 7.6 to show the spatial variation of shell characteristics in both sand, and mixed sand and gravel sediments. In Fig. 7.6, shell contents of sand samples are identified by a single value, whereas mixed sand and gravel samples have been represented by separate values for first the gravel and then the sand fractions, e.g. 90/34.

7.4.2 Gravel Fractions

From Table 7.2 it can be seen that the gravel fraction of calcium carbonate, as determined from a mean of the size fractions from -1.5 to -3.4 ϕ, varies between 3% and 100% with a composite mean value of 41%. These mean values have been plotted in Fig. 7.6. For nine of the gravel samples the contribution of calcium carbonate was more than 50%. As can be seen from Fig. 7.8, this quantity of shell induces a coarse skewed tail to the size distributions of many mixed sand and gravel samples. In Fig. 7.6 the spatial distribution of mixed sand and gravel samples has been classified into five major areas, on the basis of similarities in shell gravel/sand percentages.

Area I is found in the deepest, northern part of the deposit and consists of very high gravel fraction shell contents ranging from 79-100% with a mean of 90%, and with relatively lower sand fraction values with a mean of 22%.

Area II occupies an area of coarse gravel (samples 83, 84 in Table 7.1) in the eastern portion of the deposit near the rock reef. In Area II shell gravel is low at 8% for two samples with another two marginal samples of 18 and 13%.

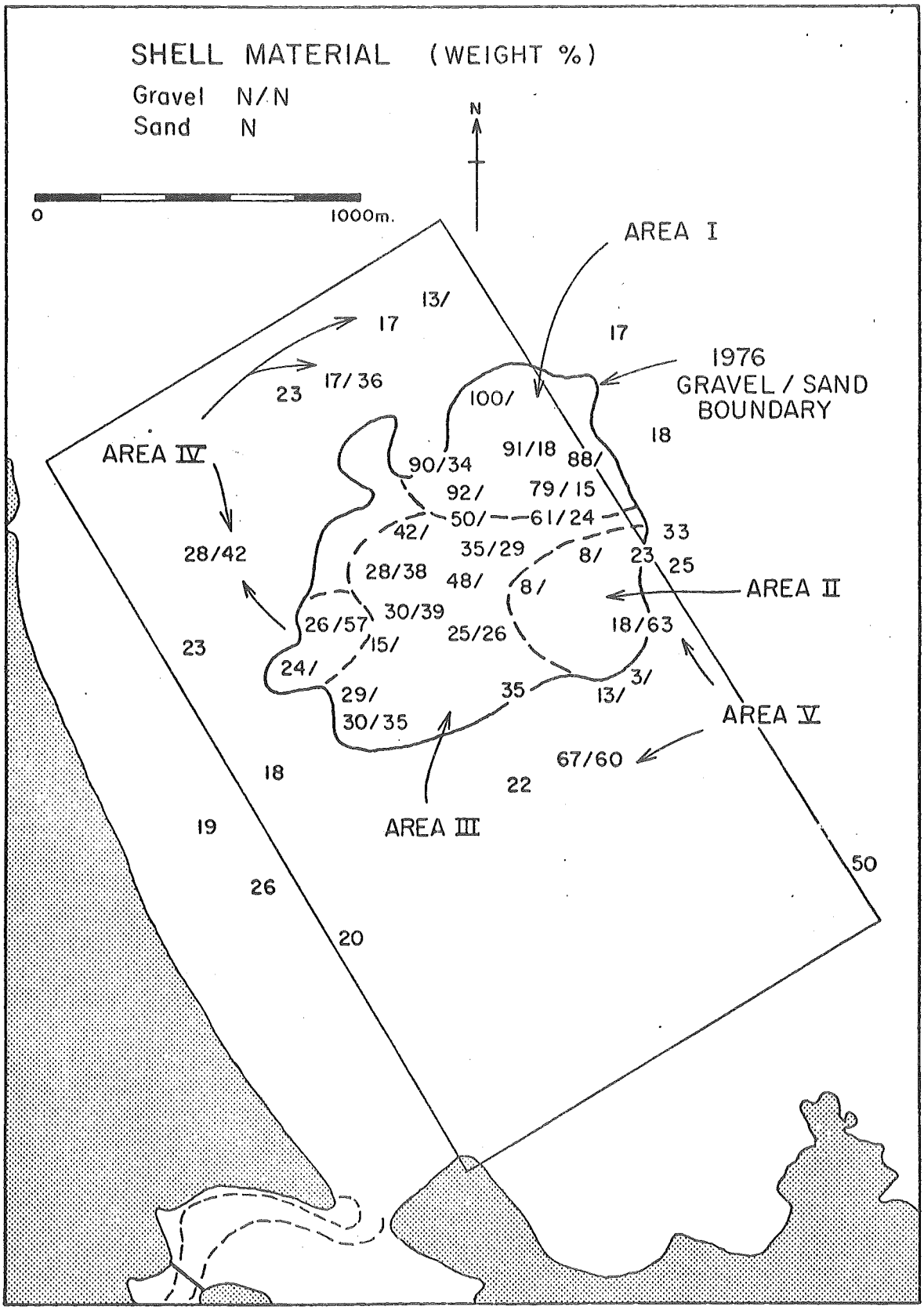

Fig. 7.6 - Seabed shell distribution map. For gravel samples N/N refers respectively to coarse and fine fractions. Areas I-V are defined on the basis of shell percentage affinities.

At the southern end of Area I, two samples with shell gravel fraction values of 50 and 60% form a transitional boundary with Area III. Area III covers the central and southern portion of the deposit, and consists of shell gravel and sand fractions in about equal proportions of 30% for gravel and 33% for sand.

The isolated gravel samples on the northwestern side of the deposit (51, 52, and 53 in Fig. 7.3 and 7.5) have relatively low shell gravel contents (respectively 13, 17, and 28%). These three samples, and two other samples with 24 and 26% shell gravel values, are probably not related to the higher carbonate Areas I and III of the contiguous gravel deposit, and have thus been designated as the separate Area IV.

Similarly, Area V also refers to samples outside or on the southeastern reef periphery of the main deposit. In Area V samples 30 and 86 (Table 7.2) have carbonate contents dominated by bryozoan and echinoderm material derived from adjacent reefs, as well as the "shell hash" of bivalve fragments.

7.4.3 Significance of Shell Gravel Areas

The shell gravel in Area I consists predominantly of dead Tawera spissa and Glycymeris modesta valves and large fragments of these species. Although shell gravel percentages are very high (mean 90%), there were no live bivalves sampled in the sediments of Area I, and all of the shell material was worn and bored.

In contrast, it was only in samples 65 and 67 of Area III that whole, live Tawera spissa were sampled. Moreover, dead shell in Area III has a much fresher appearance than the shell of Area I.

This indicates that Area III is a shell production area, and from this it can be inferred that shell material is possibly being transported in a north-northeasterly direction to be deposited in Area I. Supporting evidence for this direction of movement also comes from the data presented in Section 7.5, where the upper 0.25 m of a core taken in Area I consisted almost entirely of shell material in the form of worn valves and large fragments (core 4, Fig. 7.7). Immediately beneath the shell layer in core 4 were buried fine sands, which are exposed adjacent to the gravel deposit as the inner shelf fine sand facies. This also suggests that the shell gravel facies of Area I has migrated in a north-northeasterly direction over the inner shelf fine sand facies.

In Area II the low (8%) gravel carbonate values suggest that there is neither production nor deposition of large amounts of shell in this area. There is also a high proportion of pebbles and cobbles, and a low proportion of sand in this area (samples 83, 84, Fig. 7.4). This further indicates the non-depositional nature of this area. It is therefore interpreted to be an armoured, lag deposit.

Area IV, based on total sample characteristics, their spatial distribution, and shell contents, appears to be an area of sandy gravels with lower shell contents. As discussed earlier, this gravel area probably has a thin, variable cover of fine sands deriving from either the shoreface or the inner shelf area (Fig. 7.5). Moreover, this area does not appear to be related to the main body of the deposit in terms of sediment characteristics, i.e. to Areas I and III.

7.4.4 Sand Fraction

This discussion of the carbonate content in the "sand" fraction of Pataua samples can be divided into (i) samples which are from the finer fraction ($<0.0\ \phi$) of mostly gravel samples, and (ii) samples which are wholly fine sand. The former have been plotted in Fig. 7.6 beside the gravel fraction in the same sample. In general, the carbonate sand fraction is much less (three-five times) than the gravel fraction in the north (Area I), approximately equivalent to the gravel fraction in the middle and south (Area III), and greater (two times) than the gravel fraction for the isolated northwest gravel samples (Area IV).

For the seabed sediment samples which were totally composed of sands (those shown as A, B, C, and D in Fig. 7.4) carbonate contents were determined for the size fractions finer than either $1.0\ \phi$ or $2.0\ \phi$ (Table 7.2). This was done because in some fine sand samples there were coarse tailed fractions which commonly consisted of 90-100% shell. This was especially the case for fine sand samples near the sand/gravel boundary and reef areas. From Table 7.2 it can be seen that the carbonate content of sands varied between 17-35% with a mean of 23%. The highest values were located in the samples nearest the gravel and reef areas (samples 31, 85), while both sand areas shoreward and landward of the gravel deposit had lower values.

Generally, the carbonate content of the fine sand samples are lower and show less variation than that of coarse sand from the mixed sand and gravel deposits. This shows that carbonate content tends to be greater in medium and coarse sands than in fine sands. This is probably because the fine sand is part of the large quantity of Hauraki (B) sands in the area, whereas there are relatively lower

quantities of medium and coarse terrigenous sands derived from local greywacke rocks.

7.4.5 Summary

In the gravel fraction (-1.5 to -3.4 ϕ) of inner shelf mixed sand and gravel sediments at Pataua, shell contents vary from 3-100% with a mean of 41%. In the sand fraction ($<$0.0 ϕ) of the same deposits, shell contents range from 15-63% with a mean of 36%. For fine sand sediments the carbonate content varies from 17-35% with a mean of 23%. There is therefore a steady decline in shell content with a decrease in sediment size, which is thought to reflect the relative quantities of non-biogenic sediment in the area.

It was also possible to identify five separate areas of shell gravel contents. In particular, differences in the shell gravel content of Areas I and III have been used to infer a north-northeasterly sediment transport direction in the main body of inner shelf mixed sand and gravel deposits. Thus, shell has been used as a natural tracer to infer a long term effect. In the following chapter the results of short term tracer studies using prepared sediment show the same direction of sediment transport.

In addition, there are areas of gravel (Areas II and IV) having distinctive size and shell characteristics unlike those of the main body of the deposit. These areas are also inferred to be presently less active than the main body of the deposit.

7.5 SUB-BOTTOM CORES

7.5.1 Introduction

Shallow depth, sub-bottom cores were obtained at four sites within the mixed sand and gravel inner shelf deposits at Pataua (Fig. 7.3). The purpose in coring was to determine the depth of the deposits because this had not been revealed in the inconclusive results of the seismic survey. In addition, the types of sediment beneath the surface were not known. Therefore, coring would also provide samples for the determination of broad sub-bottom sediment characteristics such as sand, gravel, shell, and mud contents. The stratification of a portion of the Pataua inner shelf deposits has also been revealed by coring, and interpretations of this stratification, as well as other sedimentary data, have been used to infer the sedimentary history of the inner shelf area (Section 7.6).

7.5.2 Coring Equipment and Methods

The coring equipment consisted of a 3.5 m long core pipe which was driven into the seabed by a water-hammer device, powered by the water pressure from a jet boat unit (Plate 7.5). This equipment was designed by Mr C. Busck and Mr K. Tarlton, and all of the coring work was carried out from Mr Tarlton's 7 m boat.

The cores obtained using this equipment are 10 cm in diameter. The sediment within the cores is only a little disturbed and maintains the stratigraphic relationships of sub-bottom layers. However, at two core sites the length of the core retrieved was

Plate 7.5 - Water hammer corer with 3 m long coring pipe extending toward the bow. The water hammer device is centrally located and is driven by water pressure through a 15 cm diameter hose from the boat's jet unit.

Plate 7.6 - Pataua cores are, top to bottom, 2, 3-2, 3-1. Core 2, the longest at 2 m, has stiff clay in the lower portion. The other sediments are predominantly gravelly sands and sandy gravels.

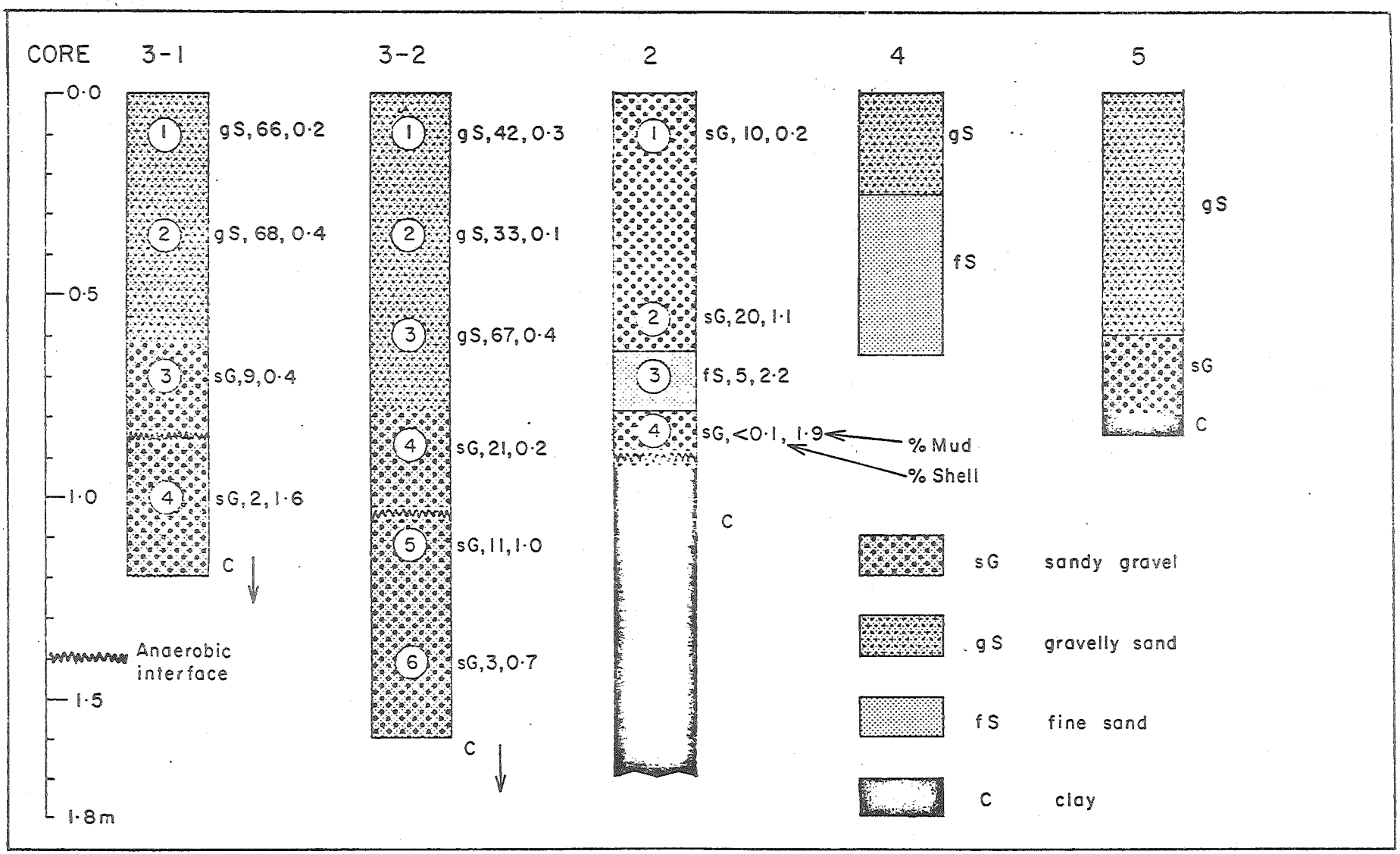

Fig. 7.7 - Pataua sub-bottom cores. Sample numbers (1), (2), etc. refer to Fig. 7.8.

about 20% less than the depth of core penetration. At these sites sample loss on withdrawal from the seabed was thought to be a more likely cause of this problem than sediment compaction within the core. Diagrams of the five cores taken from the Pataua deposit are shown in Fig. 7.7, and three of the cores are shown in their split liners in Plate 7.6. Although cores 3-1 and 3-2 did not retrieve the stiff clay which was present in core 2, there was a coating of clay on the outside lower 0.5 m of the core pipes when they were pulled out. This suggests that clay was penetrated by the coring pipe in cores 3-1 and 3-2.

7.5.3 Deposit Depths

The depth of gravel at core location 3 (cores 3-1, 3-2) is probably in the order of 1.5-2 m (Fig. 7.7). Core site 3 is centrally located within the gravel deposit (Fig. 7.3, 7.5). Towards the shoreward side of the deposit, near cores 2 and 5, the depth of gravel is about 1 m. Therefore, the deposit appears to thin out in a shoreward direction.

Furthermore, diver observations near core site 2 and along the shoreward boundary of the gravel deposit have located exposures of stiff clay on the seabed (Plate 7.4). The presence of this stiff clay at a number of core sites suggests that it forms a basement for the overlying sand and gravel deposits. The clay is a mottled yellow-brown to grey colour with a stiff, "pug-like" consistency. It is very similar to the yellow-brown clay earths which form the mantle cover on adjacent land areas. The clay earths are derived from the deep weathering of greywacke rocks in the area (Taylor et al., 1948). The stiff clay

under the inner shelf deposits is therefore interpreted as a subaerially weathered surface which represents the basement to sedimentary deposits in this area. Therefore, the deposit depths shown by cores 3-1, 3-2, 2, and 5, are not likely to exceed 2 m in the northern half of the deposit. This depth may also apply to the southern half of the deposit since seismic survey results did not show any deeper sub-bottom features here either.

7. 5. 4 Analysis of Sediment Samples from Cores

Fourteen sediment samples were selected for analysis from three cores in order to examine in greater detail the range of sediments present in the deposit (Fig. 7. 7). The samples were analysed for their particle size distributions, coarse shell contents, fines contents, and gravel particle shape. Particle size analyses were done with a sieve set which is normally used for concrete aggregates (British Standards, 1975) and which range from very fine sand (3. 75 $\emptyset$) to large gravel (-5. 25 $\emptyset$), with a 1 $\emptyset$ interval. As with previous size analyses in this study, shell material has been included in the total sample.

Gravel Particle Roundness

Rock particles retained in the -2. 25 $\emptyset$ sieve (small pebbles) were examined for their roundness characteristics using the visual roundness chart of Powers (1953). Except for chert pebbles which were sub-angular to sub-rounded, most of the greywacke pebbles were sub-rounded to rounded, with about 10% being well-rounded. These roundness characteristics did not appear to vary much from one sample to another either between or within cores.

Silt and Clay

Silt and clay were determined as the percentage of sediment passing the very fine sand sieve (3.75 ∅). Silt and clay percentages are small, the highest value being 2.2% (Table 7.3, Fig. 7.7). Generally, fines percentages increase from a low near the surface to a high towards the bottom of the core. Much of this fines content is probably the 0.25% fraction of very fine sand and silt, and therefore is not derived from the underlying stiff clay basement. The fines are more probably derived from silt present at the original time of deposition of the sediments, or have been post-depositionally incorporated. In the latter case, the coarse framework of shelly gravel sediments may cause fine material to become trapped within the lower parts of the deposits.

Furthermore, some indication of the depth to which benthic water is mixed into the interstices of the deposit is shown by the well-marked anaerobic interface which was observed in three cores (Fig. 7.7). The depth of the anaerobic interface in the three cores ranged from 0.85-1.05 m.

Particle Size Distributions

The particle size distribution characteristics of the core samples are presented in Fig. 7.8 and as derived Folk parameters in Table 7.3. Apart from one sample which was fine sand (core 2, sample 3), all of the samples were either sandy gravels or gravelly sands. Sample sorting was poor to very poor, and skewness varied from near symmetrical to coarse skewed. Apart from some strongly bi-modal distributions, kurtosis tended to be mesokurtic to lepto-kurtic (Appendix III).

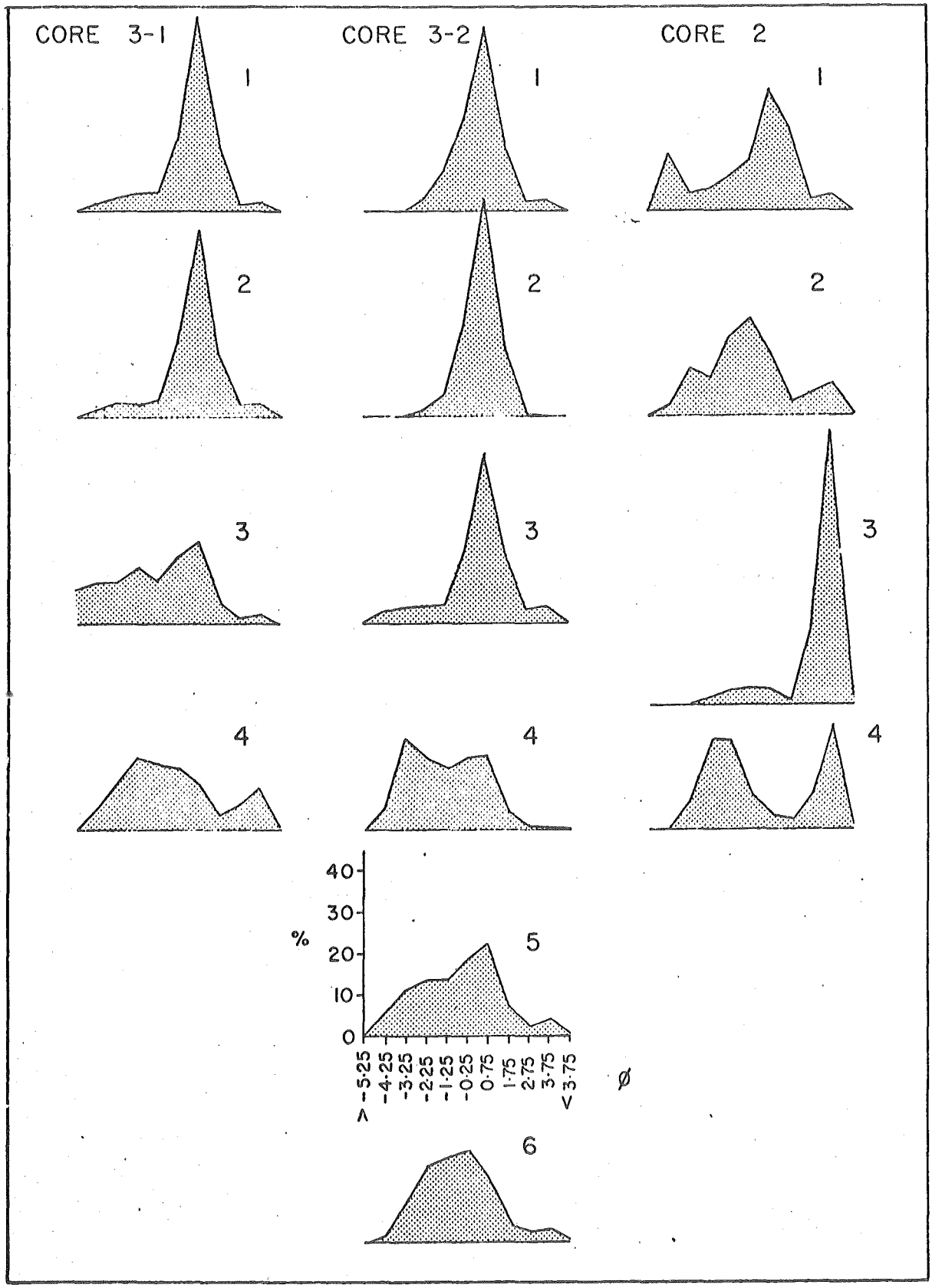

Fig. 7.8 - Particle size distributions of sub-bottom core samples. See Fig. 7.7 for sample depths and positions.

Table 7.3 - Summary of analyses of sediment samples from Pataua cores.

Core Sample Depth (m)	Folk Parameters (ϕ units) M_z	σ_I	Sk_I	K_G	Percent Shell (-2.25ϕ)	Percent Fines (< 3.75ϕ)
Core 3-1						
1 (0.1)	-0.06	+1.30	-0.30	+1.62	66	0.2
2 (0.35)	+0.10	+1.37	-0.14	+1.89	68	0.4
3 (0.7)	-1.91	+2.29	-0.14	+0.83	9	0.4
4 (1.0)	-1.13	+2.90	+0.07	+1.04	2	1.6
Core 3-2						
1 (0.1)	+0.00	+1.07	-0.07	+1.21	42	0.3
2 (0.35)	+0.05	+0.81	-0.12	+1.22	33	0.1
3 (0.6)	+0.01	+1.56	-0.15	+1.78	67	0.4
4 (0.85)	-1.81	+1.69	+0.04	+0.68	21	0.2
5 (1.1)	-1.18	+2.06	-0.08	+1.02	11	1.0
6 (1.4)	-1.31	+1.79	+0.08	+1.07	3	0.7
Core 2						
1 (0.1)	-0.85	+2.28	-0.39	+1.00	10	0.2
2 (0.6)	-0.93	+2.16	+0.10	+1.19	20	1.1
3 (0.7)	+2.71	+1.09	-0.54	+2.48	5	2.2
4 (0.85)	-0.31	+2.45	+0.43	+0.54	< 0.1	1.9

Many of the particle size distributions can be seen to be negatively skewed with coarse fraction tails. As is shown below, this is almost entirely due to a coarse shell contribution. In addition, there were some samples with marked bi-modal distributions. In most cases the bi-modal distributions are considered to be naturally produced. However, for core 2 (sample 4), the bi-modality is likely due to either post-depositional mixing of sample 3 fine sand with sample 4 granule-pebble sediment, or mixing of these adjacent sediments by the agitation of the coring process. In either case, it is thought that the two modes in core 2 (sample 4) represent separate deposits. The granule-pebble mode in sample 4 consists of rounded greywacke particles, is well sorted, and with a very low ($<0.1\%$) coarse shell content. This sediment is interpreted as a relict, gravel beach deposit. The fine sand mode, represented by sample 3, is texturally very similar to present-day shoreface sands in this area. The fine sands of sample 3 are therefore interpreted as having been deposited on top of the beach gravel as a consequence of the shoreward migration of a fine sand shoreface facies during the last post-glacial transgression. The beach gravels in core 2 lie at a depth of about 13.5 m below chart datum and therefore would have been deposited about 8,000 BP, based on Fig. 3.4. The overlying shoreface sand and sandy gravel beds (Fig. 7.7) are therefore probably younger than this age.

Coarse Shell Contents

The shell contents in Fig. 7.7 and Table 7.3 were derived as a weight percentage of sediment retained on the -2.25 $\emptyset$ sieve. The shell retained on this sieve consisted of small (5 mm diameter) whole valves and fragments, usually of Tawera spissa and Glycymeris modesta

The highest shell values were present in the upper sediments of cores 3-1 and 3-2. In addition, although not analysed, the upper 0.25 m of core 4 consisted almost entirely of shell material, with worn whole valves making up 100% of the coarsest fractions. The high shell quantities found in these three cores agrees with the seabed surface samples from the same area as described in Section 7.4 (Fig. 7.6).

In contrast, lower coarse shell contents were present in core 2, a finding which is in agreement with the area of surface samples in Fig. 7.6 (sample 3, and related samples 51, 52, and 53). In cores 3-1 and 3-2 coarse shell contents decreased abruptly with the change from upper core, gravelly sands to lower core, sandy gravels (Fig. 7.7). Within the lower sandy gravel portions of cores 3-1 and 3-2, shell contents averaged about 9%, in comparison to the average of 55% for the upper gravelly sand portions. However, at the base of both cores 3-1 and 3-2, shell fauna was still mostly Tawera spissa, i.e. suggesting an inner shelf environment. Therefore, inner shelf shells are present to the base of the gravel deposits, but this shell material was less frequent at the base of cores 3-1 and 3-2 than at the surface. From this it is inferred that (i) the complete thickness (1-2 m) of the deposits have been mixed thoroughly in an inner shelf environment and (ii) the amount of mixing or production of shell material shows an increase for the top-half (1 m) of the deposits.

As was shown previously, the lower sandy gravel portions of cores 3-1 and 3-2 were very similar to the upper sandy gravel portion of core 2. This similarity suggests that there is a continuous sandy gravel bed which is exposed in core 2, but buried beneath a more shelly, gravelly sand bed in cores 3-1 and 3-2, and probably in

core 5 as well (Fig. 7. 3, 7. 6). In this respect, the gravelly sands are equivalent to shell Area I and transitional between Areas I and III, whereas the sandy gravels represent shell Area III, II and perhaps Area IV (Fig. 7. 6). Therefore, it has been shown that the spatial variations of shell areas in Fig. 7. 6 are correlated with vertical variations in the cores of Fig. 7. 7. From this it can be inferred that the gravelly sand facies has either been formed in situ above the sandy gravel facies, or more likely that the gravelly sand facies has been deposited over the sandy gravel facies through lateral movement. From the spatial and vertical relationships shown in Fig. 7. 6 and 7. 7, the direction of movement is inferred to be towards the northwest to northeast, or generally northward.

Finally, the fine sands in the lower portion of core 4, which were buried by shelly, gravelly sands (Fig. 7. 7), also indicates that in this area the shelly, gravelly sand sediment has probably migrated north-northeasterly from the main area of mixed sand and gravel deposits. Coarse shell contents in seabed surface sediment distributions again support this interpretation (Fig. 7. 6).

7. 6 SUMMARY AND SEDIMENTARY HISTORY

Much field work has been concentrated on the Pataua area because of its small and shallow deposits, and because it is the only one of the six prospecting areas in which beach erosion was considered to be a possible result of inner shelf dredging. The chief work described in this chapter included a seabed surface sediment survey of particle sizes and shell contents, the mapping of these character-

istics with the aid of echo sounder recordings, and the analysis of the sediments and stratigraphy of sub-bottom cores.

From the analysis of 87 sediment samples collected over two years and interpretations from echo sounder recordings from one year, the broad spatial and temporal characteristics of inner shelf deposits have been determined. Three main sediment facies have been identified: (i) a shoreface fine sand facies, (ii) an inner shelf gravel facies, and (iii) an inner shelf fine sand facies. These facies are separated by abrupt boundaries and there is presently little mixing of the sediments. This has been taken to mean that the inner shelf hydraulic environment has either maintained or produced a sorting of extremes of sediment size over short distances (less than 50 m). Although there is little mixing of the facies, changes in facies boundaries occur over yearly and shorter intervals and are caused by the shifting behaviour of thin, covering fine sands. Within the gravel facies, sediment characteristics are not uniform, with varying proportions of gravel and coarse sands forming distinctive sub-areas within the deposit. It has also been inferred that the mobility of sediments varies spatially within the gravel deposit, some areas being interpreted as armoured lag deposits while other areas are active under the existing environment.

Shell makes a significant contribution to the sediment of all the facies but there is a steady decrease in shell content with size: gravel (41%), coarse sands (36%), and fine sands (23%). This trend is thought to reflect the relative availability of non-biogenic sediments in the three size fractions. It was also possible to identify five separate areas within the deposit based on shell contents. Some of

these areas (I, III, Fig. 7.6) are associated with a north-northeasterly sediment transport system while other areas (II, IV, V) are thought not to be involved in the dynamics of the main body of the deposit.

Four, shallow depth, sub-bottom core sites have shown the gravel deposit to be a relatively thin sheet (1-2 m thick), overlying a basement of clay which was interpreted as a subaerially weathered surface. The analysis of 14 sediment samples and core stratigraphy has shown that, in most of the deposit, inner shelf shells are thoroughly mixed to the base of the sediments. However, shell content increases abruptly in the top-half of the northern portion of the deposit, indicating that either the process of in situ shell incorporation decreases with depth or that the availability of shell material has increased over time. It is also likely that the upper core, gravelly sand sediments of the northern portion of the deposit have been deposited over lower core sediments by a north-northeasterly directed sediment transport system. In addition, relict beach gravels and shoreface fine sands were interpreted at the base of the predominantly sandy gravel southern portion of the deposit.

Implications for Dredging

Many research findings made in this study militate against the possibility of beach erosion occurring as a result of inner shelf dredging at Pataua. First, although both beach deposits and inner shelf gravel deposits contain appreciable amounts of a coarse sand fraction, a shoreface fine sand facies intervenes between these two deposits. Moreover, there is presently no surfical connection between these two deposits based on contemporary seabed sediment distributions. Second, the clay basement which is exposed near the shoreface/inner

shelf boundary would prevent any dredging taking place below this depth and therefore limit "drawdown" of beach and shoreface sediments into dredged areas. Third, the uniform thinness of the deposits (being 1-2 m) means that if this sheet of sediment was stripped off by dredging there would be relatively little change in the present regular inner shelf bathymetry. Therefore, there would also be little change in existing wave refraction patterns so that beach configuration should not change. Fourth, the movement of inner shelf gravel sediments, as determined in this chapter by tracing shell distributions and from stratigraphy, and in Chapter Eight using artificial tracers, is seaward or to the north-northeast. Whether this direction of movement also applies to coarse to fine sands is not known, but the existence of the shoreface fine sand facies suggests that at least medium and coarse sands are not presently moving toward the beach in appreciable quantities. In conclusion, although Pataua was the only area in which beach erosion from inner shelf dredging was considered a possibility, now this relationship does not appear to be likely based on the criteria outlined above.

Sedimentary History

By combining information on the distribution of seabed sediments, shell contents, sub-bottom profiles, and cores, the following sedimentary history is proposed for the inner shelf deposits at Pataua.

(i) The stiff clay found at the base of cores and exposed on portions of the seabed has been inferred to be a subaerially weathered surface, and thus represents the immediate basement beneath marine sedimentary deposits. This clay sub-surface probably occurs at a uniform depth of 1-2 m below the seabed since there were no indications of channel-like features in any of the sub-bottom profiles.

(ii) The gravel at the base of core 2, which is immediately above the clay basement, was interpreted as a relict beach which was created about 8,000 BP when the rising sea level transgressed over this point. However, in other cores only sandy gravel sediment mixed with inner shelf bivalves was found above the clay basement. Although the original source of the gravel may have been fluvial or some other non-marine environment, none of the present deposits have distinctive fluvial or estuarine sedimentary characteristics (such as fines contents or shell fauna). Therefore, the gravel appears to have been completely reworked in a beach or shoreface environment over 8,000-6,000 BP, and then bypassed by the transgressing shoreline to be left as a sheet in inner shelf areas.

(iii) Before, during, and after the processes in (ii) were occurring, large quantities of Hauraki (B) sands were being transported from the south into the Pataua embayment. These fine sands have not been mixed with the coarse sand and gravel inner shelf deposits, and instead have been transported shoreward to form the prograded shore of Pataua Beach and the adjacent shoreface fine sand facies.

(iv) Subsequent to the sea level stabilisation of about 6,000 BP, the sheet of bypassed gravel has been altered within an inner shelf environment so that today inner shelf shell fauna has been thoroughly mixed to the base of most of the deposit. In addition, the modern hydraulic environment appears to be producing a north-northeasterly transport of sediment in the main body of the deposit. Therefore, the inner shelf deposits are still evolving in terms of their sediment characteristics and the spatial distribution of the sediment facies.

CHAPTER EIGHT

CONTEMPORARY SEDIMENT MOVEMENT STUDIES

8.1 INTRODUCTION

Much of the environmental concern expressed about Landsea Minerals' proposal for seabed dredging has focused on two possible effects. The first effect is the change in seabed topography which will be directly due to dredging, and the persistence in time of this dredged-induced topography. The second effect stems from the direct removal of sediment which may form part of a natural sediment transport system on the inner shelf, or between the inner shelf and adjacent beaches.

The relative importance of these two effects depends to a large degree upon the contemporary mobility of inner shelf sediments. For example, if sand and gravel are sufficiently mobile, then the recovery of a dredged area will be relatively rapid and there will be a progressively decreased effect from the dredged-induced topography. At the same time, the rate and direction of movement of mobile inner shelf sediments may indicate the manner in which this material is involved in natural sediment transport systems.

The research to be discussed here can be considered under the general subject of the mechanics of sediment movement. Although this subject has received a great deal of study, as reviewed by Raudkivi

(1967), Graf (1971) and Yalin (1972), the majority of this work has been devoted to understanding uni-directional flow in channels, i.e. excluding progressive gravity waves. Furthermore, basic research in this field has been made difficult by a number of problems. Chief among these is the complex nature of sediment transport processes, which are controlled by many interrelated time and space dependent variables. This problem has usually prevented either a completely inclusive, or totally rigorous analysis of sediment transport processes. Therefore, a subjective element usually remains and choices must be made between different approaches to the problem. In this last respect, and with particular reference to the seabed transport of sand and gravel by wave action, three study approaches are usually taken. They are (i) theoretical, (ii) laboratory or scale model, and (iii) field experimentation.

8.1.1 Theoretical Approach

Theoretical studies of sediment movement by wave action have been carried out by many researchers (see reviews in Bagnold, 1963; Inman, 1963; Raudkivi, 1967, pp. 253-306; and Teleki, 1972). However, many of the phenomena controlling sediment movement in nature are as yet not well defined. For example, the wide spectrum of real ocean waves is often simplified by assuming a narrow spectrum of design waves. Also, little is known of the manner of alteration of oscillatory free stream wave velocities to actual seabed velocities in the bottom boundary layer. Furthermore, much more work has been done on the theory of sand movement, than on gravel or mixed sand

and gravel movement. Also of significance is the fact that much of this theory still lacks extensive field application and verification.

8.1.2 Laboratory Approach

The laboratory or scale model approach to sediment movement by wave action has been investigated extensively by Bagnold (1946), Manohar (1955), Yalin and Russell (1963), and Carstens et al. (1969). However, according to a recent summary of this work by Komar and Miller (1975), there is a lack of field data to support the laboratory studies. Moreover, until the recent use of full scale wave action in pulsating water tunnels (Silvester, 1974, p. 305), modelling studies with gravel-sized sediments have suffered from scale distortion problems. Of the more recent laboratory studies, that of Rance and Warren (1968) has provided the most realistic conditions for gravel movement under wave action. They were able to derive predictive data on the threshold movement of flat beds of uniform sized gravel particles. For the case of a 25 mm diameter particle, a maximum oscillatory velocity of 1.4-1.6 m/sec near the bed is required to initiate movement. At water depths of 20 m, rather large waves of either T = 10s, H = 5 m; or T = 12s, H = 4.5 m, are required to give oscillatory velocities of this magnitude (CERC, 1973, p. 2-37). This approach cannot supply a complete answer though, since the method only describes conditions for the threshold of movement. The more important rates and directions of subsequent movement cannot be predicted in this way, and must be determined for individual localities from field studies.

8.1.3 Field Approach

Field approaches to the study of sediment movement are of two main types based on time: long term and short term. Studies of sediment distribution patterns and bathymetric changes determined over years will yield long term data on the amount and direction of sediment movement. This approach has been used by Watts (1963), Gorsline and Cook (1972), Dickson and Lee (1973a; 1973b), and Carter (1977). This approach was also used in the previous chapter of this thesis to infer long term sediment movement at Pataua.

Shorter term studies which attempt to measure or infer processes and sediment transport responses are more common, and include estimates of sediment activity from wave and current meter data, bedform dynamics studies, and seabed photographs (Inman and Nasu, 1956; Inman, 1957; Sternberg and Creager, 1965; Komar et al., 1974; Sternberg, 1972; Carter, 1976; 1977). Sediment traps are sometimes used to measure suspended and bedload sand movement (Cook and Gorsline, 1972), and sediment tracer techniques have been used to measure seabed gravel movement under wave action (Crickmore et al., 1972). The use of these techniques will be discussed further at relevant points in the following sections.

8.1.4 This Investigation

The work presented here deals with the processes and responses of contemporary sediment movement on mixed sand and gravel inner shelf deposits. The study approach taken has been largely field oriented and concentrates on short term sediment movements. At

the same time, theoretical approaches and results from laboratory studies have been used where they are considered to be explanatory and applicable.

The specific features of sediment movement to be covered include measurements of wave conditions, bedform dynamics, changes in the seabed level, the frequency and magnitude of movement of gravel sized particles, and the manner in which bottom wave surge is affected by seabed bedforms.

All of these studies were conducted on a seabed site (Fig. 8. 1) located near core site 3 in the centre of the mixed sand and gravel deposit at Pataua (Fig. 7. 3). The water depth at this site is about 17 m below chart datum and is therefore at a depth of 17. 3 m during MLWS and 19. 3 m during MHWS tides. A number of seabed process experiments were established at this site in early January, 1977 with observations being taken over a four month period until late April, 1977.

8.2 PHYSICAL ENVIRONMENT

8. 2. 1 General

The physical environment conditions along the east coast of Northland (as described in Chapter Four) apply in general to the Pataua area. Therefore, this section outlines more specifically some observations which have been made at Pataua.

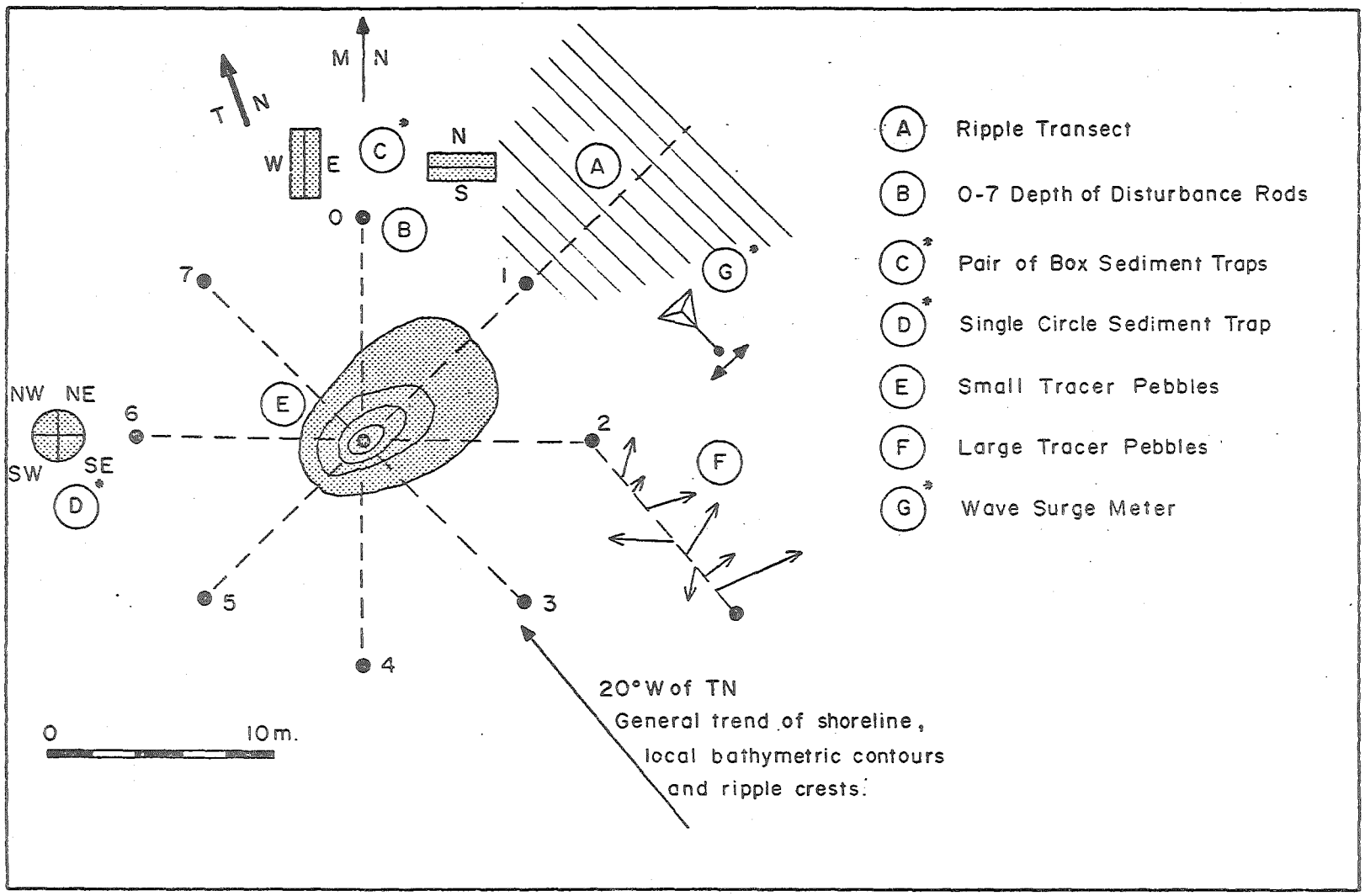

Fig. 8.1 - Pataua seabed processes study site (near core site 3, Fig. 7.3), at a depth of 18 m on mixed sand and gravel inner shelf deposits. Experiments C*, D*, and G* drawn at a slightly enlarged size.

The north to south moving East Auckland Current, which lies offshore, probably does not influence circulation within the embayment which contains the Pataua deposit. Tides in the Pataua embayment have a spring range of about 2 m, and a neap range of 1 m. Tide generated currents are slow moving except in the vicinity of the inlet to the Pataua Estuary. The ebb tide current issuing from the inlet extends its influence out into the bay in a north to northeasterly direction (Plate 4.2) and has been observed to produce discoloured water as far away as the seabed process study site. This ebb flow phenomena may be enhanced during flood conditions in the Pataua River. In addition, a very slow (<0.01 m/sec) north directed current was observed from drifting seaweed fragments on the bottom at the study site. This current may be related to ebb tidal flow from the inlet and within the embayment. All of these currents can be considered as representing calm weather conditions.

Stronger currents are generated by wave motion during calm weather, and are combined with wind and surge driven circulations during storm periods. The strength and pattern of the latter currents is not known for the study area, but as shown from studies in other coastal areas (Murray, 1970; 1971; 1972; and Carter and Heath, 1975), wind driven currents may be significant in determining net water motion during storm periods.

8.2.2 Wave Conditions

More is known of wave conditions at Pataua since observations were made at the study site at various times during a four month period. All of these observations have been summarised in Table 8.1

showing the eight major wave events which have been defined. Estimates of wave characteristics for these events were made from shore-based visual observations. In addition, smaller, fair weather wave events were recorded using the echo sounder of the diving boat (Table 8.2). This procedure yielded 15 minute duration wave records which were analysed for significant wave period and height. Discrepancies between Table 8.1 and 8.2 are small and are due to slight differences in the methods of recording and reporting wave conditions in each Table.

From Tables 8.1 and 8.2, it can be seen that wave conditions varied considerably over the four month study period and consisted of three main types of wave conditions:

(i) Northeasterly to easterly storm conditions were associated with depressions located near the coast (wave events A, C, D, F). The largest of these was event F (20-24 March, 1977) which produced maximum wave heights of 3-4 m;

(ii) Northeasterly swell conditions in four other periods (events B, E, G, H) produced a maximum of 2 m wave heights with wave periods of 10-12 s. The last wave event (H) produced uncommonly large, long period swell of 14-15 s period, arriving at the coast from the southeast from an unknown source.

(iii) Periods between major wave events were characterised by relatively calm weather, usually with offshore winds. The period 12-15 April provided one of the most valuable records of these periods since swell waves were recorded and observed to have produced seabed sediment movement (Sections 8.5, 8.6).

Table 8.1 - Major wave events at Pataua which produced seabed sediment responses during the study period January-April, 1977.

Event and Date	Type and Cause of Waves	Significant Wave Characteristics Height (H, m) Period (T, sec)
(A) 7-10 Jan.	Northeasterly seas from coastal depression	H = 1.5-2 T = 8-10
(B) 19-24 Jan.	Northeasterly swell from tropical cyclone June	H = 1-1.5 T = 12
(C) 5-10 Feb.	Easterly seas followed by easterly swell	H = 1.5-2 T = 11
(D) 13 Feb. - 4 March	A period of episodes of easterly winds and seas	H = 1-1.5 T = 8-10
(E) 11-13 March	Northeasterly swell from offshore depression	H = 1.5 T = 11
(F) 20-24 March	Northeasterly seas from coastal depression	H = 3-4 T = 8-10
(G) 8-15 April	Northeasterly swell, source unknown	H = 1-1.5 T = 10-12
(H) 23, 24 April	Southeasterly swell, source unknown(1)	H = 1.5-2.5 T = 14-15

(1) Observed at Ocean Beach only.

Table 8.2 - Summary of wave statistics from echo sounder records taken at Pataua seabed process study site.

Date	Hmax (m)	Hs (m)	Ts (sec)	Comments	
10 Feb.	1.3	0.9	10.5	Swell	
9 Mar.	1.0	0.6	10.1	"	
10 "	1.0	0.8	10.7	"	
14 "	1.0	0.8	11.5	"	
16 "	1.3	0.9	5.7, 10.0	Sea and swell	
18 "	1.0	0.7	5.5, 9.5	"	
19 "	1.3	0.9	9.6	Swell	
4 Apr.	0.8	0.6	9.7	Low swell	
5 "	0.6	0.4	9.9	"	
6 "	1.8	1.0	6.5	Seas	
7 "	1.2	0.7	8.1	Short swell	
12 "	1.0	0.9	11.3	Swell	
13 "	1.1	0.9	11.0	"	Wave
14 "	1.3	0.8	10.6	"	Event (G)
15 "	1.3	1.0	10.3	"	
18 "	0.8	0.6	10.3	Low swell	
21 "	0.7	0.6	12.3	"	
22 "	1.0	0.8	11.6	Swell	

Note: Wave analysis follows the short-cut procedure described in CERC (1973, p. 3-10). The average period of the best formed waves is selected as the significant period (Ts). The height of the wave ranked nearest 0.135 times the total number of waves is taken as the significant height (Hs).

8.2.3 Maximum Horizontal Near-Bottom Velocities

Because bottom orbital velocities are not usually measured, their prediction from theory and surface wave characteristics is a necessary step in most seabed sediment movement studies. In this respect various wave theories may be used which are valid for limiting conditions depending upon water depth and surface wave characteristics. According to CERC (1973, Fig. 2.7), linear Airy wave theory is valid for the study site depth of 18.3 m until combinations of wave height and period exceed about H = 0.5 m, and T = 8-12 s. For wave heights ranging from 0.5 to 5 m, Stokes' second order theory is considered to be more valid.

Fig. 8.2 shows the maximum horizontal near-bottom velocities calculated using Stokes' second order theory. The velocities represent a variety of wave period and height conditions which are likely to be experienced at the seabed study site. These are so-called "free stream" velocities, which are wave orbital velocities not affected by boundary conditions. They therefore represent theoretical velocities near the bottom which are probably altered closer to the seabed by the presence of the bottom and any bedform roughness elements. This aspect of alteration of free stream velocity near the seabed is investigated further in Section 8.7.

It is also interesting to note that for wave heights less than 2 m, the addition of the Stokes component to the Airy component of velocity is less than 4% of the Airy component. Therefore, for wave heights less than 2 m, the more easily computed Airy theory may be used. The use of Airy theory is also relevant since many of the

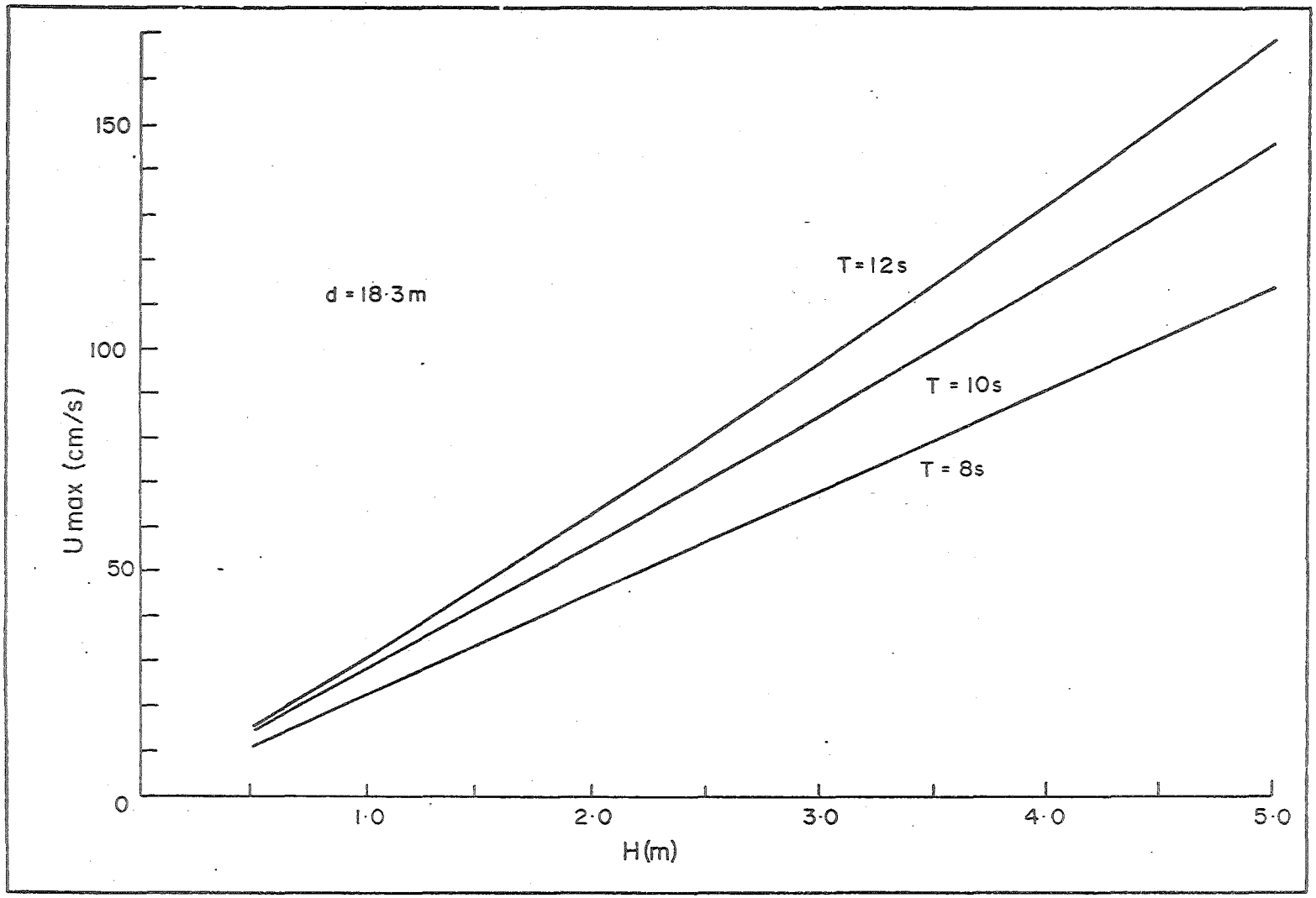

Fig. 8.2 - Theoretical maximum horizontal velocity (Umax) for near-bottom free stream conditions at the process study site. Umax is calculated using Stokes second order wave theory for conditions of wave height (H) and period (T) shown.

predictive equations which have been developed to describe states of sediment motion and bedform formation also use Airy theory (Manohar, 1955; Carstens, 1966; Komar and Miller, 1975).

8.3 BEDFORM DYNAMICS

8.3.1 Introduction

As can be seen in Plates 7.1, 7.2, and 8.1, the surface of the inner shelf mixed sand and gravel deposit is completely covered with large symmetrical bedforms. The bedforms display a number of characteristic features:

(i) At any one time bedform geometry is usually very uniform, with little variation in wavelength, height, and crestline orientation;

(ii) The bedforms have crest to crest wavelengths of about 90 cm, and trough to crest heights of about 15 cm, but this varies temporally with changes in wave conditions (Table 8.3);

(iii) Bedform crests are straight and extend continuously for 5-10 m in lines oriented approximately parallel with the shoreline of Pataua Beach (20^{o} west of north). The crest lines are thus perpendicular to the direction of landward-seaward bottom wave surge motion; and

(iv) Bedform crests typically consist of finer, better sorted sediment than is present in the intervening troughs (Fig. 8.3).

Symmetrical bedforms of this type have been reported in field studies (Inman, 1957; Cook and Gorsline, 1972) and generated in laboratory wave tanks (Bagnold, 1946; Manohar, 1955; Yalin and Russell, 1963; Carstens et al., 1969). From this work it has been

Plate 8.1 - Symmetrical dune bedform at 18 m depth in shelly, gravelly sand at Pataua. Dune height = 14 cm, wavelength = 100 cm. Each square division is 5 cm.

Plate 8.2 - Degraded dune bedform. Sediment sorting and dune morphology is not as well defined as in Plate 8.1. Also note bioturbation feature near end of knife (30 cm long).

found that bedform size increases with sediment size. The bedforms described in this study represent some of the largest of this type which have been observed in nature. The bedforms can probably best be described as dunes on the basis of their size and the size of sediment in the crests (Simon et al., 1965; Carstens and Nielson, 1967; Allen, 1970, p. 70). Terms such as "wave-ripples" and "megaripples" may also be appropriate.

8.3.2 Sediment Sorting Within Dune Forms

Both Inman (1957), and Cook and Gorsline (1972), found from field studies that sediment within dune forms is sorted into two distinct size populations, so that extremes of size and sorting exist at the dune crest and trough. For seabed sediments finer than 0.5 mm, dune crests are coarser than troughs, while for sediments coarser than 0.5 mm the reverse is the case, i.e. crests are finer than troughs. The development of these sediment sorting patterns appears to depend upon two factors: (i) the availability of different sediment sizes, and (ii) the competence of bottom wave surge to sort sediment within the dune form.

When there is an abundance of sediment finer than 0.5 mm, then bottom wave surge will interact with the dune form so that at the ripple crest, where turbulence and lift forces are most intense, only the coarsest of the transportable material will be selectively deposited. Finer sediment is placed in suspension by the vortex at the dune crest and settles into the trough. When sediment is coarser than 0.5 mm, with a relative shortage of medium to fine sands, then the competence of the higher bottom wave surge velocities selectively deposits coarse

to very coarse sands on dune crests and leaves coarser sediments (pebbles) in the troughs. The significance of dune crest sediment size is further demonstrated by Inman's observation that it is this particular sediment, along with bottom wave surge characteristics, which determines the dune size characteristics of height and wavelength.

The nature of sediment sorting within the Pataua dune forms is shown in Fig. 8.3. The dune crest sediment predominantly consists of coarse to very coarse sands, while the trough consists of the same sediment, plus about 38% gravel sized sediment. In the terminology of Folk (1974) the crests are moderately well sorted, slightly gravelly sands, while the troughs are poorly sorted, sandy gravels. In addition, trough sediments contain a fine sand fraction (mode 3.0 ϕ) which is not present in the crest sediment. It is probable that this fine sand has been placed into suspension by the higher velocities and the vortex motion at the ripple crest, and has settled into the dune trough.

In summary, the sediment sorting observed in dune forms on the Pataua seabed indicates the separate response of three sediment fractions to bottom wave surge:

(i) Sediment which is too coarse to be formed into dune crests by waves is generally confined to troughs (gravel coarser than -1.5 ϕ);

(ii) Sediment which forms the dune crests is in abundance and mobile (1.0 to -1.0 ϕ). This is the significant dune sediment size according to Inman (1957).

(iii) Sediment which is too fine for the turbulent motion of the dune crest environment is kept in suspension and only a small amount finds its way into dune trough sediments. The process which keeps fine sand suspended probably also accounts for the development of the abrupt boundaries

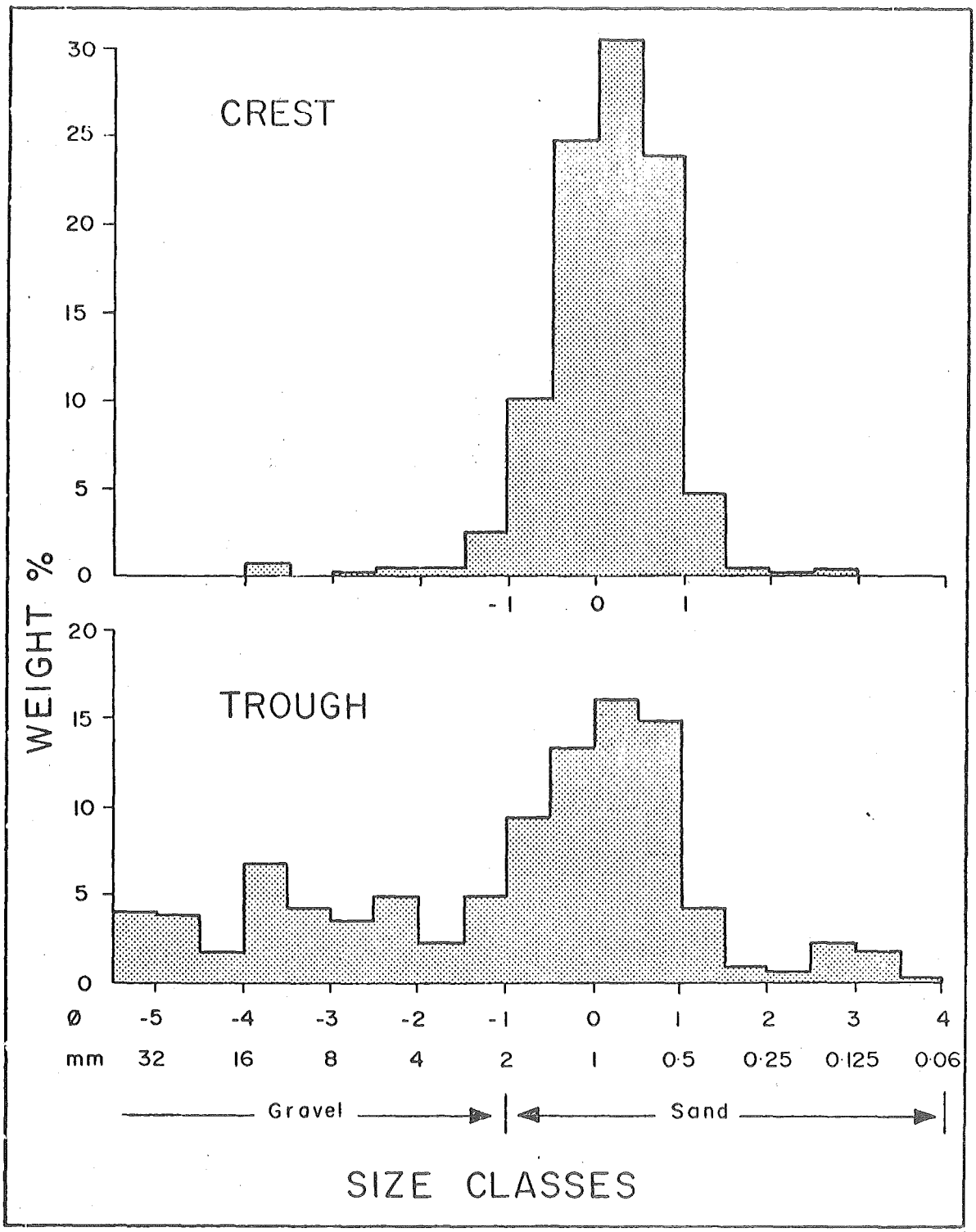

Fig. 8.3 - Particle size distribution of dune crest and trough sediments at the process study site. Note that crest sediments are predominantly coarse to very coarse sands.

between the inner shelf gravel and fine sand facies which were described in Chapter Seven.

8.3.3 Measurement of Dune Dynamics

The existence of wave-formed seabed dunes is an indication of the mobility of mixed sand and gravel inner shelf sediments. In order to further define the short term mobility of the dunes an observational procedure was established at the Pataua site. Dune dimensions (wavelength, height, and orientation) were measured at various times over the study period (Table 8.3). Wavelength was measured to 5 cm, height to 0.5 cm, and orientation to 5^{o}.

Each value in Table 8.3 represents the mean of 6-12 individual measurements which were taken continuously along a transect across the dunes at each observation time (Fig. 8.1). The wave event associated with each set of dune measurements is also included in Table 8.3. The results show the dynamic nature of dune bedforms over the study period. The largest dunes were recorded on 11 February and were formed in response to large swell waves from the easterly quarter. Conversely, the smallest dunes on 4 March, had been produced by locally generated easterly seas. Orientation of dune crests over the observation period averaged about 20^{o} west of north, which is parallel with the local shoreline orientation. However, fluctuations in orientation from 10^{o} - 25^{o} west of north indicates that wave approach is not constant, especially from the eastern quarter. When the complete series of measurements in Table 8.3 is considered together, it is apparent that dune morphology changed frequently and

Table 8.3 - Summary of dune dimensions. Each dimension represents the average of 6-12 field measurements

Date	Height (cm)	Wavelength (cm)	Height / Wavelength Ratio	Orientation (^{o} west of TN)	Shape Type	Related Wave Event (see Table 8.1)
27 Jan.	14	90	0.156	25	trochoidal	(B) H = 1-1.5 m T = 12 sec
28 Jan.	13	85	0.153	20	"	"
4 Feb.	12	85	0.141	25	degraded	"
11 Feb.	19	130	0.146	15	solitary, flat trough	(C) H = 1.5-2 T = 11
4 Mar.	8	70	0.114	10	immature development	(D) H = 1-1.5 T = 8-10
9 Mar.	8	70	0.114	15	degraded	"
18 Mar.	12	85	0.141	20	-	(E) H = 1.5 T = 11
4 Apr.	low amplitude	short crested	-	-	non-uniform, short crested	(F) ?
12 Apr.	17	105	0.162	20	trochoidal	(G) H = 1-1.5 T = 10-12

that the threshold of movement of dune crest material was probably exceeded about 25% of the time during the study period.

Dune shape was also variable. Freshly formed dunes had peaked crests and flat troughs with either a "trochoidal" or "solitary wave" type of cross-section. But, with time (27, 28 January to 4 February), dune crests became degraded and lowered. This process of degradation was caused by relatively weaker bottom wave velocities flattening the tops of the crests. This occurred through the removal of sediment from the crests which was then re-deposited on the sides of the troughs. Bioturbation was also a factor in the degradation of dune morphology (Plate 8.2).

At other times, dunes were observed, but not measured. For example, on 4-6 April dune morphology was unusually non-uniform, with low amplitude, degraded crests which had been formed by a wide spectrum of waves (both sea and swell, Table 8.2). It is also interesting to note that soon after this period, the commencement of only moderate swell conditions produced relatively large dunes (12 April, Table 8.3). This suggests that dunes observed after larger wave events probably reflect only the influence of the more moderate waves during the dying stages of an event, rather than the largest waves during the peak of an event. Here, the only criterion for dune formation is that waves have bottom orbital velocities which are high enough to move sediment into dune forms. The validity of this observation is examined in the following comparison with previous studies.

8.3.4 Comparison with Other Studies

A limited number of laboratory and field studies have been carried out on symmetrical dunes formed by oscillatory wave currents. It is worthwhile to examine these in light of the short observation period which was available for field work in this study.

Dune Height/Wavelength Ratio

From the field measurement of large dunes (50-100 cm wavelengths), Inman (1957) reported height/wavelength ratios of 0.14 - 0.18. Carstens (1966) and Carstens et al. (1969) showed from the observation of dunes in a pulsating water tunnel that, when dunes are fully developed, a mean height/wavelength ratio of 0.174 is achieved with values ranging between 0.148 - 0.206. Dingle (1975) stated from a combination of laboratory and field studies that the ratio is constant at 0.15.

The dune height/wavelength ratios shown in Table 8.3 are slightly less than those cited above with the two largest (0.156, 0.162) approaching Carstens' mean of 0.174. It is perhaps significant that the occurrence of the two higher values in this study were associated with dunes which had recently formed or were actively being formed by swell wave action (wave events B and G). These dunes may thus have been closest to representing equilibrium forms, and therefore similar to those formed in the laboratory studies. As a consequence of this, it would appear that equilibrium dune development is only approached, rather than achieved in the field. This is probably because of field wave characteristics which normally have a wider spectrum of heights and periods than is present in laboratory studies.

Laboratory studies, in which it is possible to closely control aspects of wave-sediment interaction, are of value in simulating forms

of sediment motion and bedform development which occur over a complete range of wave conditions. The study of Carstens et al. (1969) is appropriate here because full scale water motions over a bed of coarse sand were used to produce large dunes. From many individual experiments Carstens developed a sediment number (Ns) which was used to define different levels of sediment motion and bedform configuration associated with different maximum bottom velocities, where

$$Ns = Umax \Big/ \left[(s-1)\, g\, D_{50} \right]^{\frac{1}{2}}$$

Ns - Carstens' dimensionless sediment number

Umax - maximum, bottom, oscillatory velocity

s - sediment to fluid density ratio, about 2.57 for sands in sea water

g - gravitational acceleration

D_{50} - median particle diameter

Using particle diameters (D_{50}) of 0.5, 1, and 2 mm for dune crest sediments, it can be seen from Fig. 8.4 that a linear increase in Ns occurs with an increase in Umax. Also shown in Fig. 8.4 are a number of Ns levels which correspond to critical threshold or ranges of sediment motion and bedform configuration. Of particular interest are the conditions for (i) Ns = 2.3 for incipient motion on a duned bed and the induced formation of dunes, and (ii) Ns = 6.5 for the upper limit of two-dimensional dunes. Thus, for Ns = 2.3, dunes can be induced to form if a proturbance such as an existing ridge of sediment is present, otherwise for smooth beds a value of Ns = 4.9 is required for spontaneous dune formation. It can also be seen from Fig. 8.4, that for D_{50} = 2 mm, and for Ns = 2.3, then Umax = 42 cm/sec; and for Ns = 4.9, then

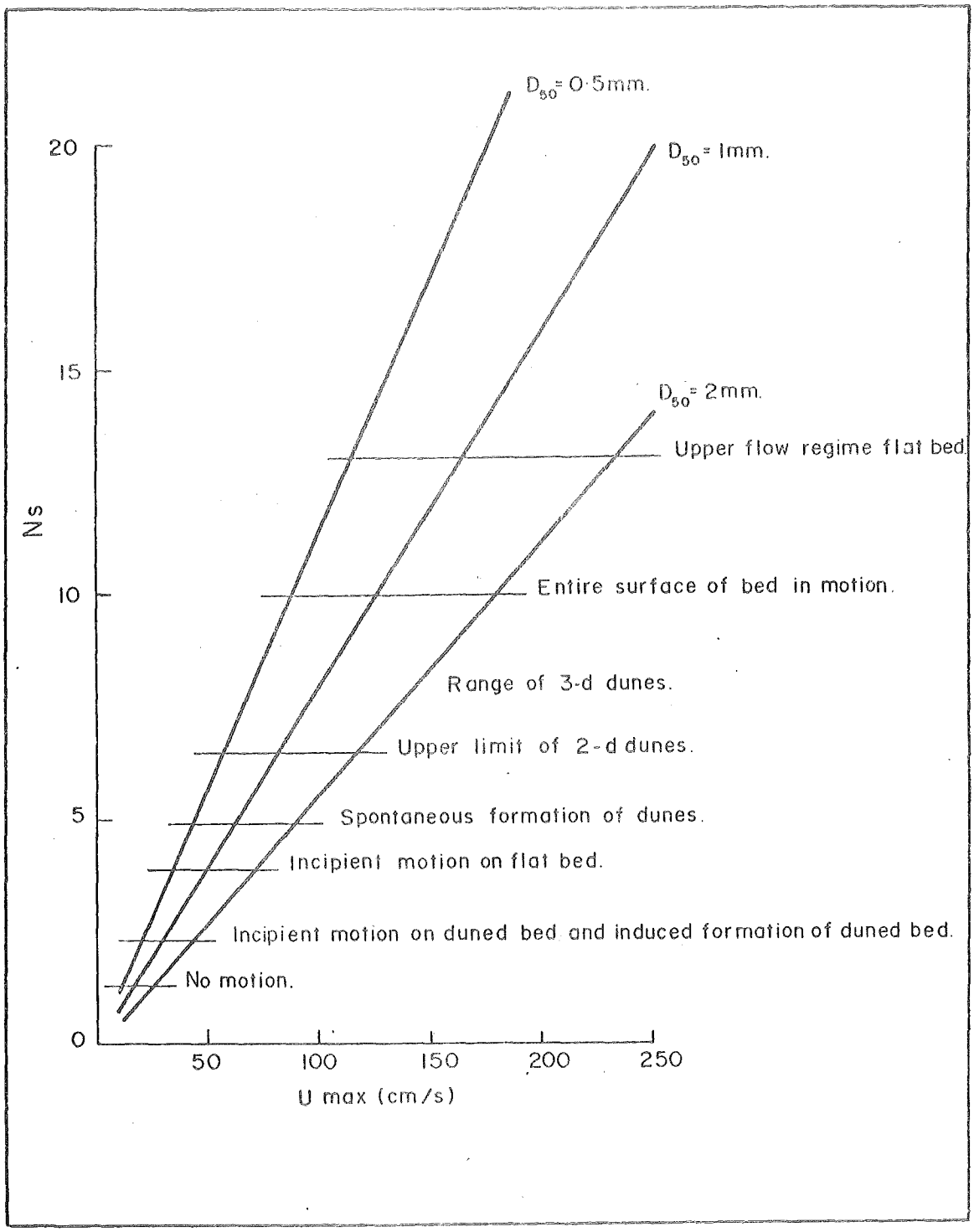

Fig. 8.4 - Sediment movement and bedform configuration states in terms of Carstens sediment number (Ns). The attainment of particular Ns value flow conditions is dependent upon sediment size (D_{50}) and maximum horizontal near-bottom velocity (Umax). Note that for spontaneous formation of dunes that Ns = 4.9, whereas induced dune formation can take place at Ns = 2.3 with a lower Umax value.

Umax = 88 cm/sec. This means that the threshold velocity required to form new dunes is reduced by a half when pre-existing dunes are present. Furthermore, the value for incipient motion of sediment is reduced from 70 cm/sec for a flat bed, to 42 cm/sec for a duned bed.

Also of significance is the upper limit of two-dimensional dunes at Ns = 6.5, which corresponds to a Umax value of 82 cm/sec for D_{50} = 1 mm. This means during higher energy wave events, when Umax values exceed 82 cm/sec, that three-dimensional dunes and higher flow regime bedforms may be in existence on the seabed. Umax values of 82 cm/sec would require wave heights of about 2.5-3.5 m over the corresponding range of wave periods of 8-12 sec (Fig. 8.2). Therefore, this confirms the previous observation that the dunes observed after high energy wave events probably reflect the dying wave characteristics of a storm event, rather than those at its peak.

Comparison of Carstens' predictive sediment number method with those of others, both laboratory and field derived, reveals considerable agreement, as shown in Table 8.4. For example, using the wave conditions observed between 4-12 April (Table 8.2), the maximum wave characteristics were not likely to have exceeded H = 1.5 m, and T = 10 sec, and the predicted Umax would be 42 cm/sec (Fig. 8.2). Referring next to Fig. 8.4 for this Umax value, it can be seen that this velocity exceeds the Ns value for incipient motion and for dune formation. Thus, observations on the formation of dunes in the field are in approximate agreement with a number of predictive methods.

In summary, this study of dune bedform morphology, sediments, and dynamics has shown that:

(i) the turbulent motion of dune crest environments keeps fine sand

Table 8.4 - Umax values derived from various predictive methods for determining critical conditions of sediment motion and bedform configuration. For T = 10 sec, D_{50} = 1 mm.

Source and Nature of Predictive Method	Initiation of Sediment Movement and/or Dune Formation (cm/sec)	Disappearance of 2-d Dunes (cm/sec)	Sheet Flow, Flat Bed (cm/sec)
(1) Manohar (1955) Graphed data from laboratory study	36/45	106	no data
(2) Inman (1957) Graphed field data	-/48	94	not observed
(3) Carstens et al. (1969) Equation from laboratory study	36.5 duned bed	103	206
(4) Dingle (1975) Laboratory and field derived equations	47/- smooth bed	79	192
(5) Komar and Miller (1975) Equation derived from the summary of many laboratory studies	37/-	158	-

suspended over the gravel deposit, and probably accounts for the development of the boundaries between inner shelf gravel and sand facies;

(ii) dune morphology was very dynamic, and the threshold of movement of dune crest material was probably exceeded for about 25% of the time over the study period. This is further defined in the following sections; and

(iii) a comparison of field observations with existing theoretical and laboratory derived predictive data showed that, although equilibrium dune development is more often approached than achieved in the field, observations of dune dynamics in the field show approximate agreement with a number of predictive methods.

8.4 VERTICAL CHANGES IN THE SEABED SURFACE

8.4.1 Introduction and Methods

Vertical changes in the level of the seabed surface are caused by processes of erosion and deposition, and give an indication of seabed sediment mobility. Using "depth of disturbance rods", seabed surface changes can be measured for any length of time and under all environmental conditions. This method is therefore especially suited to recording the effects of high energy wave events, when seabed changes are likely to be large and rapid.

Various types of depth of disturbance rods have been used on beaches (King, 1951; Clifton, 1969), and in nearshore and shoreface areas (Inman and Rusnak, 1956; Greenwood and Hale, 1978). In

this study, changes in seabed level were measured using eight steel rods arranged in a circle of 10 m radius (Fig. 8.1). Each rod was 1.5 m long and 1 cm in diameter, and was driven into the seabed leaving 0.5 m exposed. A free sliding washer was then placed on the rod at the initial seabed surface level, with a fixed clip placed just above the washer. In operation, the washer slides down the rod with bed erosion to record the maximum depth of cut, while the net bed surface change (either cut or fill) at the end of the period can be measured in relation to the fixed clip at the initial seabed level. Diver observations showed that bedforms were unaffected by the presence of the rods and that no localised scour occurred around the base of the rods.

8.4.2 Results and Interpretations

The rods were installed on 5 February, 1977. They were next observed on 11 January after wave event A (Table 8.2), and cut and fill were found to be less than 5 cm for all of the rods. Subsequently, on 24 January, the washers were reset at the seabed surface. The next observations of the site on 1 February showed changes of less than 2 cm after a period of low wave energy. The rods were next observed and reset on 4 March, and then finally observed on 14 April. Thus, two relatively long periods of change (1-2 months) were recorded (Table 8.5).

The results in Table 8.5 are mean values for the eight rods. Amounts of change for individual rods varied greatly due to changes in dune trough and crest positions. Therefore, the mean ranges (11.5 and 14.4 cm) are closely similar to the dune heights in Table 8.3.

Moreover, the maximum change for an individual rod was 18 cm, which is also similar to the maximum dune height of 19 cm observed during the study period. Therefore, it would appear that the range of local bed surface changes was of the same order as dune heights.

Table 8.5 - Mean changes in the seabed surface determined from depth of disturbance rods.

Date	Mean Range (cm)	Mean Change (cm)	Corresponding Volume Change (m^3)
24 Jan. - 4 Mar.	11.5	+4.5	+14
4 Mar. - 14 Apr.	14.4	-4.1	-13

Of more interest are the mean changes which in the first period amounted to a net fill of 4.5 cm and in the second period a cut of 4.1 cm. These changes were found to be significant at the 95% level using a weighted sign test (Freund, 1967, p. 316). Thus, over the study period the seabed surface in the area of the experiment was first raised and then lowered by small amounts. When these small vertical changes are multiplied by the area of the enclosed circle of rods (314 m^2), then the corresponding volume changes amounted to 13-14 m^3. These volume changes represent sediment which is either (i) being redistributed within the experiment area in the form of dune crest and trough positions, or (ii) moving into and out of the experiment area in a direction or directions which cannot be determined from this technique. In either case, it has been shown for a three month period that there were appreciable movements of coarse sediment on the seabed at water depths of 17-20 m.

8.5 SEDIMENT TRAP STUDY

8.5.1 Introduction and Methods

Sediment traps have often been used in rivers to measure the uni-directional movement of bedload sediment (Graf, 1971, p. 375-384). However, the use of sediment traps in the marine environment is probably less reliable because of rapidly oscillating, bi-directional sediment movements. The only account known to the author of the use of sand traps in a wave environment is that of Cook and Gorsline (1972). No studies using traps to measure gravel movement in a wave environment were found. Thus, the use of sediment traps in this study has been a novel experience! Moreover, because of resource and time limitations, it was decided to study sediment movement at the one field site over a period of time. Accordingly, deductions of sediment movement are limited to this location only.

Plate 8.3 shows one of the pair of traps that were used for all of the study period (5 January - 20 April, 1977). An additional circular sediment trap was used for a short period, but proved to be unsuccessful. Each of the pair of traps consisted of an oblong metal body which was divided in half by a longitudinal partition. Each half of a trap had a collecting box 100 cm long, 15 cm wide, and 10 cm deep, giving a volume of 15,000 cm^3.

8.5.2 Results and Interpretations

During the study it became obvious that a number of temporal and spatial constraints limited the value of the trap experiment.

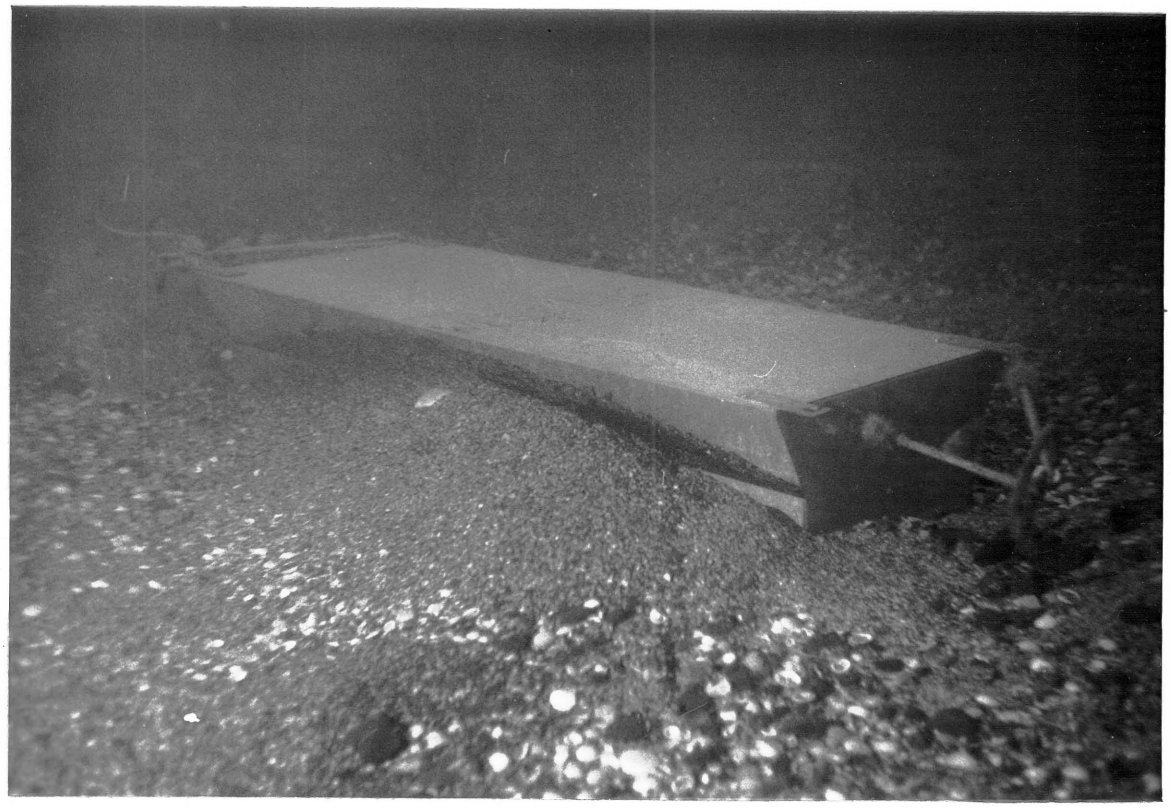

Plate 8.3 - One of the box sediment traps, viewed from the southwest. Note disturbance of natural dune morphology and the selective trapping of the finer (coarse sand) fraction of sediment.

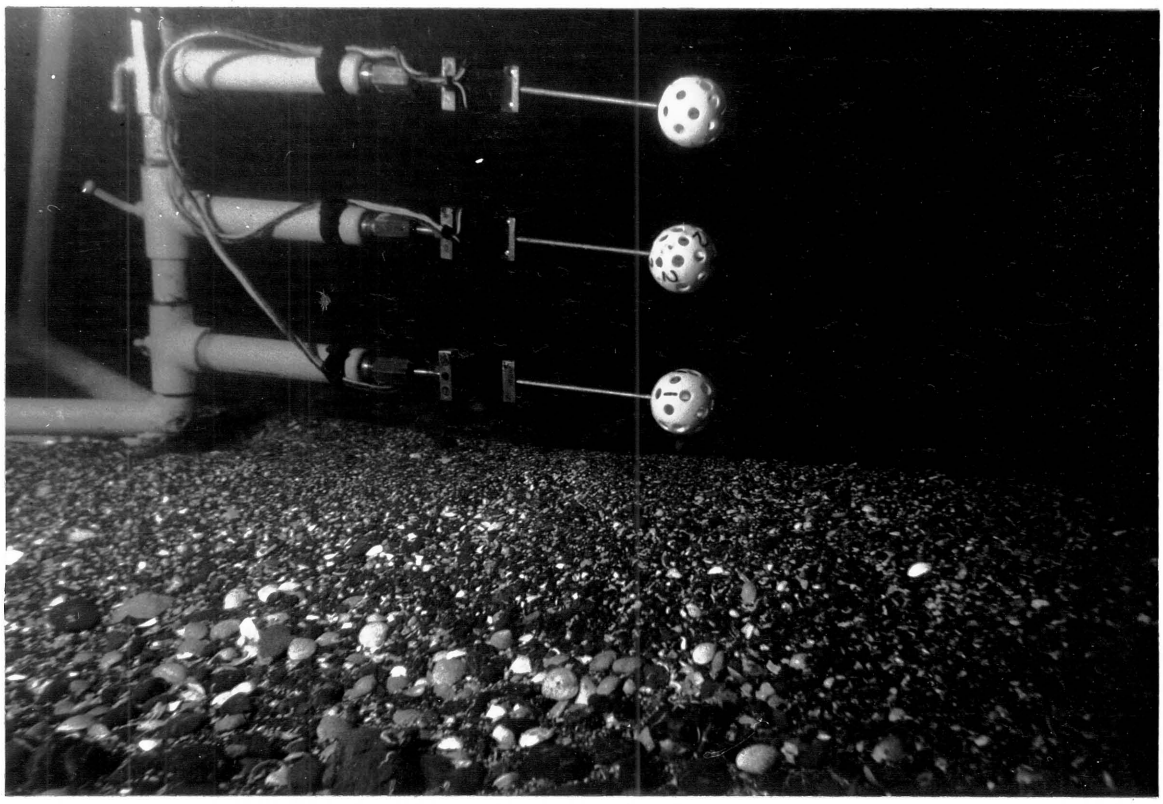

Plate 8.4 - Surge meter aligned over a dune crest. Landward-seaward wave surge motion takes place across the dune crest. Each white perforated sphere has a diameter of 4.2 cm.

Sediment accumulation could be recorded for discrete periods only, starting when the traps were emptied and finishing when they were full or partially full. Thus, the rate at which sediment accumulated could be determined only as an average for a whole period, and in cases when the traps were full, this rate was therefore a minimum. Moreover, in some cases more than one wave event was involved in a sample period. Thus, sediment movement could not always be assigned to a particular wave event. Spatial constraints were due primarily to the uneven nature of the duned seabed surface, and the disturbance of this surface by the presence of the traps. The traps were also selective in terms of the sediment sizes which entered and were retained in the collecting boxes (Plate 8. 3).

The results of the experiment are chronologically listed in Table 8. 6. The weight of sediment in each trap is shown for magnetic directions (Fig. 8. 1), whereas the vector resultants are shown as true directions. The reliability of the resultant vectors is suspect because of the temporal and spatial constraints referred to above. However, it is apparent from Table 8. 6 that, on a broad temporal scale, rates of sediment accumulation can be correlated with different wave conditions. In this context, three levels of sediment accumulation, and therefore mobility, may be recognised:

(i) Periods with none or little accumulation occurred from 25 January - 4 February, and from 4 - 8 March. These periods had wave conditions of T = 10 sec, and H $\leq$ 0. 5 m;

(ii) Periods with moderate rates of accumulation occurred from 8 - 16 March, 6 - 13 April, and 14 - 20 April. Wave conditions during these periods were T = 11 sec, and H = 1. 0 m; and

Table 8.6 - Chronological summary of sediment trap study.

Date	Description
5 Jan.	Set pair of traps.
	Wave Event (A)
11 Jan.	Traps one-third full, set too high to trap sediment.
	Wave Event (B)
24 Jan.	Empty traps. Results (5-24 Jan): N(5.8kg), E(4.7kg), S(7.8kg), W(9.8kg). Resultant vector 5.4kg from 270°.
25 Jan.	No accumulation from previous day even though sediment movement is present on ripple crests. Therefore set traps in deeper.
1 Feb.	Less than 0.5kg accumulation of ripple crest sediment.
4 Feb.	As for 1 Feb.
	Wave Event (C)
8 Feb.	N, S trap completely full; E, W trap two-thirds full.
11 Feb.	N, S trap full (as for 8 Feb.); E, W trap flipped over, partly buried.
	Wave Event (D)
4 Mar.	Reset both traps.
8 Mar.	No sediment accumulation in traps.
	Wave Event (E)
14 Mar.	Traps one-half full.
16 Mar.	Empty traps, now almost full. Results (8-16 Mar.): N(16.5kg), E(12.1kg), S(15.1kg), W(12.7kg). Resultant vector of 1.6kg from 0°. Photograph effects of traps on ripples and scour around traps.
	Wave Event (F)
4 Apr.	Both traps flipped over.
6 Apr.	Reset both traps.
	Wave Event (G)
12 Apr.	Traps three-quarters full.
13 Apr.	Empty traps. Results (6-13 Apr.): N(12.9kg), E(16.6kg), S(12.1kg), W(16.1kg). Resultant vector 0.9kg from 50°.
14 Apr.	Each trap had accumulated about 1 kg since previous day (13 Apr.).
20 Apr.	Empty traps, about three-quarters full. Results (13-20 Apr.): N(13.6kg), E(15.4kg), S(18.7kg), W(20.7kg). Resultant vector 7.2kg from 240°.

(iii) Periods with rapid rates of accumulation were measured after major wave events A, B, C, and F (Table 8.1). Wave conditions during these periods were typified by T = 8-12 sec and H $\geq$ 1.5 m. These sediment mobility conditions apply to particle sizes ranging from coarse sand to granules, since this size range formed most of the trapped sediment.

In summary, the threshold of sediment movement has been shown to occur between wave conditions of H = 0.5 m and H = 1.0 m, for T = 10 sec. For wave heights greater than about 1.0 m, sediment movement increases rapidly. This experiment, like the previous seabed surface changes experiment, has shown that appreciable amounts of sediment movement are occurring on the seabed. However, like the previous experiment, the results are also inconclusive as to the directions and rates of sediment movement. In the following section, descriptions of experiments using sediment tracing techniques have proved to be more successful in defining directions and rates of sediment movement.

8.6 PEBBLE MOVEMENTS USING TRACER TECHNIQUES

8.6.1 Introduction

Sediment tracing techniques have been used in numerous investigations attempting to measure sediment movement in the marine environment (see reviews in Ingle, 1966; Courtois and Monaco, 1969; Nelson and Coakley, 1974). Tracing studies have provided valuable

information on the rates and directions of transport and resulting patterns. In comparison to the sediment trap techniques discussed in the last section, tracer techniques are also considered to be much more established and reliable (A. J. Raudkivi, University of Auckland, pers. comm., 1975). However, with respect to this investigation, it is significant that the vast majority of marine sediment tracing studies have been done using sand sediment in beach and nearshore environments. In contrast there are a comparatively small number of studies which have used gravel sediment in wave dominated, deeper water environments (Steers and Smith, 1956; Kidson and Carr, 1959). Furthermore, it is only relatively recently that, for the first time, quantitative data was obtained on the mobility of gravel under wave action in water depths of 10-20 m (Crickmore et al., 1972).

The basic principles and assumptions involved in sediment tracer investigations are described in Nelson and Coakley (1974) and Dalrymple (1977), and include:

(i) A quantity of natural or artificial sediment is marked in such a way that it is readily distinguishable from the natural sediment of the system to be studied. The tracer material should have hydromechanical characteristics (size, shape, density) which are the same as those of the natural sediment;

(ii) The tracer material is then injected into the natural system so that it experiences the same conditions and behaves in the same way as the natural sediment; and

(iii) The resulting dispersal pattern of the tracer material can then be determined and the movement of the natural sediment inferred from this pattern. The last step is probably the most overlooked and under-

developed phase of tracer investigations. It involves considerations of sample design, tracer detection, data reduction and analysis, and interpretation.

In this study the objectives have been to obtain information on the transport behaviour of gravel sized sediment under the influence of a wave dominated, inner shelf environment. This study was also carried out on the mixed sand and gravel deposits at Pataua, at a depth of 18 m (Fig. 8.1). The investigation has involved experiments with two different sizes of gravel: large pebbles (-5.0 ϕ) and small pebbles (-2.5 ϕ). Each experiment has involved different sampling and analysis techniques, and the results are best presented separately for each size of gravel.

8.6.2 Large Pebble Movement

The mobility of the largest particles in the mixed sand and gravel deposit was investigated using painted pebbles ranging in equivalent sphere diameter from 21 mm (-4.39 ϕ) to 54 mm (-5.75 ϕ). Pebbles in this size range are found in dune troughs (Plate 7.2) and make up about 10% of trough sediments (Fig. 8.3). The specific aims of this investigation were to:

(i) measure the distance and direction of movement of large pebbles;

(ii) assess the significance of particle size and shape in controlling pebble movement, and

(iii) examine the validity of a laboratory derived predictive method for pebble movement by wave action (Hydraulics Research Station, 1969; Rance and Warren, 1968).

Pebble Selection and Preparation

Eighty-five pebbles were selected from greywacke beach gravels at Helena Bay. An attempt was made to use only rounded to well rounded pebbles, with shapes approaching ideal tri-axial ellipsoids. Pebble shapes ranged from compact spheres to very platy, bladed, and rod shapes.

All of the pebbles were painted with yellow plastic paint and individually identified with the numbers 1-85. The long, intermediate, and short axis of each pebble was measured to the nearest millimetre using a set of calipers. The weight of each pebble was determined and the equivalent sphere diameter was calculated.

Pebble Emplacement and Sampling

The 85 pebbles were placed on the seabed along the axis of a dune trough. The pebbles were placed at 0.1 m distance intervals using a measuring tape temporarily fixed to two steel rods positioned 10 m apart (Fig. 8.1). A record of the movement of individually identified pebbles was made on four successive dates. This was done by using the tape between the two steel rods to measure location changes along the emplacement line, and another tape to measure distances landward and seaward of the emplacement line. Measurements were made to the nearest 0.1 m in both directions.

Results and Analysis

The results of large pebble movements are shown in Table 8.7, and in Figs 8.5 and 8.6. Of the 85 pebbles initially emplaced the greatest number detected at any recording time was 17, or 20% recovery. At other times, when measurements were not taken, as few as four pebbles (5%) were visible. Over the whole study period

only one pebble was observed on all of the four sample times, three pebbles on three times, seven pebbles twice, and 24 pebbles once, giving a total of 51 observations of 35 individual pebbles (41% recovery). It is also interesting to note that the observation of very platy, bladed, and rod shaped pebbles was proportionally higher (by about 2-3 times) than compact sphere shaped pebbles. Thus, it would appear that compact sphere shapes tend to become buried, while pebbles with relatively higher maximum projection areas (Sneed and Folk, 1958) tend to remain unburied and available for transport on the surface. This phenomenon may be explained by the "dispersive pressure" theory of Bagnold (1956, 1966) which explains how large particles, and probably also particles which deviate from compact spherical shapes, are lifted to the surface in high density grain flows. The significance of this process is discussed further below.

Fig. 8.5 depicts the relationship between the net distance of pebble movement and pebble size, for each of the four recording times. The net distance does not consider the direction of movement, nor the movement history of pebbles that go undetected in previous recording times. Thus, the gross distances moved by pebbles would probably be much greater. Although these conditions impose some restrictions upon the reliability of the data, two features of pebble movement may be interpreted from Fig. 8.5. After the initial recording period (I), movement of up to 1.1 m had occurred with 26 mm diameter pebbles, whereas apart from one pebble of 50 mm which moved 0.2 m, three pebbles greater than about 40 mm showed no movement. After periods III and IV movement had reached a maximum of 5.65 m for one 30 mm pebble, whereas only three

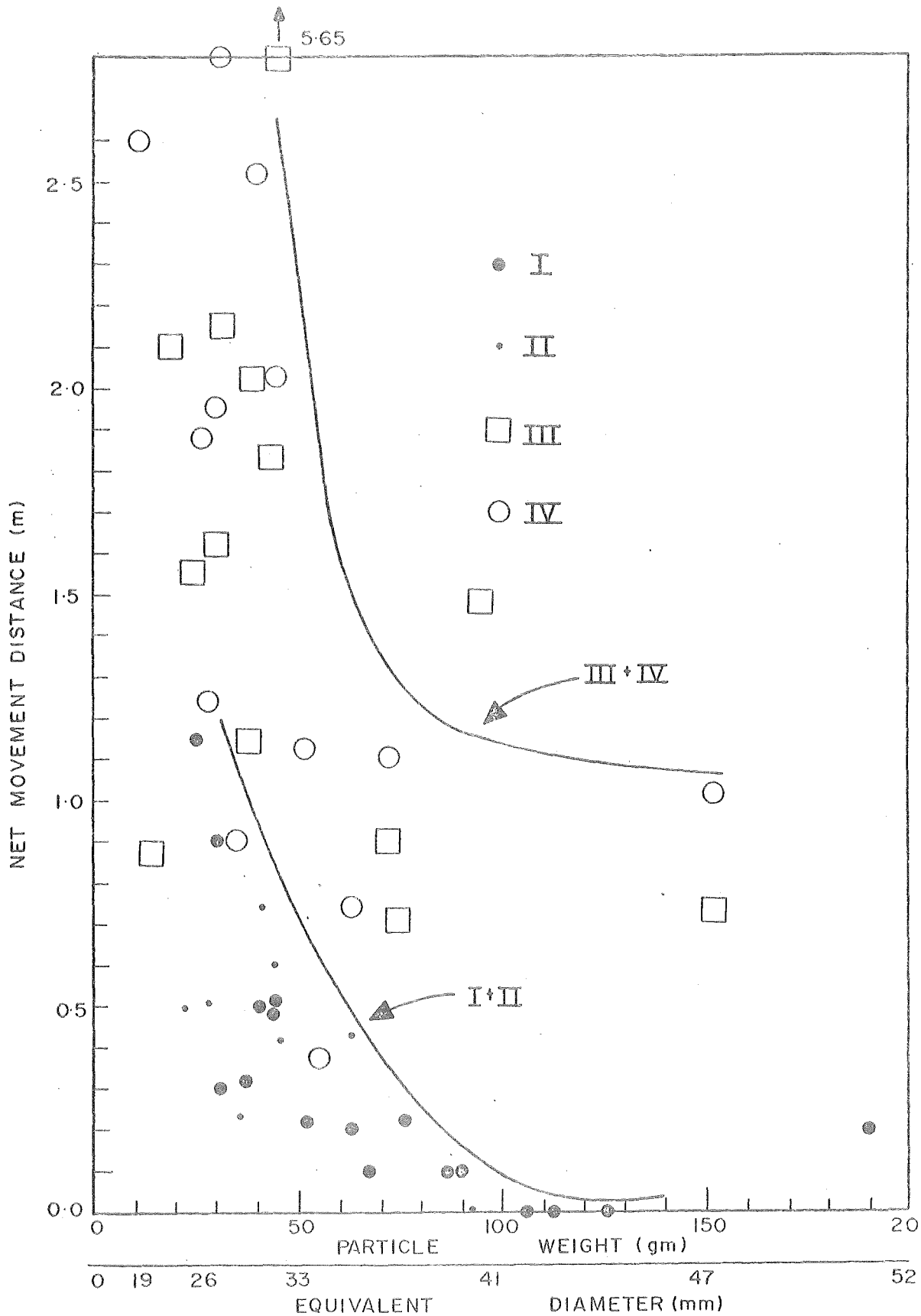

Fig. 8.5 - Net movement of large tracer pebbles for four (I, II, III, IV) sampling periods. See Table 8.7 for definition of four periods. Curves (I+II) and (III+IV) represent the approximate maximum limits of movement for the two groups of sample periods.

pebbles greater than 40 mm had moved about 1.0 m. Thus, pebbles of 30-50 mm have moved, respectively, 5 to 1 m over the study period, with a tendency for a rapid increase in mobility for pebbles less than about 35 mm.

In Fig. 8.6, all pebbles are displayed as having a common origin, i.e. their original emplacement coordinates, although the pebbles were actually placed in a line as described above and shown in Fig. 8.1. Fig. 8.6 shows, in vector form, the distance and direction of movement of the observed pebbles in each period. In the case of the four vector diagrams identified as part A of Fig. 8.6, each diagram defines the state of dispersion at the end of each period. This method of displaying the data does not attempt to attribute pebble movements to a particular period between sample times. In contrast, part B of Fig. 8.6 shows only those pebble movements which can be attributed to a particular period. Thus, in period II for example, there were only three pebbles which had also been observed in period I, so that movement of these pebbles could be attributed to period II.

Table 8.7 presents the results of an analysis of the vector diagrams shown in part A, Fig. 8.6. The formulae used in this analysis are presented in Table 8.8. Using this approach it can be seen that the magnitude and the direction of pebble dispersion varied considerably over the study period. Examining the magnitude of the dispersion first, the greatest amount occurred at the end of period III. This period corresponds to wave event F in Table 8.1, a period of large (3-4 m) storm waves. It can also be seen that there was a small, but significant, movement of pebbles in period IV (part B, Fig. 8.6). This occurred in a period of only moderate swell waves.

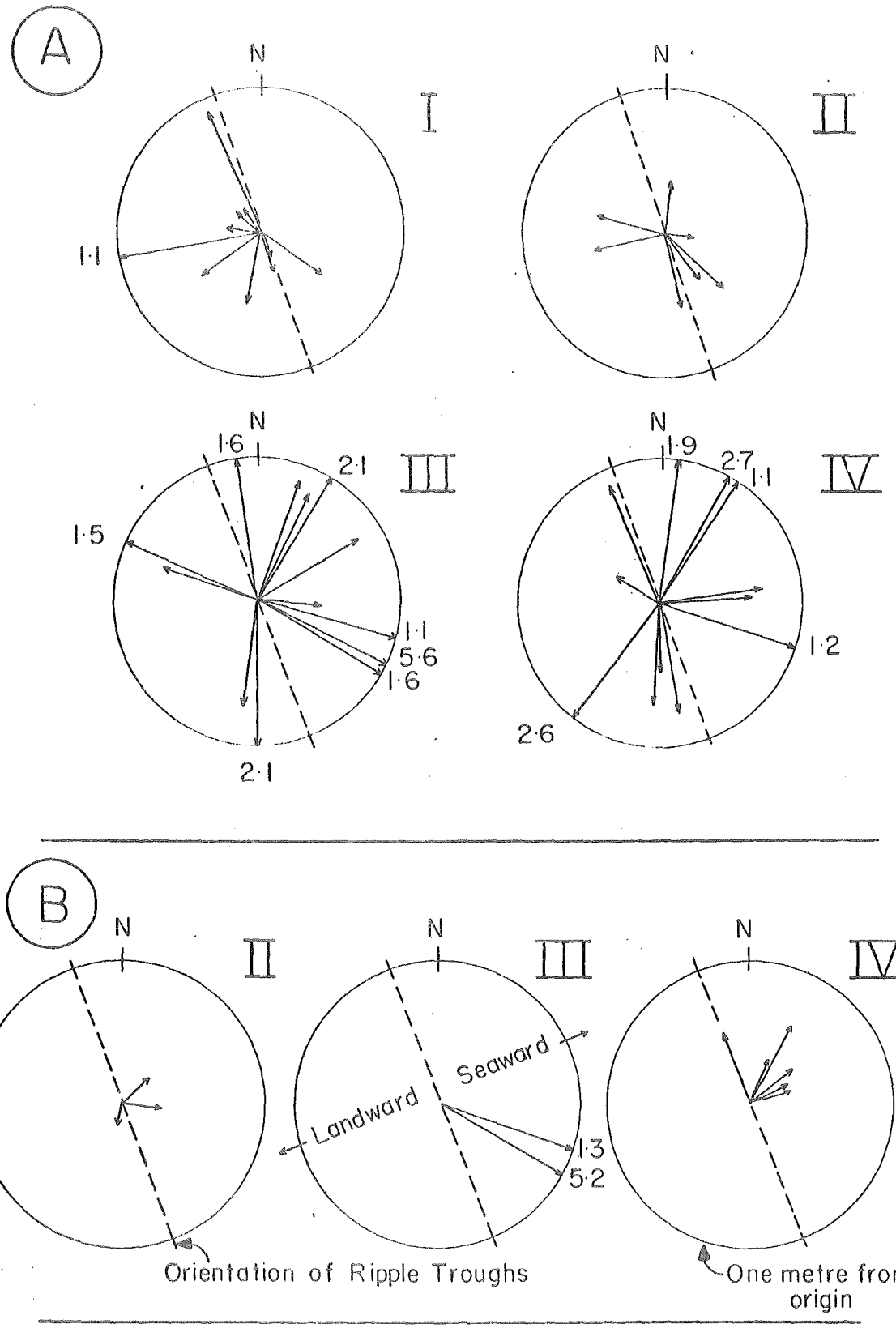

Fig. 8.6 - Individual vectors (in metres) of large pebble movement. For resultant vectors see Table 8.7. Part (A) shows state of sampled pebble dispersion at the end of each sample period. Part (B) shows only pebble movements which could be assigned to a particular period.

Table 8.7 - Results of vector analysis of large tracer pebble dispersions. Refer to part A, Fig. 8.6 for source data.

Period	Duration (days)	Wave Event	Recovery Efficiency	Direction ($\bar{\theta}$)	Magnitude (R)	Consistency Ratio (L)
I	25 Jan-11 Feb (17)	(C)	20%	230°	0.11 m	37%
II	12 Feb-18 Mar (35)	(D), (E)	9%	125°	0.14 m	31%
III	19 Mar-5 Apr (18)	(F)	15%	160°	0.38 m	28%
IV	6 Apr-15 Apr (10)	(G)	15%	76°	0.31 m	35%

Table 8.8 - Vector formulae for evaluating large tracer pebble dispersion. Modified for weighted distances from Potter and Pettijohn (1963, p. 264) and Dalrymple (1972).

Mean Vector Direction	$\bar{\theta} = \arctan(W/V)$	(degrees)
Resultant Magnitude	$R = (V^2 + W^2)^{\frac{1}{2}} \Big/ \sum_{i=1}^{n} w_i$	(metres)
Consistency Ratio	$L = (R/N)\ 100$	(percent)

Where $V = \sum_{i=1}^{n} w_i d_i \cos\theta_i$

$W = \sum_{i=1}^{n} w_i d_i \sin\theta_i$

$N = \sum_{i=1}^{n} w_i d_i$

θ_i - vector direction (degrees)

w_i - pebble weight (grams)

d_i - vector magnitude (metres)

The significance of pebble movement under the latter wave conditions is discussed below. From Table 8.7, it can also be seen that the resultant vector magnitude increases from 0.11 to 0.38 m, and then decreases to 0.31 m. These magnitudes are low when compared to the many pebbles which moved distances greater than 1 m. The probable reasons for the low resultant magnitudes and a decrease in period IV, are that pebble movement was not strongly oriented in one direction and was not the same for each period. In addition, pebbles buried in any period may provide a relict effect on the dispersion if they were observed in a subsequent period.

With respect to the direction of movement, there are also problems with relict effects. However, in period I there is a clear indication of landward movement (230^{o}), in period III a possible seaward (160^{o}) movement, and in period IV (part B) a strong trend for a seaward, northeast movement. Thus, over a period of three months, pebbles moved both landward and seaward. The final vector mean direction was seaward (76^{o}), indicating that the net result was a seaward movement.

Discussion

A laboratory derived method for the threshold movement of gravel by oscillatory wave action (Hydraulic Research Station, 1969) predicts that the following minimum wave conditions are needed to initiate movement.

Table 8.9 - Wave conditions for the threshold movement of gravel at a water depth of 18.3 m.

Particle Diameter	10 mm	35 mm	50 mm
Wave Conditions			
For T = 10 sec	H = 3 m	5.1 m	5.4 m
For T = 12 sec	H = 2.5 m	4.4 m	5.2 m

For the complete period of the Pataua study, wave characteristics can only be well defined for period IV. The largest recorded wave conditions at any time during period IV were H = 1.3 m, T = 10.6 sec (Table 8.2). There were also two short events of northeast seas which reached wave heights of 2 m, but with short periods (<8 sec). Therefore, the largest waves for period IV were certainly not greater than H = 2-3 m, T = 10-12 sec.

According to the predictive data in Table 8.9, these wave conditions should have limited movement to gravel with sizes $\leq$ 10-15 mm. However, the pebbles shown in period IV (part B, Fig. 8.6) were all greater than 25 mm diameter, and moved up to 0.5-0.6 m, with one pebble of 45 mm diameter moving 0.3 m. Therefore, the size of pebbles moved in this field study were larger than those predicted by the laboratory derived method.

Two reasons may account for this difference. First, the laboratory experiments used simulated, completely harmonic waves of a constant period and height. However, in this study, the natural wave regime had a wide spectrum of periods and heights. Therefore, it is possible that the coupling of two or more wave harmonics may momentarily create higher bottom wave surge velocities. Second,

the laboratory study used well sorted gravel beds without sand, whereas the sediments in this study consisted of mixed sand,and gravel (Fig. 8. 3). In this context, Moss (1962; 1963) has shown that gravel particles can slide or roll over surfaces of sand. Thus, the movement of pebbles in this study may have been aided by a mixed sediment surface. In addition, it was shown in Section 8. 3 on dune dynamics that, under large wave conditions, an upper flow regime plane seabed may be created. Under these conditions, grain collisions in the concentrated flow produce a dispersive pressure which is normal to the seabed. This pressure causes larger particles to be supported higher up in the concentrated grain flow (Bagnold, 1956, 1966), and this may also explain the higher pebble mobility found in this study.

8. 6. 3 Small Pebble Movement

Tracer Selection, Preparation, and Emplacement

This tracer experiment used small pebbles in a size range from 4 mm (-2. 0 ϕ) to 10 mm (-3. 3 ϕ), with a mean size of 5 mm (-2. 6 ϕ). This size of pebbles occurs naturally in dune troughs (Fig. 8. 3), and forms about 12% by weight of trough sediments. The pebbles were predominantly quartz, with well rounded, near spherical shapes. They were obtained by selectively sieving a quantity of commercial aggregate known as "Fruit Salad", which is available from Winstone Ltd. The sieved material was given a thin coat of yellow plastic paint by mixing pebbles in a 1. 25 litre can with a small quantity of paint. The pebbles were then spread out on a plastic sheet to dry. After drying some disaggregation was necessary to give the size characteristics referred to above. Exactly 20 kg of this tracer material was emplaced on the

seabed study site within a 0.5 m radius of the central rod (Fig. 8.1). With an average pebble weight of 0.34 gm, the 20 kg was equivalent to approximately 60,000 pebbles. This amount was mixed with the local mixed sand and gravel sediment to a depth of about 5 cm.

Sampling and Concentration Determination

Both surface and subsurface samples were taken in order to map the dispersion of the tracer through time. Using a central rod, sampling lines were run radially out to eight other rods at major points of the compass (Fig. 8.1). Intervening sampling lines were also run, giving a total of 16 radial sampling lines. Because of the dune bedform morphology, and the preferred position of tracer sediment in trough sediments, a large sampling quadrat of 1 m^2 was used at each sampling point in order to give a representative sample. Since the pebbles were clearly visible on the bottom it was only necessary to place the sampling quadrat on the seabed and count the number of tracer pebbles in the sampling area. Using this technique at least 40% of the total dispersed tracer area was sampled each time.

In order to determine the amount of subsurface tracer material, shallow cores were taken in trough sediments with a rectangular scoop. The size of the cores was 5 cm deep, 10 cm wide, and 25 cm long, giving 1250 cm^3 of material. Separation of the tracer material from the total core material was done by sieving and by hand. Calibration curves were then constructed to show the relationship between the amount of surface and subsurface tracer material at any site, so that the total quantity of injected material could be accounted for (Fig. 8.7). Finally, using the quadrat data on surface pebble counts, and an average pebble weight of 0.34 gm, maps of dispersion distributions were prepared for each sampling time (Fig. 8.8).

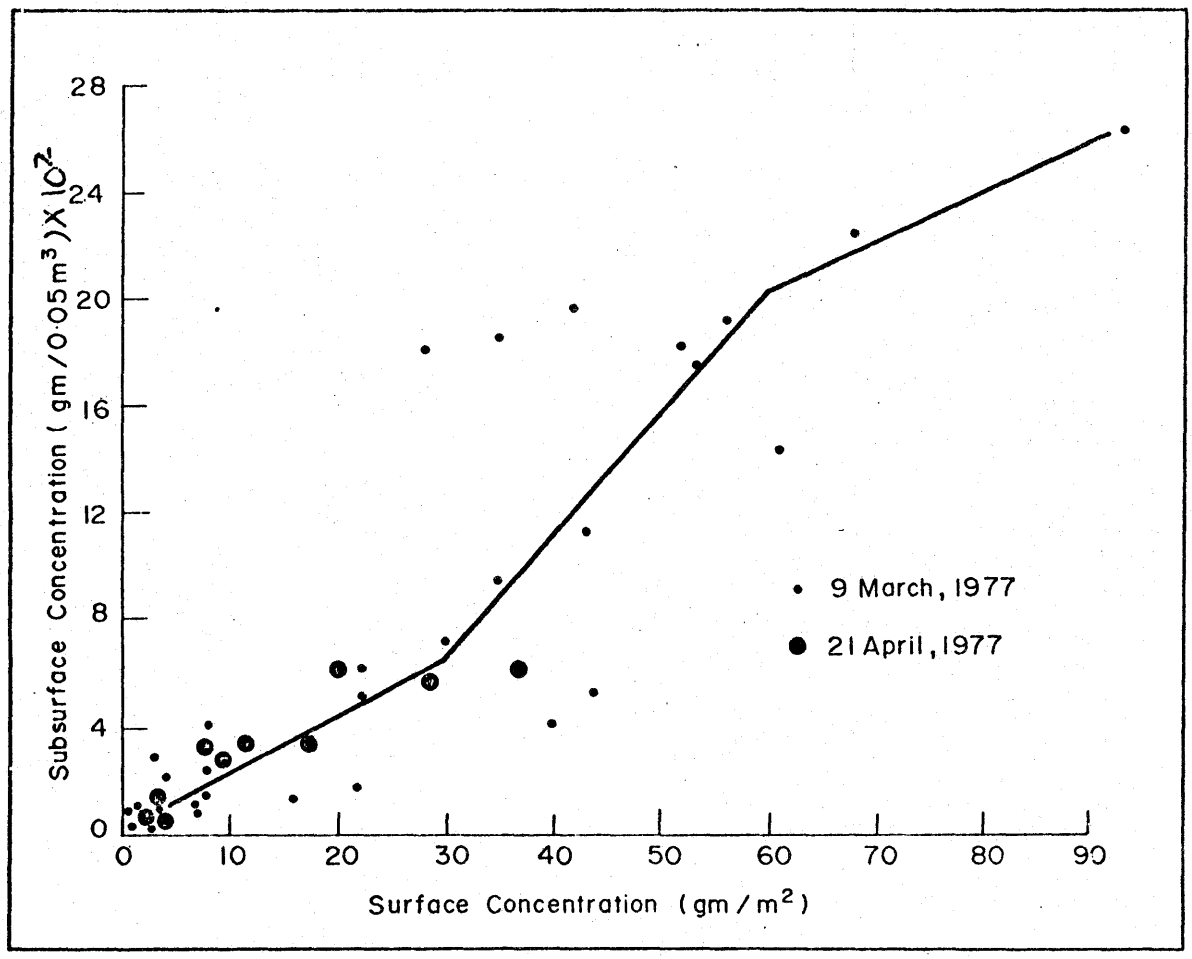

Fig. 8.7 - Calibration for small pebble dispersions showing relationship between surface and subsurface pebble concentrations. Subsurface concentrations for the top 5 cm of the seabed. Calibration line fitted by eye.

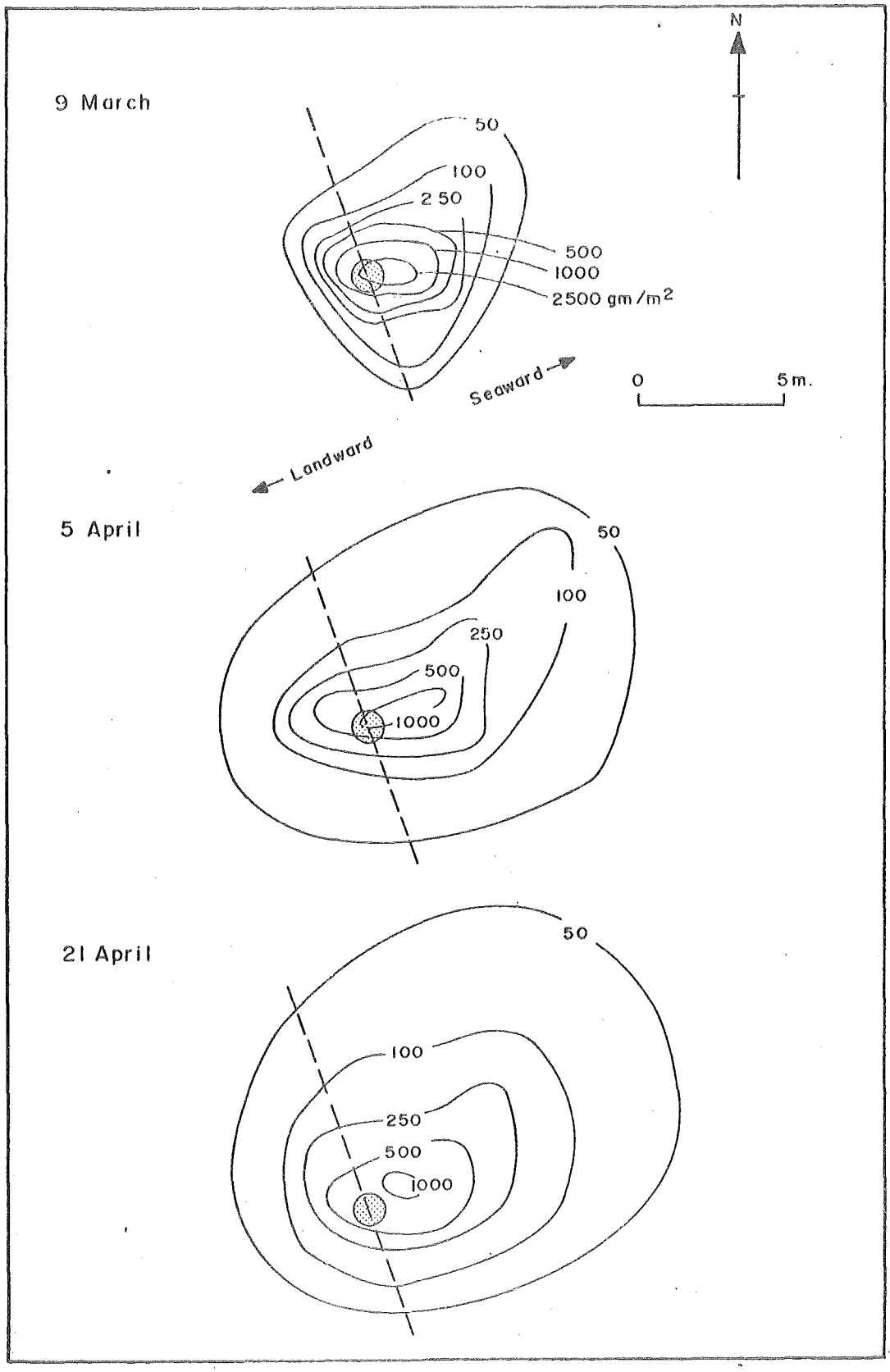

Fig. 8.8 - Small pebble dispersion distributions at three sample times. Concentration values for a seabed depth of 0.05 m. Dashed line through dispersion origins represents orientation of dune crests and shoreline (approximately 20° W of N).

Results and Analysis

The tracer material was emplaced on 25 January, 1977 and until at least 1 February, and probably until 4 February, no movement occurred. The pebbles were probably first dispersed from 5-10 February, during wave event C (Table 8.1), since on 11 February considerable dispersion was visible. However, this dispersion could not be properly sampled until 7-9 March, which unfortunately was after the additional wave event D. The dispersion distribution was subsequently sampled on 5 April after wave events E and F, and lastly on 21 April after wave event G.

Fig. 8.8 shows maps of pebble dispersion for the three sampling times. The tracer concentrations are given in units of gm/m^2 for a depth of 5 cm. The depth of 5 cm represents the depth of coring and includes the complete "mobile layer" of sediment, as was shown by the depth of disturbance results (Section 8.4). An estimate of the reliability of the dispersion maps in Fig. 8.8 can be obtained from the value of the sample recovery efficiency for each time. By measuring the area of each concentration band, multiplying by the concentration of that band, and then summing for the whole dispersion, it is possible to obtain the total amount of tracer accounted for. By comparing this to the injected amount (20 kg) it was found that for the three sampling times, the recovery efficiency was 89%, 107%, and 130%. Recovery efficiencies of greater and less than 100% are due to inaccuracies in the estimating procedure. However, these are very good recovery efficiencies compared to other studies, for example, usually less than 50% in Dalrymple, 1977. This indicates that the dispersion maps are reliable.

In qualitative terms, the tracer material showed a preferred direction of movement to the northeast for all dates of sampling. This direction represents a seaward movement. However, movement of pebbles occurred in all directions, and in order to quantitatively describe the distributions, the equations presented in Table 8.10 and the following procedure were used. An x, y coordinate grid system was used to sample the contoured dispersion patterns. The x-axis was aligned along the azimuth of the maximum direction of movement and concentration values were taken for each (x, y) coordinate at 1 m grid intervals. This procedure yielded from 150 to 250 sample points for each of the three dispersion distributions.

The analysis outlined in Table 8.10 can be considered as a statistical summary of a two-dimensional, spatially integrated distribution. The analysis uses statistical moments (mean, standard deviation) to describe the dispersion for each sampling time. These equations have also been used by Dalrymple (1977) and others (Courtois and Monaco, 1969; Crickmore, 1967).

Table 8.11 summarises the derived statistics and parameters to describe each of the distributions. The recovery efficiencies (Re) given in this table are slightly different from those mentioned previously because point count data, rather than area data, have been used. Furthermore, the sediment discharge values (Q) have been standardised for 20 kg to eliminate the influence of the recovery efficiency (Re). From Table 8.11 it can be seen that the tracer material maintained a northeasterly movement ($\alpha_o = 70^o, 55^o, 48^o$) over the whole study period, with individual period directions showing a progressive shift to the north-northeast ($\alpha_t = 71^o, 42^o, 26^o$). Throughout this time the elongation ratio remained similar at about 1.3, showing that dispersion

Table 8.10 - Equations used in analysis of small pebble dispersions shown in Fig. 8.8.

Statistical Parameter	Formula
Sample concentration for x, y coordinates	$C_i(x_i, y_i)$
(1) Centroid $(\bar{X}, \bar{Y})$	$\bar{X} = \sum c_i x_i / C, \quad \bar{Y} = \sum c_i y_i / C$ where $C = \sum c_i$
(2) Standard Deviation (S_x, S_y)	$S_x = \sqrt{((\sum c_i x_i^2)/C) - (\sum c_i x_i / C)^2}$ $S_y = \sqrt{((\sum c_i y_i^2)/C) - (\sum c_i x_i / C)^2}$
(3) Elongation Ratio (E)	$E = S_x / S_y$
(4) Average Distance of Net Movement (D)	$D = \sqrt{\Delta\bar{X}^2 + \Delta\bar{Y}^2}$ where $\Delta\bar{X} = \bar{X}_b - \bar{X}_a, \ \Delta\bar{Y} = \bar{Y}_b - \bar{Y}_a$
(5) Direction of Movement (α)	$\alpha = \arctan(\Delta\bar{Y} / \Delta\bar{X})$
(6) Velocity of Centroid Movement (V)	$V = D / \Delta T$, where $\Delta T = t_b - t_a$
(7) Sediment Discharge (Q)	$Q = VC$, C standardised for 20 kg.

Source: Dalrymple (1977)

Table 8.11 - Results of analysis of small pebble dispersions.

Parameter	t = 1 25 Jan-9 Mar	t = 2 10 Mar-5 Apr	t = 3 6 Apr-21 Apr
C (kg)	19.36	21.00	28.05
Re %	97	105	140
T_o, T_t max	12, 12	20, 8	28, 8
T_o, T_t min (days)	40, 40	67, 27	83, 16
(1) $(\bar{X}, \bar{Y})$ (m)	(0.93, -0.46)	(2.26, -0.38)	(2.97, -0.14)
(2) (S_x, S_y) (m)	1.50, 1.17	3.04, 2.28	3.26, 2.52
(3) (E)	1.28	1.33	1.29
(4) (D_o) (D_t) (m)	1.04, 1.04	2.29, 1.30	2.97, 0.83
(5) (α_o) (α_t)	71^o, 71^o	55^o, 42^o	48^o, 26^o
(6) $(V_o)(V_t)$ max	0.087, 0.087	0.115, 0.163	0.106, 0.104
$(V_o)(V_t)$ min (m/day)	0.026, 0.026	0.034, 0.048	0.036, 0.052
(7) $(Q_o)(Q_t)$ max (kg m/	1.74, 1.74	2.3, 3.2	2.1, 2.1
$(Q_o)(Q_t)$ min day)	0.52, 0.52	0.7, 1.0	0.7, 1.04

Subscript "o" refers to parameters with respect to t = 0, i.e. the time of injection; "t" refers to specific time intervals t = 1, 2, 3.

has been slightly greater in the landward-seaward direction than alongshore.

The rate of movement varied by a factor of less than two between the sample periods. In Table 8.11, parameters have been calculated for both total and net movement relative to the original position of emplacement (T_o, D_o, α_o, V_o, Q_o), and also for discrete movement within each period (T_t, D_t, α_t, V_t, Q_t). Furthermore, the quantities of sediment velocity (V) and discharge (Q) have been calculated for both maximum rates (using only the duration of days that movement was likely to have occurred), and minimum rates (using the total duration of days between sampling times). In general, maximum rates of movement were about two-four times greater than minimum rates of movement. Maximum rates of movement (V_{tmax}) were greatest in the second period, and less in the third and first periods. Sediment discharge quantities (Q) are expressed in terms of kg m/day for a unit width of 1 metre in the direction of transport. Values of Q are directly related to the velocity of the dispersion centroid and are standardised for the total recovered tracer material. The highest sediment discharge value was 3.2 kg m/day due to wave events E and F in the period 9 March - 5 April (Table 8.1).

8.6.4 Summary

At a depth of 18 m on the inner shelf mixed sand and gravel deposits at Pataua, many large pebbles moved distances greater than 1 m over a three month period. The direction of movement varied with time and consisted of periods of both landward and seaward movement. However, the net movement was to the northeast (seaward).

This direction corresponds approximately to that inferred from the distribution of shell material in Chapter Seven. Therefore, there is general agreement between short term and long term transport directions on the deposits, and it would appear that the main body of the deposit is moving north-northeastward.

Pebble size and shape in mixed sand and gravel sediments has an effect on particle movement. Smaller pebbles, especially those with diameters less than 35 mm, moved further than larger pebbles. Pebbles with higher relative projection areas were observed proportionally more often on the surface than were sphere shaped pebbles.

A laboratory derived predictive method for determining the threshold movement of pebbles was shown to underestimate the size of pebbles which can be moved in a wave dominated, deep water environment. The reasons for this are probably related to ocean wave coupling phenomena in the velocity field and the behaviour of gravel particles in concentrated flows of mixed sand and gravel sediments.

It was also found that the direction of movement of the small tracer pebbles was similar to that of the large pebbles. This was especially true for the last period of movement in April. The direction of movement of the small pebbles is therefore also in agreement with the direction inferred from long term studies in Chapter Seven.

8.7 BOTTOM WAVE SURGE MEASUREMENTS

8.7.1 Introduction

Under the influence of wave motion, water particles move in oscillatory orbits which become elliptical with depth and eventually completely horizontal near the bottom (CERC, 1973, Fig. 2-4). The usual method of determining near-bottom horizontal velocities is to take surface wave characteristics and calculate near-bottom free stream velocities from theory. However, this method can only give approximate estimates of actual seabed velocities since seabed roughness and boundary layer conditions are not considered. When seabed roughness elements, such as symmetrical dunes are present, then free stream velocities are likely to be significantly altered within the boundary layer close to the bottom. In this respect, some discrepancies with theory have already been demonstrated in early sections of this chapter. Therefore it would be desirable to measure seabed velocities in the field.

The wave bottom boundary layer has been shown to be a region of complex and rapidly changing velocity conditions. Based on laboratory experiments, Jonsson (1963; 1967) suggests that the boundary layer can probably be regarded as completely turbulent in the presence of large duned sediment surfaces in nature. In addition, vortex motion in the lee of dune crests has also been shown from laboratory experiments to contribute significantly to sediment transport processes (Horikawa and Watanabe, 1970; Kennedy and Locher, 1972). As discussed earlier in Section 8.3, the threshold of sediment

motion is also likely to be much less for a duned surface than a flat one. This has been demonstrated by Carstens et al. (1969) in the laboratory and by Davies et al. (1977) in the field.

Most of the work to date on wave bottom boundary layers has been done in laboratory experiments (Bagnold, 1946; Manohar, 1955; Carstens et al., 1969; Komar and Miller, 1975; Davies and Wilkinson, 1977). Since little of this laboratory work has been verified in the field, there may be difficulties in translating it to natural field conditions. In particular, this is probably the case for laboratory studies using monochromatic waves which cannot simulate the variability of wider wave spectrums and coupled wave phenomena in nature.

The aims of this section of the thesis have been to measure wave surges immediately above a duned seabed surface, and to observe the effects of these surges on sediment motion. Comparisons have also been made with theoretical and laboratory derived predictions in order to assess their validity under natural conditions.

8.7.2 Description of Bottom Wave Surge Meter

In order to measure the rapidly oscillating flow conditions in a wave bottom boundary layer, a special meter was needed. It would have to respond to velocities ranging from 1-100 cm/sec, and which also change direction by 180° in half a wave cycle (5-6 sec). Therefore, a meter had to have the characteristics of low inertia and a very fast response time. Conventional current meters, such as cup wheels, propellors, and Savonius rotors, do not meet these characteristics. Therefore, the design of a strain-gauge anemometer (Morrison, 1968)

has been adopted. The strain-gauge meter is also similar in design to those described by Inman and Nasu (1957), and Smith and Harrison (1970), and is relatively simple and inexpensive.

The surge meter consists of a vertical array of three independent sensor assemblages, mounted to a tripod frame (Plate 8.4). Each sensor assemblage consists of a lightweight, perforated, plastic drag sphere (a 4.2 cm diameter practise golf ball). In operation the drag sphere experiences forces due to the motion of water over its surface. These forces are instantly transmitted by a thin rod to a sheet metal beam which flexes in proportion to the force. The flex in the beam is measured electrically by a bi-directional strain-gauge balance glued to the sides of the beam. As the strain-gauges change in electrical resistance due to mechanical flexing, an unbalanced voltage is produced in a bridge circuit and recorded in analogue form on a chart recorder.

Power for the strain-gauge bridge circuits was supplied by a 6 volt battery. This was located with a chart recorder in the work boat. The input voltage and output signals were transmitted between the surface and the seabed by wires inside a 2.5 cm Alkathene tube. In addition, since the chart recorder had only a single channel, simultaneous vertical recordings of surge could not be made, and a small switch box was needed to change the recorded signal from one sensor to another.

When operated in the field the meter was lowered from a boat and accompanied by a diver. On the seabed the tripod was oriented to measure landward-seaward wave surges perpendicular to the axis of the strain-gauges. The height of each sensor assemblage could also be adjusted to measure surges over dune troughs or crests (as shown in Plate 8.4).

There were also two main limitations to the use of the surge meter in the field. First, because the power supply and recording units were located in a boat, the surge meter could not be left on the seabed for long periods, or operated during storm events. Thus, recording times have been limited to fair weather, swell wave events. Second, since the chart recorder was only single channel, simultaneous vertical surge measurements could not be made. To overcome this problem, surge recordings for each sensor level have been compared for similar recorded wave conditions at different times.

While bottom wave surge motions were being recorded with the surge meter, a simultaneous, time-correlated record of the surface wave profile was obtained from the boat's echo sounder. An example of each of these recordings is shown in Fig. 8.9.

Estimate of Errors

The echo sounder record was enlarged three times to allow more accurate measurements of wave heights to 0.05 m ($\pm$ 0.05 m) and wave periods to 0.5 sec ($\pm$ 0.25 sec). The surge meter voltage output could be measured directly from the chart recordings to a resolution of 0.02 mv ($\pm$ 0.02 mv). All of these measurements represent a resolution of about $\pm$ 5% of full scale.

8.7.3 Meter Calibration and Theoretical Surge Motion

Each sensor assemblage was calibrated using the method described in Morrison (1968), where known forces are statically applied to a drag sphere and a voltage response is recorded. All of the sensors showed similar, linear calibrations within $\pm$ 5% of each

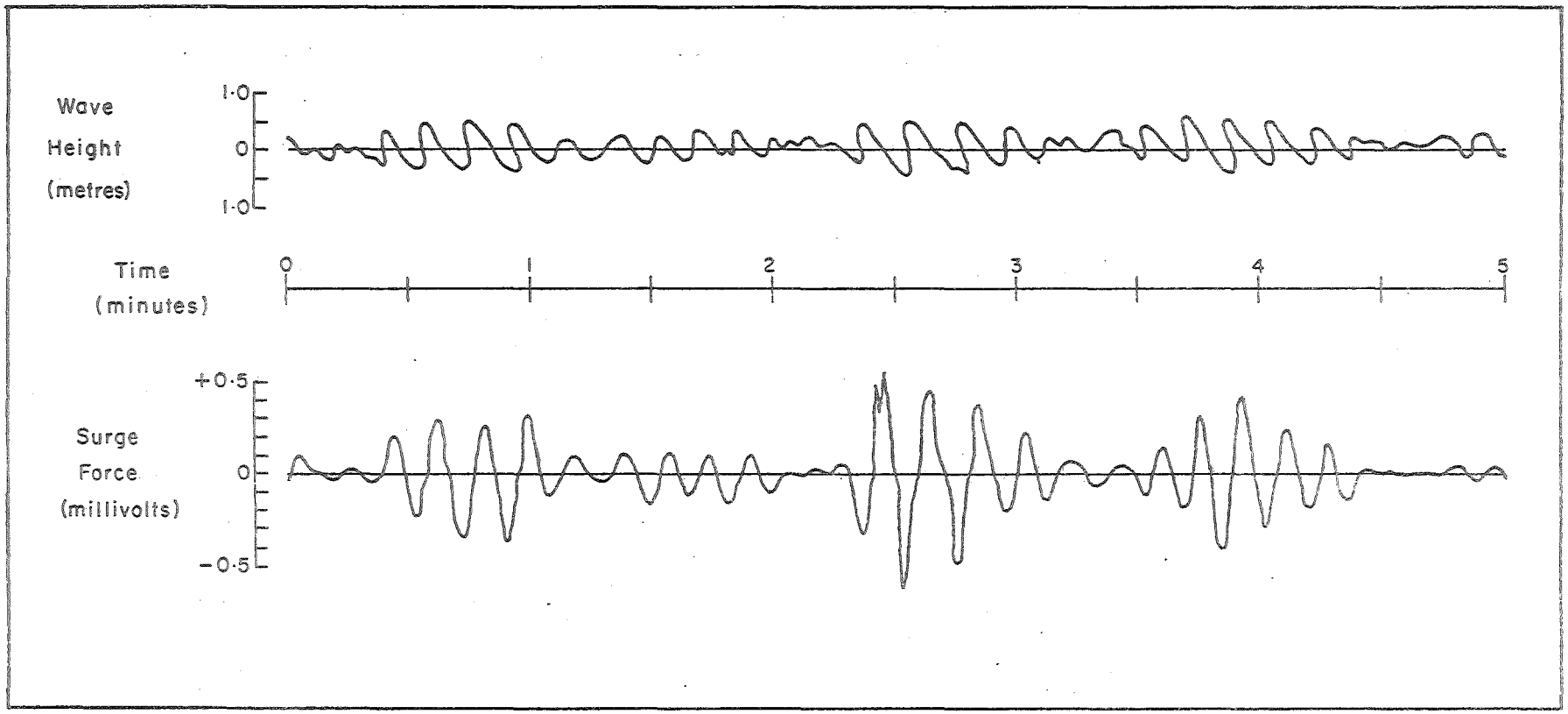

Fig. 8.9 - Time correlated records of wave height and bottom wave surge force (millivolt equivalents). Wave profiles are inclined because of circular echo sounder trace.

other. A typical applied force of 9,800 dynes (10 gm) produced a voltage response of 0.41 millivolts.

Using this calibration it is possible to directly convert recorded chart voltages to surge forces. It would also have been desirable to have carried out another calibration, either in a towing tank for steady velocities, or under simulated prototype wave surge conditions. In either case, the fluid drag and response characteristics of the sensing assemblages could have been empirically assessed and a voltage-velocity calibration would have been available. However, this has not been done and in order to convert a force to a wave surge velocity the use of an equation and a number of assumptions is necessary.

According to Smith and Harrison (1970), the force experienced by a drag sphere in unsteady flow conditions (which applies to oscillatory wave surges) is derived from two force components. The first is a drag force (Fd) due to velocity, and the second is an inertial force (Fi) due to acceleration (Table 8.12). In addition, assumptions must be made about the coefficients (C_D, C_M). Using the force equations of Table 8.12 and additional theory from linear wave motion equations (CERC, 1973, Fig. 2.6), the theoretical wave kinematics and force history for the drag sphere have been derived for a typical design wave (Fig. 8.10). The horizontal velocities and accelerations are intended only to represent free stream conditions near the bed. Note that velocity is in phase with the water surface profile, with maximum velocities occurring under the wave crest and trough. Note also that acceleration is a quarter of a wave cycle out of phase with velocity. Finally, the drag force (Fd) shows a direct square relationship with velocity, and the

Table 8.12 - Theoretical wave and force equations used to derive relationship shown in Fig. 8.10. Wave equations for simple linear Airy wave theory (CERC, 1973, p. 2-34), force equations for a sphere in unsteady flow (Smith and Harrison, 1970).

Wave Equations

$$n = (H/2)\cos\theta$$

$$u = (HgT/2L)\,(1/\cosh(2\pi d/L))\cos\theta$$

$$a = (g\pi H/L)\,(1/\cosh(2\pi d/L))\sin\theta$$

where n - water surface profile

u - horizontal near-bottom velocity

a - horizontal near-bottom acceleration

H - wave height

T - wave period

L - wavelength

d - water depth

g - gravitational acceleration

π - phi, 3.14159

θ - wave phase angle

Force Equations

$$Fd = 0.5\,C_D P_f A u^2$$

$$Fi = C_M P_f V a$$

where

Fd - drag force

Fi - inertial force

C_D - drag coefficient (0.65)

C_M - coefficient of mass (0.65)

P_f - fluid density of salt water (1.03 gm/cc)

A, V - cross-sectional area and volume of the drag sphere sensor for a radius of 2.1 cm

u, a - velocity and acceleration as above

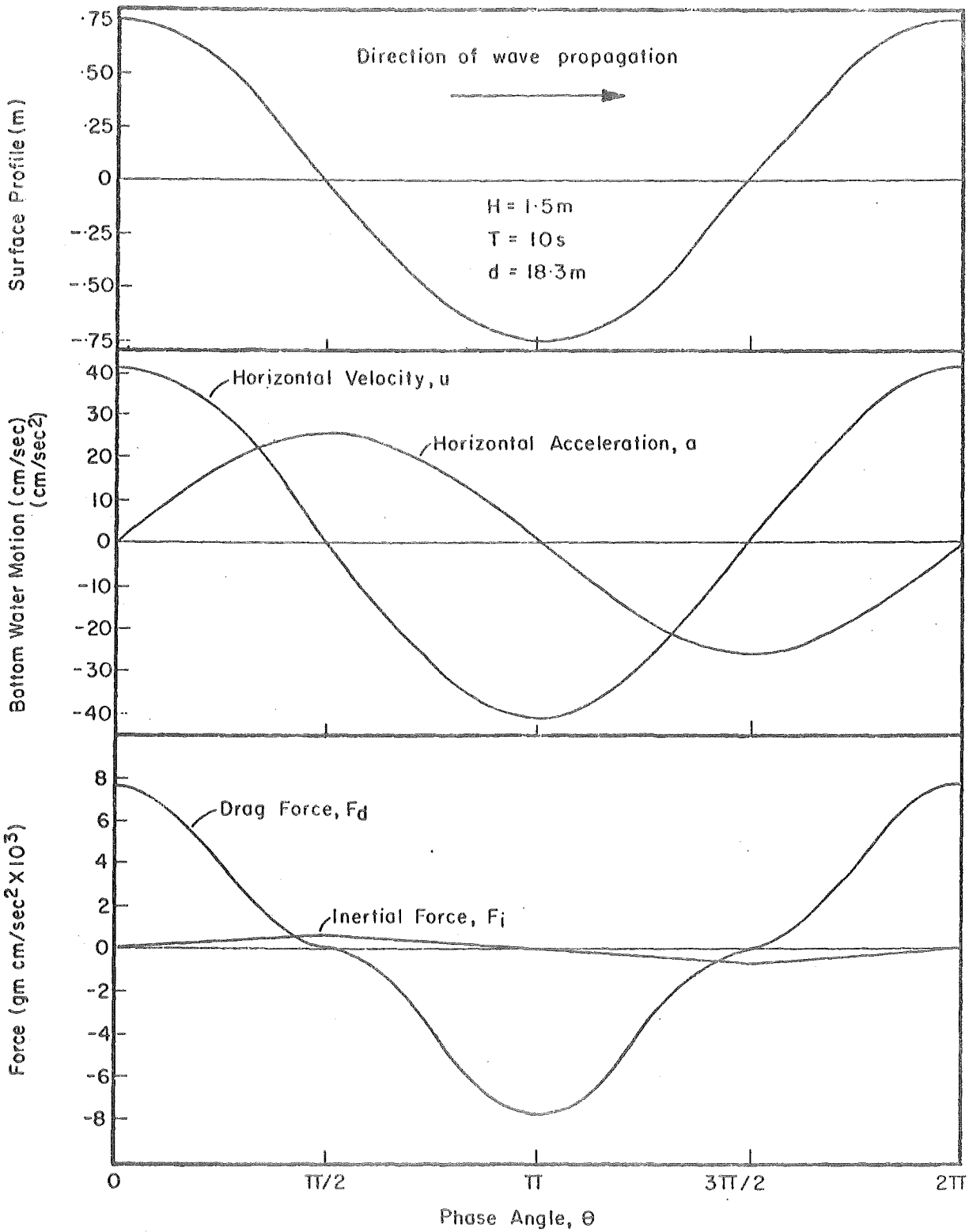

Fig. 8.10 - Wave kinematics and force history for a typical wave. Wave kinematics prepared from linear Airy wave theory (Table 8.12) for wave characteristics as shown. Force history for the drag sphere sensor from equations listed in Table 8.12.

inertial force (Fi) is much smaller than the drag force. In particular, when the acceleration is zero, then Fi = 0, and the maximum drag force (Fd) occurs when velocity is a maximum. Therefore, it is possible assuming the relationship shown in Table 8.12, to convert maximum surge forces to maximum surge velocities.

8.7.4 Field Results and Analysis

The field experiment was carried out on 14 April, 1977 on a duned seabed at a depth of approximately 18 m at Pataua. The dune dimensions were similar to those of 12 April (Table 8.3). A number of features are clear from the record shown in Fig. 8.9. The waves have periods of 9-11.5 sec with heights of 0.5-1.3 m. Surge motions are correlated with the water surface wave profile, and both landward and seaward surges (respectively, under wave crests and troughs) show approximately equal magnitudes for similar wave heights. At times there is a slight asymmetry of surge direction (either landward or seaward) but this depends on prevailing surface wave trough and crest amplitudes. Over the whole record period there is no apparent preferred direction of surge asymmetry.

It was from records like those shown in Fig. 8.9 that data were abstracted to compare surge motions at different heights above the crest of a dune. Well formed sequences of waves and bottom surges were selected for detailed measurements. For the wave records, individual crest and trough amplitudes, and wave periods were measured. In order to compare waves with different heights and periods, theoretical maximum bottom velocities were obtained from the graphed relationship for Stokes' wave theory in Fig. 8.2.

From the surge records, measurements were made of the maximum surge motions which corresponded to the crest and troughs of waves from the echo sounder records.

Using this form of analysis approximately 50-70 correlated measurements of maximum bottom wave surge force and calculations of theoretical bottom velocities were obtained for each of the three sensors. This data has been plotted in Fig. 8.11, with power curves of the general form $Y = aX^b$ having been statistically fitted to each distribution. In Fig. 8.12, each of the curves from Fig. 8.11 has been compared with the theoretical curve from Table 8.12.

A number of points should be noted from Fig. 8.11 and 8.12. There is considerable scatter to each of the distributions in Fig. 8.11. As regards the accuracy in calculating the theoretical maximum velocity (Umax), errors in measurements of wave height and period probably contribute $\pm$ 5% error in Umax at a value of 30 cm/sec. Therefore this value could vary from 28.5 to 31.5 cm/sec. It can be seen that this range accounts for most of the variation in Umax.

For maximum surge force measurements (Fmax), the scatter is greater than can be accounted for from error measurements alone (only about $\pm$ 5% or $\pm$ 750 gm cm/sec^2). Physically, this means that for particular measured wave characteristics, and thus calculated Umax values, the amount of bottom surge can show considerable variation (about $\pm$ 20%). This variation can most likely be explained by the existence of more than one wave train of differing periods and heights. These wave trains interact to produce coupled, instantaneous surge motions which have not been accounted for by the simple measurements of wave height and period. In this respect, a background

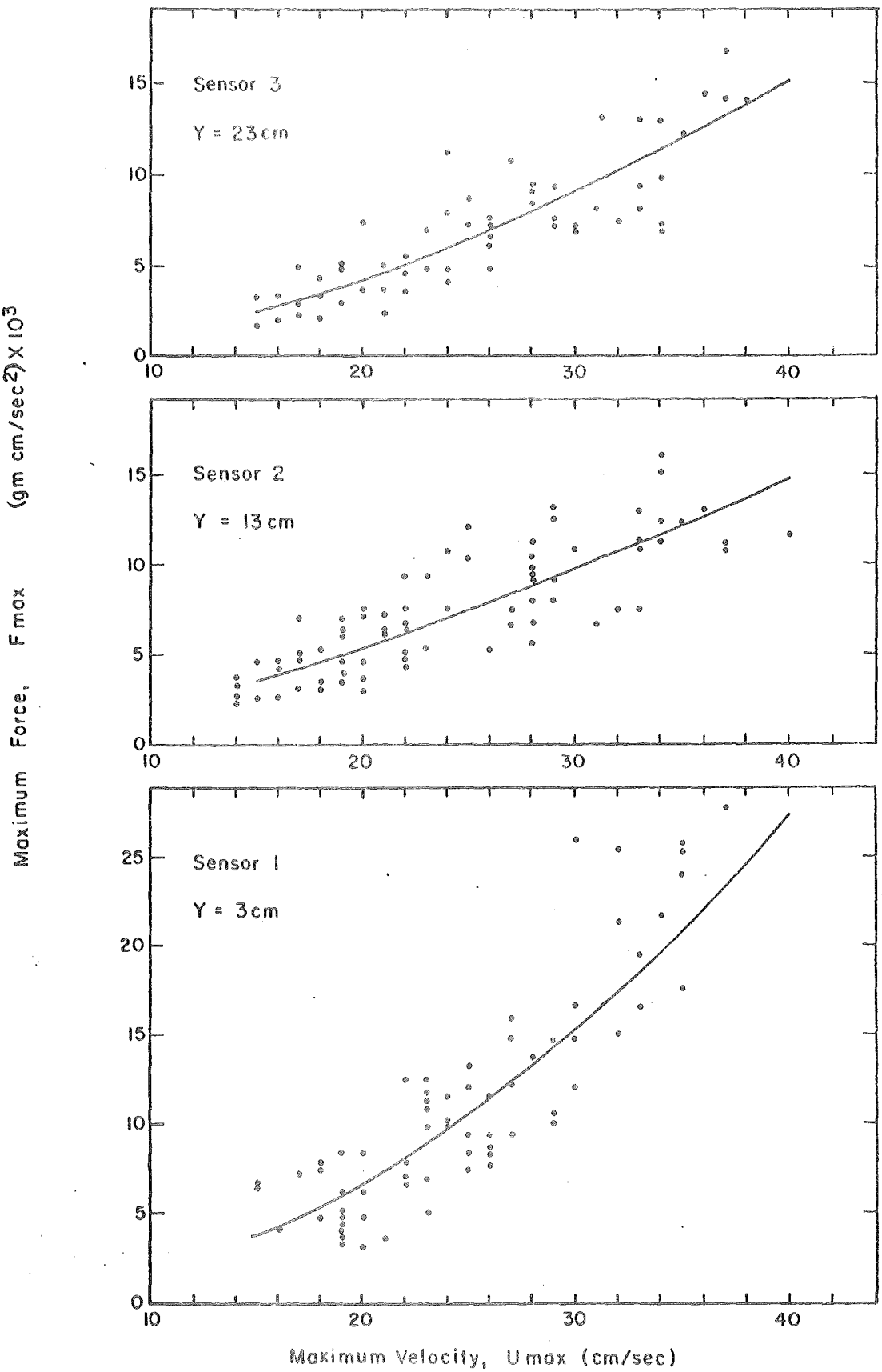

Fig. 8.11 - Regression of Fmax against Umax, for the three sensor levels above a dune crest (Plate 8.4). Fmax measured directly from surge meter records. Umax calculated from wave record measurements.

wave train of H = 0.5 m, T = 10 sec is probably always present, with additional wave trains arriving from other sources with different characteristics.

The statistically fitted curves are considered to be reliable as shown by their moderately good correlation coefficients (r^2), and highly significant "F" statistic (Table 8.13). There is also a difference in the exponents for sensors two and three (respectively 1.45 and 1.85), in comparison to sensor one (2.06), and the theoretical value (2.0) which is a squared relationship.

Table 8.13 - Results of statistical analyses of distributions shown in Fig. 8.11 using the power function of the general form $Y = aX^b$.

Statistic	Sensor (1)	(2)	(3)
$Y = aX^b$	$Y = 13.6X^{2.06}$	$Y = 66.9X^{1.46}$	$Y = 16.5X^{1.85}$
r^2	0.69	0.71	0.74
F	145	177	166

Note: Y = Fmax, X = Umax
F values significant at less than 1% level.

From Fig. 8.12 a number of features can be seen. First, considerably higher surge forces are experienced by all of the sensors when compared to that of the theoretical force predicted from the equation in Table 8.12. In terms of surge force, the curves of sensors two and three (the sensors furthest from the seabed) exceed the theoretical curve by approximately two times, which corresponds to velocities greater by about 1.5 times (derived from $\sqrt{2.2}$).

There are at least two possible reasons for this difference. First, there are higher velocities due to flow alteration near the seabed (which is apparent from sensor one). This may be so, but the similarity in response of sensors one and two suggests that they were both located above the intense surge alterations shown by sensor one. Second, all of the three sensors may have drag coefficients (C_D) and active cross-sectional areas (A) which are greater than those proposed in Table 8.12, which considers only the perforated sphere and not its mounting rod or the beam itself. How important this factor is cannot be assessed until towing tank or other dynamic fluid calibrations are made. If the second reason is accepted, then the force curves of sensors two and three should be used to represent unaltered, theoretical, free stream conditions. Until further calibration tests can be conducted this is a necessary assumption.

Accepting this assumption the marked departure of the force curve of sensor one is thought to be due to flow compression over the dune crest. For higher flow conditions (>25 cm/sec) the additional factor of an increase of fluid density (ρ_f) may also have operated, due to sand grains being incorporated into the flow over the dune crest. The impact of these sand grains on the sensor could have provided an additional impulse force.

Sediment Motion

In this last respect, sediment motion on dune crests was observed a number of times while the surge meter experiments were being carried out. It has thus been possible to correlate sediment motion with surface wave and resulting bottom surge conditions. In one case, four successive wave surges were observed to cause the

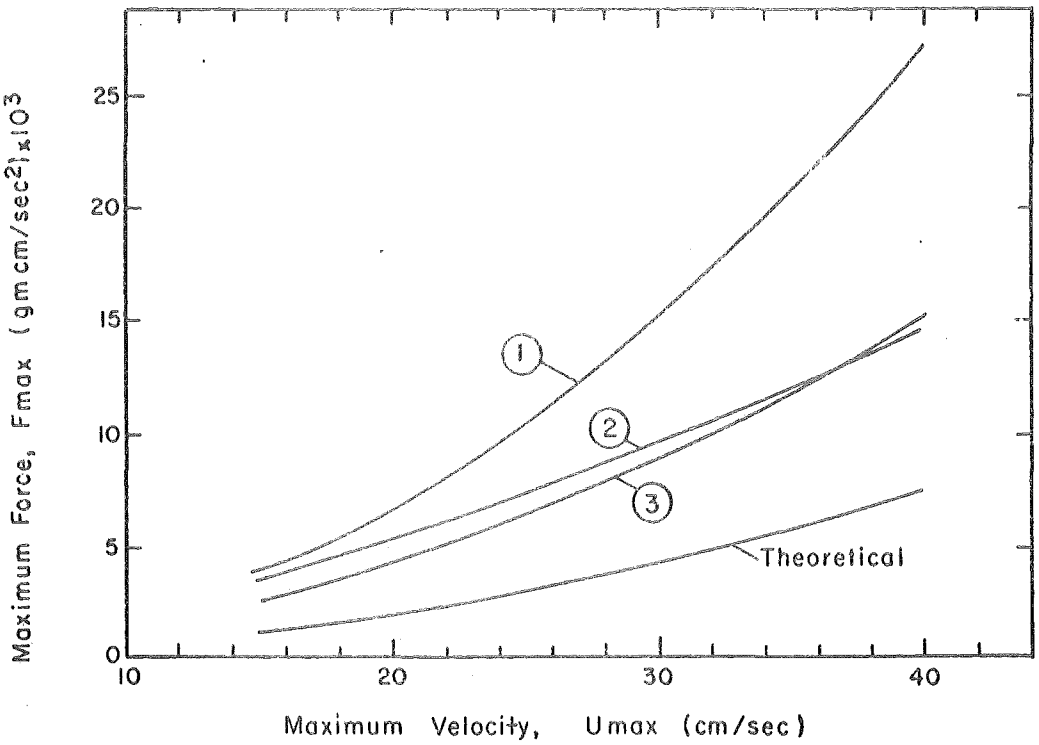

Fig. 8.12 - Comparison of Fmax-Umax relationships for three sensor levels from Fig. 8.11, with the theoretical curve predicted for Fd in Table 8.12.

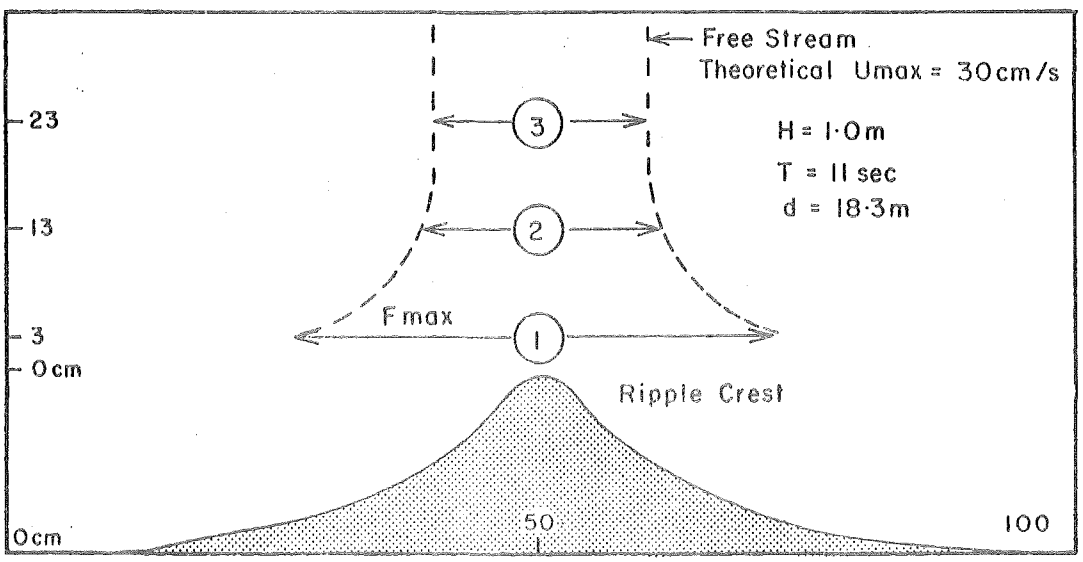

Fig. 8.13 - Vertical distribution of dimensionless maximum surge force, relative to free stream conditions of Umax = 30 cm/sec at sensor three level.

movement of all the sand grains (ranging in size from 0.5-2.0 mm) on the highest 5 cm of a 15 cm dune crest. Vortex motion was also present on the alternating lee sides of the dune crest.

The surface waves producing this movement had heights of 0.8-1.0 m with a period of 11 sec, which corresponds to theoretical free stream velocities of 25-30 cm/sec (Fig. 8.2). According to the predictive estimates shown in Table 8.4, bottom velocities of 35-45 cm/sec are required to initiate sediment motion of sand particles with D_{50} = 1 mm. Therefore, a substantial amount of sediment movement was observed to occur at free stream velocities which were less by about 30% than those required for threshold movement of a number of laboratory derived equations. Thus, it follows that actual seabed velocities were at least 30% higher over the dune crest, than were free stream velocities at a low height above the crest.

Vertical Distribution of Surge Forces

Fig. 8.13 illustrates the vertical distribution of maximum surge forces (Fmax) within the bottom boundary layer in this study. The relative magnitudes of the surge forces have been taken from the curves in Fig. 8.12, for a representative theoretical free stream Umax of 30 cm/sec. Note that the Fmax vectors are dimensionless, and have been represented in terms of sensor three which is assumed to be in the unaltered, free stream flow.

It can be seen that maximum surge forces at the sensor one level are about two-times the magnitude of those at the sensor three level. Corresponding to this, maximum surge velocities are greater by about 1.4 times at the lower level. This finding, along with the information on sediment motion described above, confirms that field

measured seabed velocities exceed laboratory and theoretically predicted velocities by about 30%.

8.8 SUMMARY

A predominantly field oriented approach has been used to study the contemporary mobility of mixed sand and gravel inner shelf sediments over a three month period. A field approach was used because much of the existing theoretical and laboratory derived predictions for seabed sediment movement lack extensive field application and verification. In addition, there has been very little work done on the movement of gravel size particles in a wave dominated, inner shelf environment. In this respect, limited wave observations and measurements taken over the study period have provided considerable information for the interpretation of seabed sediment transport processes.

Symmetrical dune bedforms, which completely cover the seabed surface, are wave generated and very dynamic, varying over time with changes in wave conditions. Measurements of dune trough and crest sediments, and dune dynamics have indicated that there is approximate agreement between other studies and the present one, although natural dunes probably only approach rather than attain an equilibrium form in the study area. In addition, the characteristics of dunes present on the seabed after a large wave event probably reflect wave conditions during the dying stages of the event rather than those at its peak intensity.

Measurements of vertical changes in the seabed surface using depth of disturbance rods have shown that local cut and fill ranges up to the height of dune bedforms (15-20 cm), and that mean changes in seabed surface levels are $\pm$ 4-5 cm which indicates that horizontal redistribution of sediment is taking place. Attempts at measuring sediment movement using traps roughly defined three periods of none or little movement, moderate rates of movement, and rapid rates of movement for coarse sand to granule sized sediments.

Study of the movement of small and large pebbles using tracer techniques was more successful than sediment traps in quantitatively determining the amount and direction of sediment movement. Large pebbles (20-50 mm) were mobile during moderate swell and larger wave events with a rapid increase in mobility for pebbles less than 35 mm. In addition, a conservative estimate indicates that pebbles which are two-three times larger than those predicted from a laboratory derived method can be moved. Small pebbles and large pebbles both showed a northeast (seaward) direction of movement which indicates that short term measurements support the inferred long term sediment transport direction determined in Chapter Seven.

An instrument was built to measure bottom wave surge force immediately above a seabed dune surface. The effect of dune bedforms on free stream flow is to create maximum bottom surge velocities predicted from wave theory for unaltered near-bottom conditions.

In conclusion, it has been shown that the contemporary mobility of inner shelf sediments, up to large gravel size, is appreciable. Therefore, it is not likely that any shallow ($<$1 m deep) dredging-induced topography would persist for periods of more than a few years.

Moreover, the direction of movement of gravel sized inner shelf sediments at the study site was found to be seaward, which suggests that this sediment is not involved in a natural transport system between the inner shelf and the adjacent beach.

CHAPTER NINE

CONCLUSION

This thesis has presented results from a variety of geomorphic and sedimentary investigations on the sand and gravel deposits of the coast and inner shelf along the east coast of Northland. The investigations were conducted in order to assess the possibility of environmental impacts resulting from the dredging of inner shelf deposits. Research was conducted with two, broad objectives:

(i) to describe the characteristics of the deposits, and the role played by geologic, geomorphic, and physical environmental factors in their formation. This objective has also included determining origins of the deposits and present-day relationships between coastal and inner shelf sediments;

(ii) to study the contemporary dynamics of inner shelf sediments, particularly the wave-induced transport of coarse sediment.

Specific investigations which were carried out have included a review of previous studies in the field area, and other studies on inner shelf sedimentation from within New Zealand and overseas. The role and significance in the study area of various geologic, geomorphic, and physical environmental factors was also assessed, based mostly on pre-existing information. Field work was conducted during two summer seasons of five months each. Major field investigations have included the survey of coastal deposits for their sediment and morpho-dynamic features; the survey of inner shelf deposits using an echo sounder,

seismic profiler, surface sediment samples, and sub-bottom cores; and detailed sediment transport studies on inner shelf deposits, using sediment tracing techniques and a bottom wave-surge meter. A summary of the major findings from these and other investigations is presented in the following. Based on these findings the implications for inner shelf dredging are discussed and some suggestions are made for further research.

9.1 SUMMARY OF MAJOR FINDINGS

Previous Research

A review of the international literature on sedimentation in coastal and inner shelf areas demonstrated a high degree of geographic diversity, and the need for specific regional studies such as the present one. In this respect, many of the findings from previous work, which has been concentrated in North America and Europe, were found to be inapplicable to the study area. Moreover, within New Zealand, geographic variation in many factors also militates against the areal extrapolation of research results within the country. However, more general concepts of coastal and inner shelf terminology and development could be usefully applied in this study.

Geologic and Geomorphic Factors

The Northland coast and inner shelf is narrow and steep, the shelf almost everywhere reaching 50 m depths within 5 km of the coast. Exposed beach deposits occupy only 15% of the shoreline and occur as isolated deposits of limited size. Gravel inner shelf deposits usually occur at depths of 30-50 m, and are also localised and limited in size.

Major regional structural trends have produced large coastal embayments between high standing blocks which form lengths of cliffed coast. The inner shelf deposits studied in this thesis were located adjacent to these lengths of cliffed coast. Other deposits, of probable relict fluvial origin, may occur in the embayments seaward of existing rivers, but are probably buried beneath more recent sands.

The evolution of the shelf in Pleistocene times has occurred under relative tectonic stability, with vertical movements of $\pm$ 10-20 m in 100,000 years. In comparison, greater rates of oscillatory sea level change have been 100 m in 20,000 years.

Physical Environment Factors

An examination of existing information on the magnitude, frequency, and significance of contemporary processes has identified the following main features of the study area. Weather systems, and wind and wave climates, show not only a seasonal pattern, but also variability from year to year. The effects of this temporal pattern on beach dynamics can be expected to usually cause beach erosion in winter, accretion in spring-early summer, and a variable response in late summer-autumn. It was also shown that the combination of high spring tides and storm surge effects could produce conditions conducive to episodic beach erosion in any month of the year. Furthermore, long term sea level rise may also be causing slow, but steady, beach erosion.

The effects of currents on sediment transport in inner shelf regions were separated into fair-weather and storm periods. Under fair-weather conditions, transport processes comprise weak oscillatory bottom wave surge motion coupled with tide generated currents. Under storm conditions, moderate to high bottom wave surge motion coupled

with tidal, wind driven, and storm surge induced currents, is likely to exert a predominant influence on the movement of coarse sand and gravel sediments.

Coastal Deposits

This investigation has demonstrated marked spatial and temporal variations in, respectively the sediments and morphology, of beaches in the study area. The Bay of Islands Sand Facies, which was studied in more detail than was originally done by Schofield (1970), has been further defined in terms of the variability of shell and greywacke rock fragments in beach sediments. Shell sand in beach sediments ranges from 2.3-82% by weight with differences between areas probably being due to the combination of shell production, transport and deposition, and dilution by other sediment sources.

Historical coastal changes, determined from air photos for 30-40 year periods, were usually <10 m, with most areas showing stability (<5 m change). In comparison to other areas around New Zealand, beaches in the study area can be regarded as relatively stable over long periods. In contrast, seasonal and annual beach changes were as great or greater than long term changes with exposed sandy beaches experiencing horizontal changes of up to 40 m in a few months. The temporal pattern of beach changes was found to agree approximately with the quasi-seasonal nature of the wind and wave climate.

At some locations in the study area, beach-inner shelf relationships were demonstrated to exist in the form of the supply of shell material to beach sediments (which have a regional, mean shell sand content of 40%). However, this relationship varies geographically

within the study area depending upon the amount of sediment from other sources (terrigenous, and non-biogenic marine).

Inner Shelf Deposits

With the exception of Pataua, the prospecting areas studied in this investigation are all located off rocky, cliffed coasts, and are underlain by planed, bedrock surfaces at water depths of 30-50 m. A comparison of sediment samples, both between and within the areas, did not show marked clustering based on either textural characteristics or geographic location. This was taken to mean that the deposits have similar origins.

Most of the deposits occur as 3-10 m thick pockets and discontinuous sheets. A sub-bottom profiler survey did not reveal buried river channels beneath the deposits in the prospecting areas, although they were found in other areas. A previously proposed hypothesis for a fluvial origin of the deposits has therefore been rejected in favour of one which is more consistent with the data and observations found in this study. The gravels are now thought to have been originally derived directly from the erosion of adjacent coastal rock exposures. This would have occurred both throughout a series of sea level highs 20-40 m below present in the last glaciation, and since that time during the last post-glacial transgression.

In addition, shell is present at levels of 36-56% in coarse and fine gravel fractions, and has been mixed to a depth of at least 1.5 m. Furthermore, because this shell is from inner shelf communities, it is concluded that the deposits are now at least palimpsest, and may even be modern because of the contemporary inner shelf biogenic and physical processes which are determining deposit characteristics.

Pataua Inner Shelf Deposits

A detailed survey of seabed surface sediments identified three main sediment facies which were separated by abrupt boundaries with little mixing of size fractions. Thus, the present inner shelf environment has either maintained or produced this well-defined, spatial sorting of extremes of sediment size. Shifts in facies boundaries were also found to occur over a year and shorter periods and were probably associated with storm events and the resulting movement of a fine sand facies.

Within the gravel facies, sediment characteristics were not uniform, with distinctive areas of sandy gravels and gravelly sands. Sediment size data and shell content distributions also showed mobility of sediments within the deposits. The main body of the deposit is active and is involved in a north-northeasterly sediment transport system. Other gravel areas do not appear to be involved in the dynamics of the main body of the deposit and are apparently less active. Shell contributes significantly to all the sediment facies, but there is a steady decrease with size: gravel (41%), coarse sand (36%), and fine sand (23%). This trend is thought to reflect the relative availability of non-biogenic sediments.

Seismic and coring studies have shown that the gravel forms a relatively thin (1-2 m) sheet overlying a basement of stiff clay. The latter has been interpreted as a subaerially weathered surface. No river channels were found in the basement surface, although the original source of the deposits may have been fluvial or other non-marine. However, inner shelf shell is presently mixed to the base of most of the deposit. Thus the deposit is thought to represent a

coarse sand and gravel sheet which was modified in a beach environment and laid down by the last post-glacial transgression, and appears to still be evolving in its sediment characteristics and spatial distribution.

Contemporary Sediment Movement Studies

Sediment movement was studied in detail over a four month period for a site at a 18 m depth at Pataua. The seabed sediments comprised mixed sand and gravel which were formed into large, symmetrical dunes with heights of 15 cm and wavelengths of 100 cm. Dune dimensions varied over the study period in response to wave conditions, and it was estimated that dune crest sediment (coarse sand) was actively moving about 25% of the time. Dune formation was observed in the field under particular wave conditions. A comparison of these conditions with the threshold of dune formation predicted from a laboratory derived technique showed approximate agreement.

Vertical changes in the seabed surface displayed a range similar to that of dune heights, whereas mean changes of 4-5 cm were due to net sediment movement. In this respect, seabed sediment traps, although being unsuccessful in determining rates and directions of movement, showed periods of differing amounts of sediment movement.

Pebble movements were very successfully determined from tracing techniques. Large pebbles were moved distances of 1-5 m in 3 months. The sizes of pebbles moved exceeded the threshold sizes predicted by a laboratory derived technique. Small pebble dispersion showed a northeasterly trend which agreed with the long term direction inferred from seabed sediment distributions.

A bottom wave surge meter was also used successfully in measuring the alteration of free stream wave velocities in the boundary layer close to the seabed. In particular, it was shown that actual seabed velocities were about 30% greater over dune crests than those predicted from theory.

9.2 IMPLICATIONS FOR DREDGING

One of the objectives of this thesis was to determine the possibility of environmental impacts resulting from the dredging of inner shelf deposits. The environmental impacts which have been considered are all geological and are based on the extent of contemporary relationships between prospecting areas and coastal deposits. On this basis, for five of the six prospecting areas (Stephenson Island, Nine Pin, Home Point, North Gable, and Awarua Rock), the possibility of beach erosion resulting from inner shelf dredging is remote. In particular, these prospecting areas are located off rocky coasts, with either no exposed beach deposits on the adjacent coast or no connection to beach deposits further along the coast. In addition, submarine profiles surveyed off beaches also show areas of rock reef which intervene between beach and inner shelf areas, and where sediment is present in shoreface regions it is typically a thin and patchy cover over the underlying bedrock basement.

As regards the possibility of fines (silt and clay) being stirred up by the dredging process, it has been shown that only small amounts (1-2%) of fines are present within the deposits. Moreover, although a naturally occurring, temporarily variable, veneer of fines may occur

in deep (50 m) areas, coarse inner shelf deposits in the study area are not ultimate sites of deposition for fine sediments.

Although Pataua was the only area in which beach erosion was considered to be a possible result of dredging, this does not now appear to be likely based on the following criteria:

(i) similar beach and inner shelf sands are separated by a shoreface fine sand facies;

(ii) a stiff clay basement limits the depth of dredging and thus the draw-down of sediments;

(iii) undesirable changes in wave refraction are not likely to result from dredging because of the uniformly thin nature of the deposit;

(iv) the natural movement of coarse inner shelf sediments is offshore, and do not appear to supply the beach with sediment.

Although all of these criteria militate against erosion, it is advised that monitoring of beach, shoreface, and inner shelf areas should be established on a continuous basis if dredging is permitted at Pataua.

9.3 SUGGESTIONS FOR FURTHER RESEARCH

The research in this thesis is the first attempt at extensively examining coastal and inner shelf deposits in the study area. Because the objectives of the thesis have concentrated work near to the six prospecting areas, there are large parts of the coast and inner shelf which were not examined. In particular, this includes the spits at Ngunguru and Whananaki, and the large embayments of Whangaroa Bay, Bay of Islands, Whangaruru Harbour, Sandy Bay, and Ngunguru Bay.

It is quite likely that relict, fluvial deposits and buried river channels occur in these embayments.

Phenomena which show temporal variation, such as weather patterns, wind and wave climates, and beach morphology, have been studied in detail for only two years. The proposed quasi-seasonal nature of these phenomena could be usefully confirmed from longer term surveys. Such information would be valuable in a wide variety of local, planning contexts.

Sediment tracing techniques were successfully applied in this study but were labour intensive. Consequently, both tracer techniques and data recording for the surge meter should be automated so that they may be applied more efficiently.

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APPENDIX ONE

BEAUFORT SCALE OF WIND (1, 2)

Beaufort Number	Descriptive Term	Equivalent Mean Velocity Range (metres/sec)	Corresponding International Scale of Sea State Wave Heights (metres)	
0	Calm	0 - 0.2	Calm, Glassy	
1	Light Air	0.3 - 1.5		
2	Light Breeze	1.6 - 3.3	Rippled	(0- 0.3)
3	Gentle Breeze	3.4 - 5.4	Smooth	(0.3- 0.6)
4	Moderate Breeze	5.5 - 7.9	Slight	(0.6- 1.2)
5	Fresh Breeze	8.0 - 10.7	Moderate	(1.2- 2.4)
6	Strong Breeze	10.8 - 13.8	Rough	(2.4- 4.0)
7	Near Gale	13.9 - 17.1	Very Rough	(4.0- 6.1)
8	Gale	17.2 - 20.7		
9	Strong Gale	20.8 - 24.4		
10	Storm	24.5 - 28.4	High	(6.1- 9.1)
11	Violent Storm	28.5 - 32.6	Very High	(9.1-13.7)
12	Hurricane	$\geq$ 32.7	Phenomenal	(>13.7)

Sources: (1) Beaufort Number, Descriptive Term, and Equivalent Mean Velocity Range from Kerr (1976).

(2) Corresponding International Scale of Sea State from Bascom (1964.)

APPENDIX TWO

GRAIN SIZE PARAMETERS

(after Folk, 1974)

Graphic Mean $$M_z = \frac{(\phi 16 + \phi 50 + \phi 84)}{3}$$

Inclusive Graphic Standard Deviation

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Inclusive Graphic Skewness

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

Graphic Kurtosis

$$K_G = \frac{\phi 95 - \phi 5}{2.44\,(\phi 75 - \phi 25)}$$

Where $\phi 16$, $\phi 50$, etc. are the phi values of the 16th, 50th, etc percentile taken from the cumulative size distribution curve.

Verbal Classification Scales (ϕ units)

Inclusive Graphic Standard Deviation (Sorting)

<0.35	very well sorted
0.35-0.50	well sorted
0.50-0.71	moderately well sorted
0.71-1.0	moderately sorted
1.0 -2.0	poorly sorted
2.0 -4.0	very poorly sorted
>4.0	extremely poorly sorted

Inclusive Graphic Skewness (Asymmetry)

+1.00 to +0.30	strongly fine-skewed
+0.30 to +0.10	fine-skewed
+0.10 to -0.10	near symmetrical
-0.10 to -0.30	coarse-skewed
-0.30 to -1.00	strongly coarse-skewed

Graphic Kurtosis (Peakedness)

<0.67	very platykurtic
0.67-0.90	platykurtic
0.90-1.11	mesokurtic (normal curve = 1.00)
1.11-1.50	leptokurtic
1.50-3.00	very leptokurtic
>3.00	extremely leptokurtic

APPENDIX THREE

PARTICLE SIZE SCALE

Millimetres	∅ units	Wentworth Scale	
		Boulders	
256	-8		
		Cobbles	
64	-6		
		Large pebbles	GRAVEL
16	-4		
		Small pebbles	
4.0	-2		
		Granules	
2.00	-1		
		Very coarse sand	
1.00	0		
		Coarse sand	
0.50	1		
		Medium sand	SAND
0.25	2		
		Fine sand	
0.125	3		
		Very fine sand	
0.0625	4		
		Silt	
0.0039	8		MUD
		Clay	

Source: Folk (1974, p. 25)