DEVELOPMENT OF SHORE PLATFORMS ON KAIKOURA PENINSULA, SOUTH ISLAND, NEW ZEALAND

A thesis

submitted in fulfilment

of the requirements for the degree

of

Doctor of Philosophy in Geography

in the University of Canterbury

by

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University of Canterbury

1997

ABSTRACT

Shore platforms on the Kaikoura Peninsula have been examined to determine the roles of marine and subaerial weathering processes in platform evolution. Erosion was measured to assess rates of development and processes of erosion. Lowering rates on platforms are presented from two years of monitoring using a traversing micro-erosion meter. Cliff retreats were calculated using aerial photographic interpretation. Marine processes were investigated by using deep water wave data, by measuring waves on shore platforms and by analysing measured tidal data. Weathering processes were investigated using tidal data, climate data, the Schmidt Hammer test, and a laboratory experiment on wetting and drying.

Lowering rates over two years ranged from 0.07 to 19.80mm, and annual rates ranged from 0.154 to 9.194mm/yr. Rates of erosion varied with lithology and the type of platform. Erosion on Type A mudstone platforms was 1.98mm/yr; on Type B mudstone platforms erosion was 0.733mm/yr; and on limestone platforms it was 0.88mm/yr. The grand mean lowering rate for all shore platforms was 1.13mm/yr. These rates fall in the middle of the range of published rates from previous studies at Kaikoura and at locations around the world. For the first time, erosion data from a traversing micro-erosion meter were presented as volumes of material eroded. The total volume of rock eroded from study sites having, each with an area of 45.4cm^2, ranged from 1.20 to 92.50cm^3. A significant finding was that rock surfaces swell up as indicated by a rise in surface level rather than lowering from erosion. The maximum measured swelling was 8.90mm. At some measurement sites as much as 90 per cent of measurements showed swelling over a period of 98 days. Values for erosion and swelling were higher during summer months. Both erosion and swelling were shown to be statistically related to season, suggesting that weathering is the group of processes causing both erosion and swelling. Summer provides better conditions for wetting and drying, which is thought to be the most important weathering process on shore platforms. Horizontal retreat rates were calculated over 52 years for cliffs, beaches and lagoon deposits backing shore platforms at Kaikoura, these ranged from 0.05 to 0.91m/yr.

Investigation of marine processes showed that the deep water wave environment off the Kaikoura Peninsula is very energetic, but the amount of wave energy delivered to platforms is very low. A comparison of deep water wave energy flux with wave energy flux at the landward cliff of platforms, showed that there was a reduction by as much as five orders of magnitude. An analysis of the role of breaking waves revealed that these were ineffective as an erosional agent

because the depth of water offshore causes breaking well before waves arrive on platform surfaces. Shear stresses and dynamic forces under waves were calculated from waves measured on shore platforms. This showed that these forces never exceeded the compressive strength the platform rocks at Kaikoura. It was concluded that wave forces are not directly capable of causing erosion.

Evidence of weathering on shore platforms came from a number of distinctive surface morphologies on platforms: honeycombs, salt crystal growths, water layer weathering; and slaking. Schmidt Hammer test data showed: firstly, that weathering had occurred; and secondly, that rock strength was reduced through weathering by as much as 50 per cent. Weathering processes on shore platforms rely on repeated wetting and drying, and for this reason the number of wetting and drying cycles was estimated. The number of cycles ranged from 104 to 379 per year, the variation was due to tidal influences and the growth of algae during winter months. At elevations low in the tide range fewer cycles occurred; the greatest number occurring between the peaks of spring and neap tides, where rainfall adds to the number. Most cycles were estimated to occur between 0.6 and 0.9m above mean sea level on the more landward margins of platforms. It was at these elevations and locations that the highest rates of erosion were measured. Laboratory experiments on wetting and drying showed that only one cycle was needed to cause erosion.

Waves were shown not to cause erosion, while subaerial weathering does. Statistical analysis showed significant relationships between erosion, and wetting and drying and elevation. Based on these results it was concluded that the development of shore platforms at Kaikoura relies on weathering resulting from repeated wetting and drying. This is contrary to recent work which proposed that shore platforms result from marine erosion. Published mathematical models of shore platform development were found to be invalid at Kaikoura, because they were designed on the assumption that platforms are indeed wave cut features. This assumption is incorrect for shore platform development at Kaikoura. An empirical model is presented to explain platform evolution and the differences in platform morphology. A separation between platform types is presented based on the ability of weathering to cause erosion and on compressive strength. This is contrary to a published demarcation between types based on the erosive force of waves and on compressive strength. The type of equilibrium that platforms tend towards is considered. It is proposed that there are two ways to consider equilibrium. First, platforms may be lowered to an as-yet-unidentified elevation; this was viewed as being a static form of equilibrium. Secondly, platforms may continuously widen because weathering is an ongoing process. It was proposed that there is no equilibrium width for shore platforms.

ACKNOWLEDGMENTS

The completion of a thesis requires a great deal of help from a great many people, and this one was no exception. First and foremost I would like to extend my warmest thanks to Karen Stephenson without whom none of this would have been possible. Your continued love and support has been the one primary source of motivation through out the course of preparing this thesis. Thanks for all those hours spent collecting MEM data. To my parents who have always supported my university career, thanks heaps.

Bob Kirk, my supervisor has provided invaluable support through out this thesis by reading and critically reviewing drafts, providing ideas and importantly, encouragement when needed. Bob also made available data from the original MEM data. Thanks Bob for all this, and giving a lad from Hornby a chance.

Jonathan Allan with whom I shared the Ph.D. experience. We've both come a long way Jon since being undergraduates together. Thanks for the hours of recreation at your field site, and I hope you enjoyed the recreation at mine. Thanks also for all the help with fieldwork, I hope you find those sea legs that you never seem to have when we're in a boat together. Its been great having your friendship along the way. Hamish McGowan helped in the field work and provided a cool head under pressure. The effort of dragging a generator around the Kaikoura Peninsula was above and beyond the call of duty.

Peter Tyree skilfully constructed a second traversing micro-erosion meter and drilled holes all over the Kaikoura Peninsula for MEM bolts. All I can say Pete is that I don't think it will fall apart any time soon! Thanks also for providing useful suggestions on the technical aspects of the field work. Most importantly thanks for showing me how to have fun in the field and not get caught. Thanks to Gary Smith who provided further technical support and help with field work. I hope Gary we have shown you how to have fun in the field and not get caught.

Jack van Berkel manager of the Edward Percival Field Station provided useful insights into the vagaries of the Ph.D. processes. Most importantly he provided support for fieldwork and a bed. The station was wonderful place to based while doing fieldwork. I shared Kaikoura with many marine biologists, Joe, Robin, Chris, Alan, and Craig, who all tried to change my point of view. At the very least you showed me another way to view a remarkable environment.

Janet Bray (Department of Geography Map Librarian) methodically proof read the thesis. I am eternally grateful Janet for you being so willing to undertake such a laborious task. While Janet has done a remarkable job, responsibility for any remaining errors is entirely with the author.

The Department of Geography provided funding, and logistical support without which this thesis could not have been completed. Thanks to all the staff who have contributed to this thesis through discussion and providing ideas. Special thanks to Michelle Rogan who drafted figures 2.10, 3.3, 3.8, and 4.1, and Tim Nolan who drafted figure 3.5.

Robin Jenkinson of the Kaikoura District Council kindly allowed the tide gauge to be installed on the wharf at Kaikoura. N.I.W.A. provided financial support for the installation of the tide gauge. Thanks to Derek Goring for facilitating this, and for subsequent modifications to the instrument. Mr. Wayne Collier of CANDAC-Perry Joint Venture made available Wave Rider data, to him and Fred Smits of N.I.W.A who facilitated this, I am very grateful. These data made a very important contribution to this thesis.

Finally thanks to all those fellow students and staff with whom I have spent time doing Geography, its been a whole lot of fun.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

α = platform slope.

ρ = weight of water

κ = a constant

β = gradient of the inherited slope

Γ = nondimensional constant

τ = shear force

α_* = a wave height attenuation coefficient

α'_* = is an attenuation coefficient for bore height.

$(H_o)_b$ = the height of the deep water wave which breaks in front of the cliff

ω_o = weight of water per unit volume

A = erodibility factor

A = is a nondimensional constant representing abrasion

a_0 = is a reduction coefficient

a_f = is a reduction coefficient of F_W

B = a constant representing discontinuities in the cliff

B = a nondimensional constant representing reduction in strength due to weathering

C_f = a nondimensional coefficient of friction

d = water depth from still water level to cliff base

dD = increment of platform down cutting in time

D_e = duration

D_i = the duration in (hrs/yr) of the tide at n at an intermediate point on the tidal cycle.

dW = increment of cliff retreat in time

dX/dt = the rate of cliff erosion

F = still water level

F = the erosive force of waves.

F_n = tidal duration factor given by:

F_R = resisting force of rock

F_{RS} = the resisting force of rock against surface lowering.

F_W = the assailing force of waves

$F_W(z)$ = the assailing force of waves at depth z (negative value) measured from still water level

F_{WS} = the wave assailing force causing surface lowering

g = acceleration due to gravity

h = depth of water at base of the cliff taken from still water level

H = wave height

H= wave height in front of the cliff

h_a = wave base

H_b = breaker height

h_b = breaking depth

H_b = height of breaking wave

$ho = (\pi H^2/L)coth(2\pi h/L)$

I_e = gradient

l = distance from breaking point

L = wave length

L_b = wave length at break point

n = number of time the cliff has collapsed and debris removed

n = platform level 1,2,3...

n = platform level 1,2,3...

N_e = number of high or low tide levels at n

N_i = the number of high and low tides above or below n.

p = pressure.

p_m = maximum pressure intensity

p_o = pressure at still water level

R = erosion (cm/yr)

S = amount of debris removed in a year

S^*_c = compressive strength of the rock accounting for discontinuities,

S_c = compressive strength of the rock,

t = time (years)

T = wave period

$tan\ \beta$ = bottom gradient

$tan\ \alpha_{n-1}$ = submarine slope at each time interval

$T_{n,x}$ = total time taken to undercut cliff and remove debris

T_r = tidal range

U = amount of cliff undercutting in a year

U = water velocity

V = amount of energy required to erode 1cm of rock.

V_{pc} is the longitudinal wave velocity measured in a specimen without visible cracks.

V_{pf} is the longitudinal wave velocity measured in situ

W = deep water wave energy delivered per hour

W_e = width

Wo = initial platform width

x = depth of notch at point of collapse

x_1 is the horizontal distance from the shoreline to the wall and

x_2 is the horizontal distance from the shore line to the limit of wave run if the wall did not exist.

z = increase in water depth

Z_c = critical depth of erosion, that is, the elevation of a platform

1. INTRODUCTION

1.1 THE THESIS PROBLEM

This thesis investigates how shore platforms are developing on the Kaikoura Peninsula of the South Island of New Zealand. Shore platforms are commonly defined as horizontal or near horizontal surfaces at the shore line, but less commonly stated is that shore platforms are erosional features. How shore platforms develop has been of interest to geomorphologists since the early and mid Nineteenth Century when Hawkins (1827), Ramsey (1846), and Dana (1849) first commented on the existence of such features. Even though a large body of literature has arisen, a satisfactory explanation of how shore platforms develop has not been forthcoming because different processes leading to development have been identified. It was argued by Dana (1849), Bartrum (1924, 1926), Edwards (1941, 1951), Sunamura (1978a, 1992), and Trenhaile (1987), that the primary agent of shore platform development is the erosive force of waves while Bartrum (1916, 1938), Wentworth (1938, 1939), and Hills (1949), identified subaerial weathering as the formative process. This difference of views, led to a "wave versus weathering" debate. However, belief in the action of both in concert has also been stated by Bell and Clarke (1909), Bartrum and Turner (1928), Bartrum (1935), Jutson (1939), Mii (1962), and Kirk (1977).

While both wave erosion and weathering have been recognised as being important in the development of shore platforms, the problem has been to explain the relative contribution of each to the development of shore platforms. Studies that have recognised both weathering and wave erosion as having a role in platform development have tended to emphasise one over the other, assigning either weathering to a secondary role (Bartrum and Turner 1928; and Bartrum 1935) or waves to a secondary role (Hills 1949; and Wentworth 1938, 1939). Few studies have suggested that both processes are of equal importance. An exception was Kirk (1977), who speculated that shore platforms develop as a result of the interaction of subaerial weathering and erosive marine processes. He proposed that this interaction exists because there is a gradient from subaerial weathering on the landward edge of shore platforms to true marine processes at the seaward edge, but rigorous testing of this hypothesis has not been undertaken. It is the intention of this study to make such a test and in the same area where Kirk examined platforms.

An understanding of shore platform development is needed for its own sake and because of interest in reconstructing former sea levels during the Quaternary. Because of their longevity as features in the landscape shore platforms have been used extensively for this purpose, despite uncertainties of linking the elevations of shore platforms to sea level. This point was made as early as 1960 by E.S. Hills in an address to the Geological Society of London. "Unless we understand the ways in which shore platforms are formed it is obviously fruitless to draw conclusions from them about relative movements of land and sea." At a more fundamental level, shore platforms are of interest because they constitute much of the New Zealand and indeed world coastlines. They form up to 20 to 30 per cent of the 10000kms of the New Zealand coast (Kirk 1977). Emery and Kuhn (1982) estimated that 80 per cent of the world's coastline can be classified as rocky. What percentage of this could be classified as having shore platform morphologies can only be speculated about, but a figure similar to Kirk's (1977) may be plausible. This lack of an estimate of the proportion of the world's coastline that has shore platforms itself highlights a paucity of attention paid by geomorphologists to this coastal feature in recent years. Modern research into the development of shore platforms is limited to the work of only a few individuals while coastal studies has grown immensely of the past three decades. Studies of shore platforms contribute to the understanding of landform evolution, the reconstruction of past sea levels and our knowledge of rocky coast geomorphology but they are currently studied by only a few coastal scientists.

One reason for the lack of understanding of how shore platforms develop is that the bulk of early research was characterised by qualitative, explanatory and descriptive writing; even to the point that morphology was described in words. There was almost no attempt to quantify either the processes or the rates of morphological change. The problems that arose from such investigations were suitably encapsulated by Mii (1962) who wrote that, "processes have been inferred mostly from morphological detail, the 'process' then being employed in the explanation of further morphologies. Arguments can thus become easily circular because morphology is a notoriously ambiguous indicator of process and of process rates". Another problem caused by qualitative investigations was identified by Kirk (1977) who stated that as a result of such research, "it is difficult to compare studies from one environment with another, and there are few hard data with which to rigorously test different hypotheses of shore platform development". He continued... "there is a need for quantitative studies of both shore platform erosion and cliff retreat and to relate such data to the hypotheses of development [of shore platforms]".

Attempts to measure erosion rates have been made by Emery (1941), Revelle and Emery (1957), Hodgkins (1964), Horikawa and Sunamura (1967 and 1970), Evans (1968) and

Sunamura (1973). Such studies attempted to measure either the rate of surface lowering on the horizontal surface of a platform, or the rate of cliff retreat at the back of a platform. These studies were followed by Robinson (1976, 1977a,b,c), Trudgill (1976a,b) and Kirk (1977), who each used the then newly developed micro-erosion meter to accurately measure rates of surface lowering on platforms. This method has since been used more widely (Spencer 1981, 1985; Gill and Lang 1983; Mottershead 1989; and Stephenson and Kirk 1996). Investigations using the micro-erosion meter focused on a single process or a group of processes without being able to identify the precise role or contribution each makes to platform erosion. The use of a technique that allowed precise quantification of erosion rates did not lead to a clear elucidation of processes. While precise measurements of erosion rates are now possible the number of published rates is still few and restricted spatially and temporally. Cliff recession is commonly measured at the scale of two to three decades, but platform lowering has most often been measured over periods of about two years (Trudgill 1976a, 1976b, Robinson 1977a, 1977b, 1977c; and Kirk 1977). Since shore platform development is thought to occur at a scale of thousands of years, extrapolating short term data may not validly estimate rates of development. While erosion rates were measured, quantitative descriptions of morphology also became more common (Mii 1962; Trenhaile 1971, 1972, 1974a, 1974b; Robinson 1977a, 1977b, 1977c; and Kirk 1977). Platform elevation in relation to sea level, width, and gradient were the morphological features most often measured using surveying techniques.

In the last 20 years the body of literature containing published erosion rates has increased, going some way to addressing the problem identified by Kirk (1977) that there "are few hard data to compare studies...." yet there are no published accounts of process measurements on shore platforms. Wave erosion has been identified as a formative process but surprisingly, there have been no measurements of waves on shore platforms! Such measurements may show if waves can cause erosion and if wave erosion is concentrated on the outer edge of a platform and weathering inner margins. Recent studies (Tsujimoto 1987; and Sunamura 1990, 1991) have used deep water wave data to investigate wave dynamics on shore platforms, but have not been able to account for the loss of energy as waves shoal across platform surfaces. Our knowledge of wave characteristics on platforms is therefore very poor. As with wave processes, there are no accounts of measurements of weathering processes on shore platforms. While it may not be possible to directly measure weathering it is possible to measure those climatic variables that control it. There is therefore a need to directly measure processes thought to be responsible for platform development because it may be possible to determine the effectiveness of each process as an erosive agent. Direct measurement would also address the problem identified by Mii (1962) of the ambiguity in using morphology to interpret processes.

Rather than investigate erosion rates and platform morphology, a different approach to studying shore platform development was adopted by Japanese researchers (see Sunamura 1992). The approach they used has been to examine the development of shore platforms through the investigation of wave dynamics and geomechanics. The guiding paradigm has been that shore platforms only develop when the erosive force of waves (F_W) exceeds the resisting force of rock (F_R). Investigations have been concerned with quantifying both variables. This work was supported using physical laboratory modelling (Sunamura 1973, 1975). The difficulty with this approach is that it does not explain what happens when resistance is over come. From physical modelling and field investigations, models have been developed to predict the elevation, width and gradient of shore platforms (Sunamura 1978b, 1990, 1991, 1992), and the relationship between wave force and cliff retreat (Sunamura 1977).

Elsewhere, models were developed to investigate types of equilibria that platforms may attain (Trenhaile 1974a), the relationship between tides and platform development (Trenhaile and Layzell 1980 and 1981), the relationships between platform width and time (Trenhaile 1983a), and the role of Holocene sea level fluctuations in shore platform development (Trenhaile and Bryne 1986). Models based on the relationship between F_W and F_R have provided conflicting results and conclusions with those models developed by Canadian researchers. For example, Trenhaile (1974a) concluded that shore platforms are in a state of dynamic equilibrium, whereas Sunamura (1990) indicated that platforms tend to a static state. Trenhaile and Layzell (1981) showed that tidal range controls platform gradient and width, while Sunamura (1978b, 1990, 1991) showed width and gradient are related to wave height, depth of water in front of the platform, and rock strength. One reason for these contradictions was that different assumptions about processes were used in the design of models. These contrary assumptions resulted because of different interpretations of shore platform development.

While there are contradictions between models of shore platform development, there are also other problems in existing models that need further research. Fundamentally, all models are designed on the premise that wave erosion is the formative process. This is surprising because the question of how platforms develop has not been satisfactorily answered. The assumption that platforms are wave-cut must be questioned since the relative roles of waves and weathering in platform development remains uncertain. If this assumption can be shown to be correct then there are a number of ways in which models can be improved. Models based on the relationship between the erosive force of waves (F_W) and the resisting force of rock (F_R) have represented F_W using either breaker height or wave pressure calculated from deep water wave data, but these wave parameters cannot account for the either the action of sediments under waves that act as abrasives and missiles on platforms, or the more violent action of waves impacting directly on platforms. Nor do they account for the attenuation of waves due to shoaling. If is accepted that wave erosion is the formative process then there is a need for better understanding and quantification of it to allow accurate modelling.

The resisting force of rock (F_R) has been represented by rock strength using the unconfined compressive strength of the rock forming the platform. In some cases this has included a discontinuity index to account for the reduction in rock strength due to variations in lithology such as bedding and joints. Subaerial weathering has not been modelled as a formative process in shore platform development but as a process that reduces rock strength (F_R). Models developed by Japanese researchers often include a nondimensional constant for weathering but this needs to be defined quantitatively. Problems of representing F_W and F_R were noted by Sunamura (1994:270) who wrote that future research should seek to "determine more appropriate parameters for the assailing force of waves when they have abrasive or explosive action and the resisting force of rocks when they are susceptible to weathering".

1.2 THESIS AIMS

The impetus for this study arises from the need to gain a more detailed understanding of the role of wave erosion and weathering in shore platform development. This will be achieved by addressing the issues discussed above. These issues are summarised into five needs for research; and these form the main aims of this thesis. The aims are:

1) To extend the small body of literature relating to measured rates of erosion. This will allow data from shore platforms on the Kaikoura Peninsula to be compared with those from other studies, thus addressing the problem of a lack of comparison between studies identified by Kirk (1977). Erosion data may also be used to interpret processes operating on platforms.
2) To measure wave and weathering processes directly to allow the assessment of each in the development of shore platforms.
3) To answer the following questions. How do shore platforms develop? Are they wave-cut or weathered or some combination of both? Do shore platforms develop as a result of a process gradient across the platform profile as proposed by Kirk (1977)? Answering these questions will allow testing of the underlying assumption of models that shore platforms are wave-cut features.

4) To test the validity of models of shore platform development with data from the Kaikoura Peninsula.
5) To explore equilibrium development of shore platforms. Two questions are asked. Do shore platforms have equilibrium forms? If they do what are they?

1.3 THESIS OUTLINE

This chapter has introduced the thesis problem by showing that the current state of knowledge cannot satisfactorily explain how shore platforms develop. It has identified: the problem of a lack of data to make comparisons with other studies; that there is a the need to measure processes thought to cause shore platforms development; the need to examine how shore platforms develop; a requirement to address problems with models of shore platforms development and investigate the types of equilibria shore platforms may tend towards. From these issues five aims have been set for the study.

Chapters Two and Three provide the context for this study through a review of the body of literature relating to shore platforms. Both chapters provide a synthesis of the current state of knowledge of shore platform development and highlight in detail 'gaps' in the present state of knowledge. Chapter Two reviews the role of wave and weathering processes and factors that influence platform development such as geology, morphology, and biological activity. Studies that have used the micro-erosion meter are also reviewed. Chapter Three provides a context for this study by reviewing models of shore platform development.

Kaikoura Peninsula, as the chosen field area, is described in Chapter Four. The geology, geomorphology, climate, wave and tidal environment and shore platforms of the peninsula are described. Chapter Four also presents descriptive data of platform morphologies collected during field investigations. Included are the results of surveys, both of shore platforms and the submarine topography. Other data presented include the compressive strength of the rocks in which platforms are developed.

Chapter Five presents results from measuring erosion rates. It starts by describing the micro-erosion meter method and variations on the original design The results from measurements of surface lowering rates on platforms are presented. Surface lowering rates at larger scales than that measurable with the micro-erosion meter are also presented. Rates of retreat of cliffs backing platforms are calculated from aerial photographs.

An investigation of the processes operating on shore platforms at Kaikoura is presented in Chapter Six. Techniques used to measure these processes both directly and indirectly are presented. Included in this chapter is an analysis of wave, tidal and weathering data. The results of measurements of waves from both offshore and on the shore platforms are presented. The role of tides is investigated using tidal data collected during the study period. Weathering is investigated through the analysis of climate and tidal data. The effectiveness of wave erosion and weathering is assessed throughout Chapter Six.

Chapter Seven uses data presented in Chapters Four, Five, and Six to explain how shore platforms on the Kaikoura Peninsula have developed or are developing. It assesses the assumption that shore platforms are wave-cut features. From this it tests the validity of a number of models presented in Chapter Three when they are applied to shore platforms at Kaikoura. It presents an empirical model to explain how shore platforms on the Kaikoura Peninsula develop. Finally it considers the type of equilibria shore platforms are in at Kaikoura.

Conclusions from the study are presented in Chapter Eight. This chapter also makes recommendations for future research.

2. THE DEVELOPMENT OF SHORE PLATFORMS - A REVIEW

2.1 INTRODUCTION.

In Chapter One shore platforms were described as horizontal or near horizontal erosional rock surfaces at the shoreline. It is difficult to provide a clear definition of what a shore platform is because many different interpretations have been made when attempting to provide a name for such features. Terms have often been intended to give some genetic information and/or an indication of the major morphology of the feature being described. Three major morphologies of rocky coasts have been identified; platforms that slope gently into the sea, platforms that are nearly horizontal and terminate abruptly with a cliff or ramp at the seaward edge, and plunging cliffs in which shore platforms have not developed. Sunamura (1983 and 1992) distinguished between the two platform morphologies by assigning the designations Type A to sloping platforms and Type B to horizontal platforms (Fig 2.1).

Many different terms synonymous with shore platform have been used, often having quite different genetic and morphological meanings. Such terms include: **shore platform** (Dana 1849; Bartrum 1935, 1938; Jutson 1939; Wentworth 1938, 1939, 1940; Hills 1949; Edwards 1951; Cotton 1963; Mii 1962; Bird and Dent 1966; McLean and Davidson 1968; Healy 1968a, 1968b, Hills 1971, 1972; Trenhaile 1971, 1972, 1974a, 1974b, 1978, 1980, 1983a, 1983b; Abrahams and Oak 1975; Takahashi 1975, 1977; Kirk 1977; Robinson 1977a, 1977b, 1977c; Sunamura 1978a, 1983, 1990, 1991, 1992; Trenhaile and Layzell 1980, 1981; Hansom 1983; Trenhaile and Bryne 1986; Tsujimoto 1987; Lawrie 1993; Griggs and Trenhaile 1994), **rock bench** (Bell and Clarke 1909), **high water rock platform** and **Old Hat Type platform** (Bartrum 1916), **abrasion platform** (Johnson 1919; Cinque et al. 1995), **shore bench** (Bartrum 1926), **storm wave platform** (Bartrum 1926, 1935; Edwards 1941), **marine bench** (Wentworth 1938, 1939) **sloping wave bench** (Edwards 1941), **inter-tidal platform** (Hills 1949; Kirk 1977; Miller and Mason 1994),), **sea-level shore platform** (Mii 1962), **wave-cut terrace** (Dietz 1963; Raju and Wagle 1996), **surf cut terrace** (Dietz 1963), **coastal platform** (So 1965), **bench, abrasion bench, denuded bench** and **tidal bench** (Zenkovich 1967), **wave cut bench** (Thornbury 1969), **rock platforms** (Phillips 1970a, 1970b), **high water rock ledges** (Trenhaile 1971) **wave ramp**

(Hills 1971, 1972), **wave-cut platform** (Sunamura 1975; Bradley and Griggs 1976), **wave cut terrace** (Sunamura 1978b), **wave-cut shore platform** (Trenhaile 1983b) and **bedrock platform** (Bray and Hooke 1997).

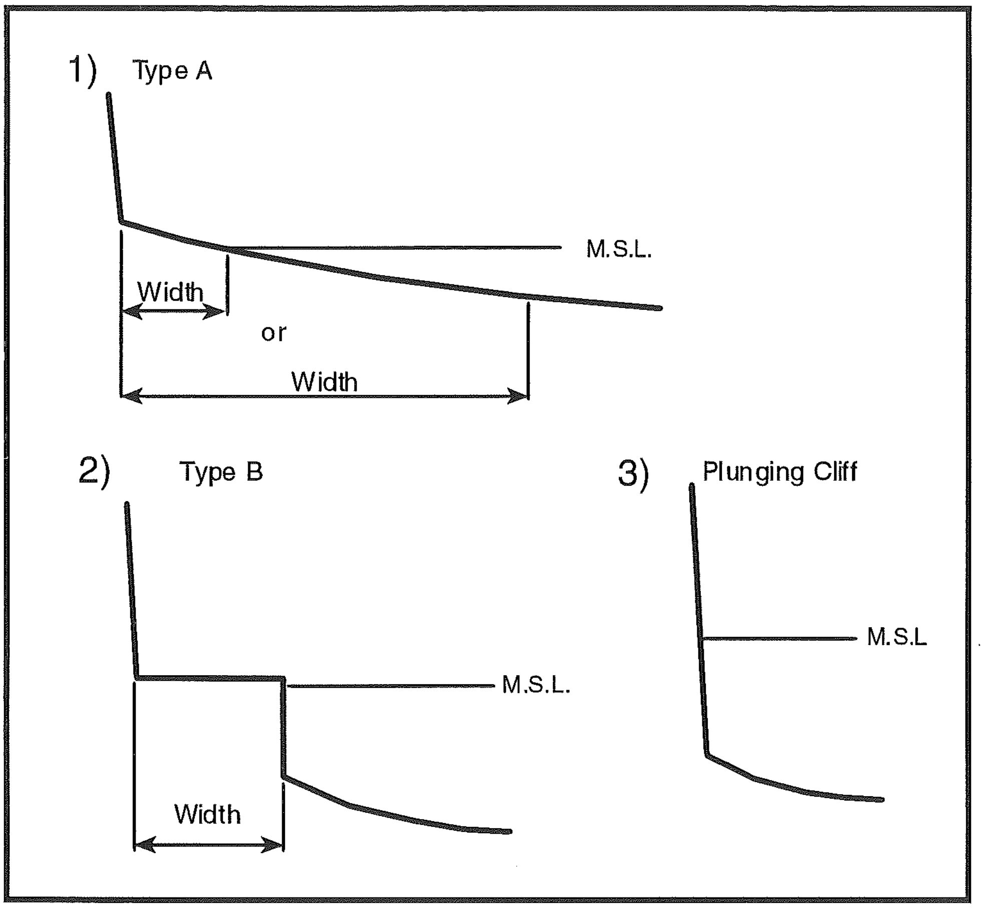

Figure 2.1 Three major morphologies of rocky coasts: two types of shore platform 1) Type A, 2) Type B and 3) plunging cliffs (Sunamura 1992 Fig 7.2).

Clearly the wide variety of terms used reflects different interpretations of morphology and processes by individual workers, and of the relationship between a surface and sea level. From the above paragraph it is obvious that the term "shore platform" has been the most widely used, probably because it has no genetic connotations. Sunamura (1992) noted that it is the most appropriate term since the development of shore platforms and the processes involved are still not fully understood. The present study adopts this view and "shore platform" is the term used throughout this investigation to describe any horizontal or near horizontal rock surface occurring at the shoreline, the elevation of which is related in an undetermined way to sea level and that is actively eroding as a result of its proximity to the sea. Given that a clear working definition of what is meant by the term "shore platform" has been provided, it is possible to precede with a review of the literature pertaining to the development of "shore platforms". Such a review is necessary in order to place the present study within a scientific context, to present current understanding of how shore platforms develop, and to identify how that understanding can be improved.

2.2 EROSION BY WAVES

Any discussion of the role of wave action on a rocky coast must consider the three types of waves that can act on it: standing waves, breaking waves, and broken waves (Figure 2.2). Which type of wave will act on a cliff is dependent on the relationship between the breaking depth (h_b) of the incoming wave and the depth of water (h) in front of the cliff (Sunamura 1992). This can be summarised: if $h > h_b$ then standing waves result; if $h = h_b$ then breaking waves occur and if $h < h_b$ then broken waves occur (Sunamura 1992). In the absence of sediments, waves may cause erosion through exerting hydrostatic and hydrodynamic pressures on rock surfaces. Each wave type exerts varying degrees of both hydrostatic and hydrodynamic pressure. Hydrostatic pressures result from the mass of water and air above a surface and hydrodynamic pressures result from turbulence and the compression of entrained air. What is of interest to the geomorphologist is the duration and distribution of these pressures as waves impinge on a cliff or platform. Figure 2.3 illustrates the relative durations of pressure exerted by standing, breaking, and broken waves. In order to understand how wave pressures act on shore platforms investigations have adapted the theory of wave dynamics in front of coastal structures (typically vertical seawalls) to identify pressure distributions and to calculate pressures exerted on cliffs by waves.

The maximum pressure caused by a standing wave on a vertical wall can be calculated using the formula of Sainflou (1928):

$$p_m = \left\{ \frac{\omega_o H}{\cosh(2\pi d / L} + \omega_o d \right\} \left(\frac{H + h_o}{h + H + h_o} \right) \qquad 2.1$$

where:

p_m = maximum pressure intensity

H= wave height in front of the cliff

L = wave length

d = water depth from still water level to cliff base

$ho = (\pi H^2/L)coth(2\pi h/L)$

ω_o = weight of water per unit volume

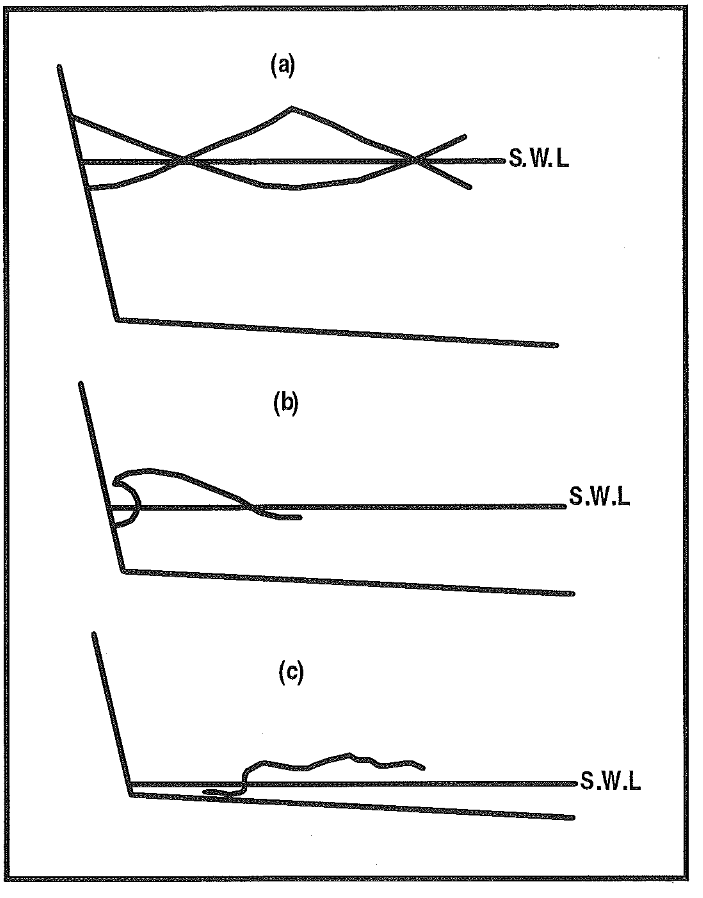

Figure 2.2 Types of waves in front of a cliff, a) standing waves b) breaking wave c) broken wave (Sunamura 1992 Fig 2.16).

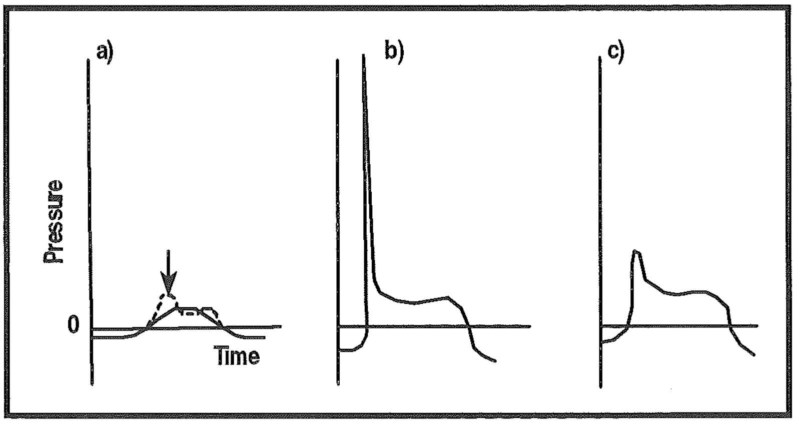

Figure 2.3 Schematic pressure time curves at still water level a) standing wave, b) breaking wave c) broken wave (Sunamura 1992 Fig.2.17).

The distribution of pressure resulting at the crest from a standing wave is illustrated in Figure 2.4. P_m has been found to occur at the still water level (Sainflou 1928 in Sunamura 1992).

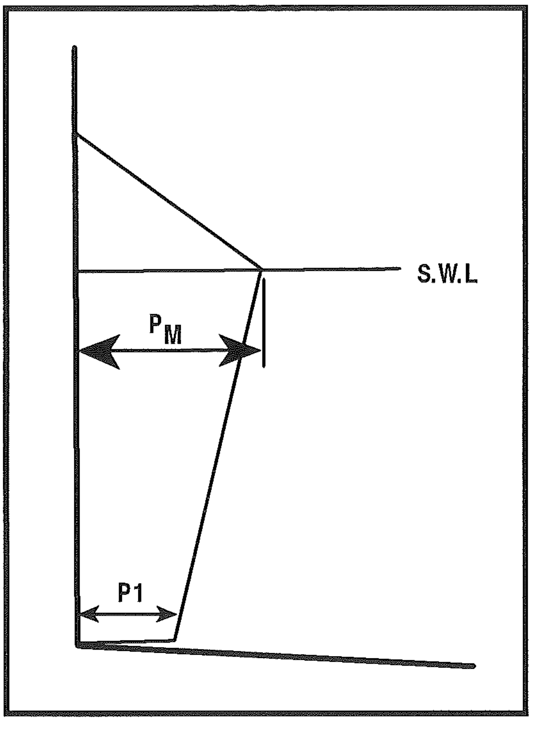

Figure 2.4 Pressure distribution resulting from a standing wave on a vertical wall (Sunamura 1992 Fig. 2.19).

The maximum pressure induced by a breaking wave has not been fully described because of the complicated nature of these waves. The main complicating factor is that a pocket of air can be trapped as the wave breaks. This air pocket decreases rapidly as the breaking wave compresses it, causing a dynamic shock pressure, until the air bursts upwards (Bagnold 1939). Equations to predict maximum pressure are based on empirical and theoretical evidence. Sunamura (1992) proposed that the equation:

$$p_m = 35\rho g(H_o)_b \qquad \textbf{2.2}$$

where:

$(H_o)_b$ = the height of the deep water wave which breaks in front of the cliff

ρ = unit weight of water

g = acceleration due to gravity

provides a sufficient estimate of the maximum pressure. This equation has been based on work by Denny (1951), Ross (1955) and Mitsuyasu (1963). Figure 2.5 illustrates the pressure distribution under a breaking wave. P_m has been found to occur at or slightly above still water and it decreases significantly with depth (Minikin 1963).

Breaking waves exert high dynamic pressures of short duration. These pressures only occur when the vertical front face of a wave impacts on a wall and only after air is trapped between the wave front and the wall (Bagnold 1939) (Figure 2.6). Bagnold (1939) found that pressures were negligible where the thickness of the pocket of air was more than half its height Because of these strict conditions true impact pressures occurred infrequently, so that only 10 per cent of waves generated in a laboratory wave tank produced impact pressures (Bagnold 1939). Miller et al. (1974) failed to record impact pressure in the field. Theoretically high impact pressures also occur through water hammer. Trenhaile (1987) defined water hammer as the impact between a body of water and a solid. Water hammer results when the wave front is vertical as it strikes a vertical wall. True water hammer can only occur if no air is trapped by the wave front (Bagnold 1939). Ackermann and Chen (1974) failed to generate water hammer in laboratory testing. Although the occurrence of water hammer is restricted, Trenhaile (1987) considered that this is compensated for by the high pressures it generates. High impact pressures and water hammer probably do occur in the field but given the necessary preconditions required the frequency of such events is probably very low. Further research is required to establish the role of impact pressures and water hammer under breaking waves in the development of shore platforms.

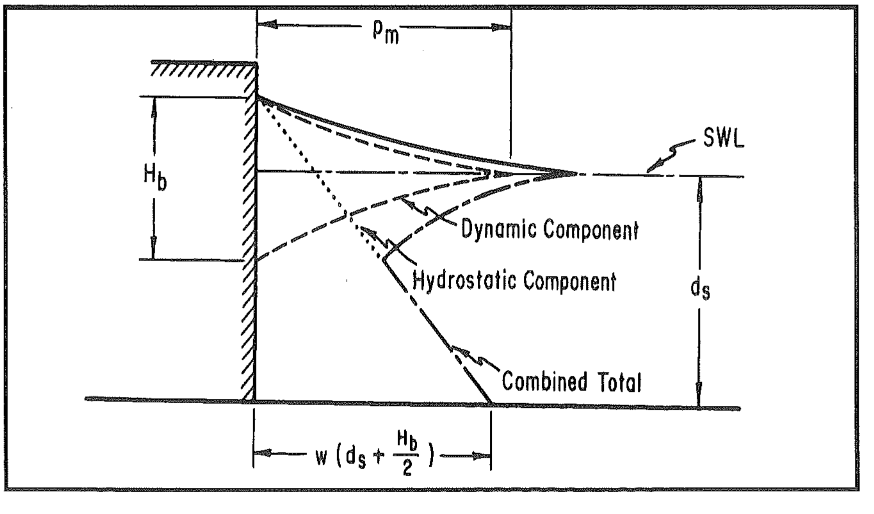

Figure 2.5 Pressure distribution of a breaking wave (CERC 1984 Fig7-99)

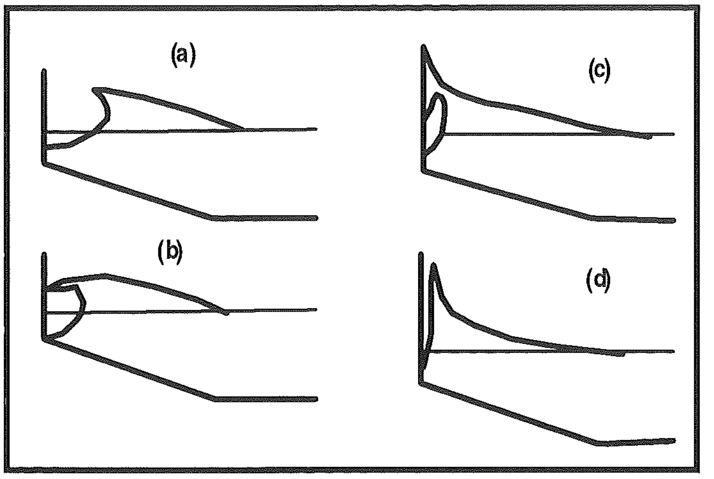

Figure 2.6 The entrainment of air by a breaking wave (Bagnold 1939 Fig. 11).

It is possible to determine whether or not breaking waves are a significant erosional agent on a shore platform. CERC (1984:7-6) using empirical data from Goda (1970) and Weggel (1972) provide graphs for determining the depth of water in which a wave of a particular height will break. Breaking is dependent on deep water wave steepness, bottom slope, and water depth (Goda 1970). By relating offshore topography and deep water wave statistics and using the technique set out by CERC (1984) it is possible to determine whether waves break at the foot of the landward cliff, on the platform surface or on the seaward cliff of a Type B platform.

As a wave breaks, particle motion changes from oscillatory to translatory, this results in the formation of a bore (CERC 1984). A bore is a body of highly turbulent and aerated water moving shoreward. Energy is dissipated by the entrainment of air (Führböter 1970, Hwung et al. 1992). As with breaking waves, prediction of pressures exerted by broken waves relies on experimental and empirical evidence. Sunamura (1992) presented the equation below for estimating p_m, in front of a vertical wall seaward of the still water level:

$$p_m = 0.5\rho g h_b \qquad 2.3$$

where: h_b = depth of breaking.

The hydrodynamic pressure exerted by a broken wave is distributed uniformly above still water to a height of $0.78H_b$ (Figure 2.7) (CERC 1984).

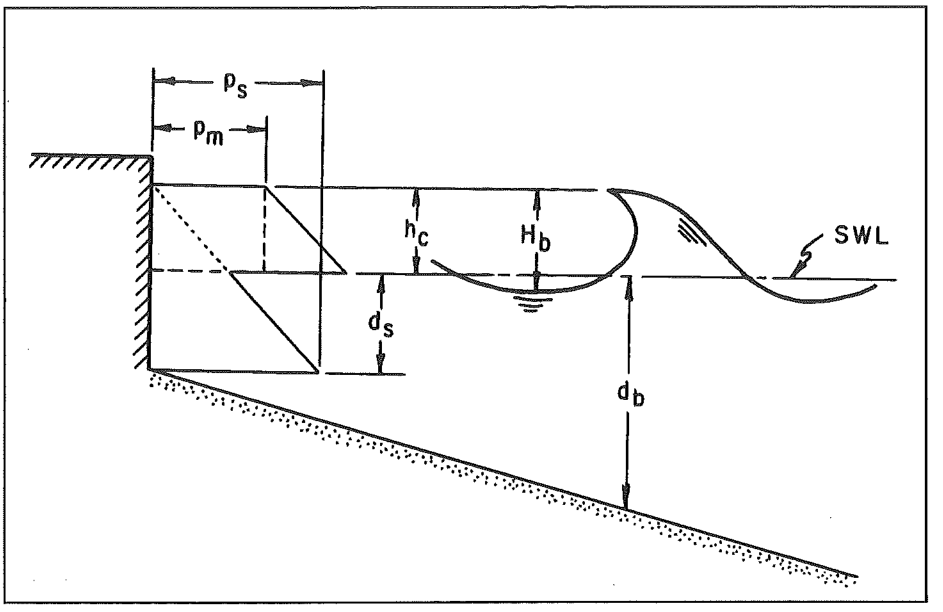

Figure 2.7 Vertical distribution of dynamic pressure caused by a broken wave on a vertical wall seaward of the still water level (Sunamura 1992).

CERC (1984:7-195) provide a means to calculate the maximum pressure exerted by a broken wave on a vertical wall shoreward of the still water level. The dynamic pressure is assumed to act uniformly over the height of the broken wave at the toe of the wall (h´) (Figure 2.8), hence the dynamic component of force is given by:

$$R_m = \frac{wd_b h_c}{2}\left(1 - \frac{x_1}{x_2}\right)^3 \qquad \textbf{2.4}$$

From Figure 2.8 x_1 is the horizontal distance from the shoreline to the wall and x_2 is the horizontal distance from the shore line to the limit of wave run if the wall did not exist.

Camfield (1991) revised the model presented by CERC (1984) for calculating the total wave force on a vertical wall shoreward of the still water line. Wave decay data from Nakamura et al. (1966), Horikawa and Huo (1966) and Camfield and Street (1969), showed that broken wave height at the shore line h_s (Figure 2.9) never exceeded 20 per cent of the breaker height H_b. The CERC (1984) model assumes that h_s (Fig 2.9) and h_c are the same, which causes over estimation of the wave force. From Camfield (1991) wave force (F) is given by:

$$F = 4.5\rho g h^2 \qquad \textbf{2.5}$$

where :

$$h = 0.2H_b\left(1 - \frac{x_1}{x_2}\right) \qquad \textbf{2.6}$$

The method predicts the total wave force and does not give a pressure distribution (Camfield 1991). It also applies only to slopes exceeding 1 per cent and not more than 10 per cent (Camfield 1991).

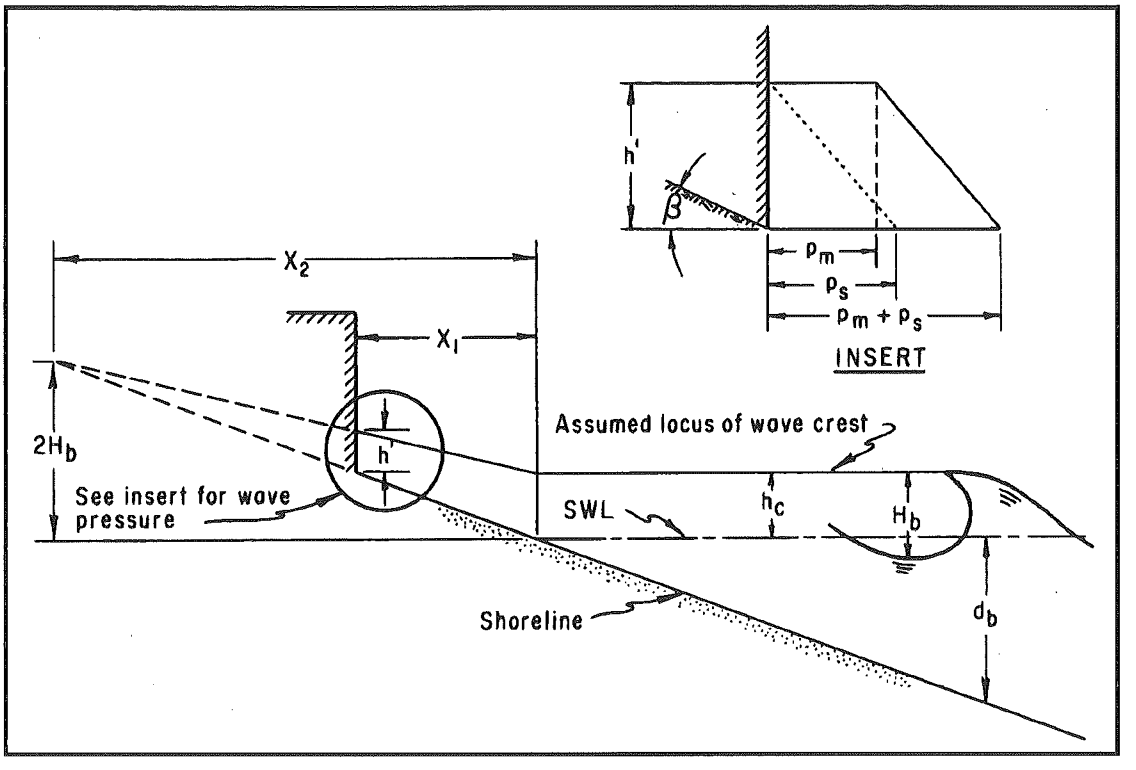

Figure 2.8 Definition sketch for a wall landward of the still water level and pressure distribution (after CERC 1984).

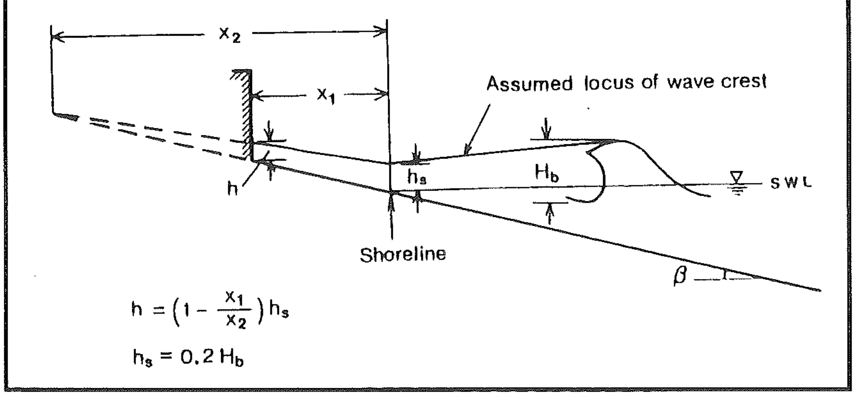

Figure 2.9 Definition sketch for the estimation of the height of a broken wave on a wall seaward of the shoreline. Note the difference between h_s and h_c from Fig. 2.8 (Camfield 1991).

The pressures exerted by waves as they impinge on a platform or a cliff can cause a number of different erosive processes. Sanders (1968a) identified breaking wave shock, water hammer, air compression in joints, hydrostatic pressure, cavitation and abrasion as causes of erosion (Figure 2.10).

Wave Quarrying

Wave quarrying is thought to be the most important erosive process on shore platforms in the storm wave environment of the northern hemisphere (Trenhaile 1980). Quarrying is the breaking free and removal of rock fragments by shock pressures from breaking waves, water hammer and the compression of air in rock joints. While shock pressures and water hammer are generated by breaking waves, both breaking and broken waves can cause compression of air in joints. Air is compressed in joints and bedding planes as water rushes in; this is followed by a sudden explosive release as the water recedes (Trenhaile 1987). Robinson (1977b) proposed that quarrying becomes more effective when sand is washed into cracks and keeps them open. He called this process wedging. Wave quarrying is limited in extent over a shore platform, since maximum pressures occur at or close to still water level. The position of still water level on a shore platform and in front of a cliff is controlled by the tide.

Cavitation and Hydrostatic Pressure

Little work has been undertaken to assess the importance of cavitation and hydrostatic pressures. Cavitation occurs when high water velocities at the bottom cause a drop in pressure. If vapour pressure is attained then the rock surface can be damaged by the sudden formation and destruction of vapour pockets (Trenhaile 1987). Since cavitation depends on high water velocities and an absence of air, the best conditions are under standing waves approximately 0.25 of the wave length in front of a vertical wall where water velocities are twice that of the incident wave (Sainflou 1928 in Trenhaile 1987:25). Hydrostatic pressures increase with the depth of water. Since depth changes frequently under waves, variations in pressure occur at the bed. For these variations to cause erosion the strain must exceed the strength of the rock (Trenhaile 1987). In the surf zone a platform is subjected to low intensity high frequency pressure variations. It remains to be determined whether or not these variations cause erosion (Trenhaile 1987).

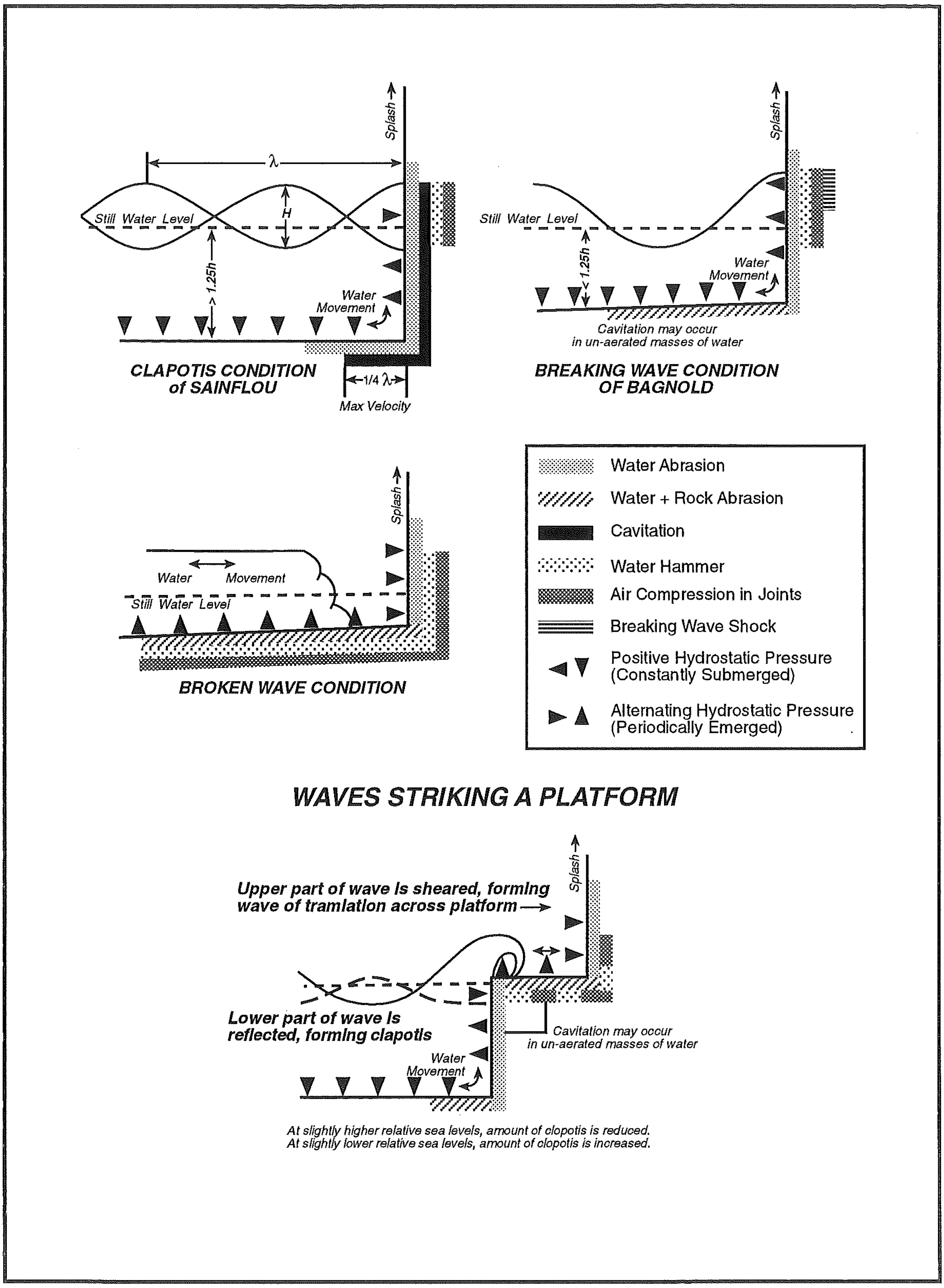

Figure 2.10 Summary of hydraulic forces acting on a vertical wall and platform (Sanders 1968a).

Abrasion

Abrasion has been identified as an important erosive process (Sunamura 1976, Robinson 1977b,c). Trenhaile (1987:25) defines abrasion as "the result of sweeping, rolling, or dragging of rocks and sand across gently sloping rock surfaces, or the throwing of coarse material against steep surfaces". Abrasion relies on the presence of sediment and sufficient wave energy to move it. Robinson (1977b,c) found that abrasion was more effective during winter when storms have a higher incidence. Abrasion occurs in a narrow zone, the size of which is controlled by the character of the wave environment and the accumulated sediment. Robinson (1977c) found that abrasion occurred at a height of 10cm above a beach at a cliff foot and extended 14.5cm below the beach. Waves moved sediment at a depth of 5cm and as deep as 13.5cm under the largest waves (Robinson 1977c). Sunamura (1976) noted that large or very thick accumulations of sediment can prevent abrasion by acting in a protective manner.

2.3 WEATHERING

Weathering occurs in two forms, one chemical and the other mechanical. Chemical weathering includes:

1) *hydrolysis* which is the reaction between H^+ and OH^- ions in water with mineral ions;
2) *oxidation* occurs when the loss of an electron results in an atom taking on a positive charge;
3) *reduction* which is the opposite of oxidation;
4) *carbonation* is the reaction of carbonate and bicarbonate ions with minerals;
5) *hydration* is the absorption of water so that water molecules are loosely bonded to other minerals; and
6) *solution* occurs when minerals dissolve in water.

Mechanical weathering includes:

1) *thermal expansion and contraction*;
2) *pressure changes associated with crystal growth*, especially salts;
3) *swelling* caused by wetting and drying;
4) *frost action*; and
5) *unloading*.

Both chemical and mechanical weathering can and usually do, operate in unison. The degree of interaction depends on environmental conditions.

The two most commonly described weathering processes on shore platforms are salt weathering and water layer weathering (Bartrum 1935; Wentworth 1938; Hills 1949; Sanders 1968a, 1970; Sunamura 1978a; and Trenhaile 1980, 1987). A distinction has been made between the two by many authors as a matter of convenience for discussion but in reality the two processes are closely related. Cooke and Smalley (1968) identified three mechanisms by which salt causes weathering:

1) pressures exerted by crystals as they grow from solution;
2) pressures exerted by expanding salt crystals due to heating; and
3) pressures from volume changes induce by hydration.

There are three variables that control the effectiveness of salt weathering:

1) the nature of the salts and their solutions;
2) the properties of the affected materials; and
3) the nature of the environment in which salts may cause the materials to disintegrate (Cooke 1979).

Cooke and Smalley (1968) noted that the degree of saturation of the solution is important, as is the duration of exposure to supersaturation conditions. The capacity to absorb water, porosity, microporosity, the rate at which solutions penetrate rocks and tensile strength, are properties of rock that control the effectiveness of salt weathering (Cooke 1979). Goudie et al. (1970) found that igneous rocks were little affected by salts, whereas chalk, limestone and sandstones broke down rapidly after repeated immersion in saline solutions. Cooke and Smalley (1968) proposed that the growth of crystals from solution is important in humid coastal deserts, where dissolved salts are abundant. Thermal expansion and hydration are important in deserts where high temperatures and extreme diurnal changes are experienced.

Water layer weathering was first recognised by Bartrum and Turner (1928). The term replaced "water level weathering" originally published by Wentworth (1938). Johnson (1938) was critical of the term water level weathering because it could be construed to mean weathering in relation to mean water level and hence sea level. Hills (1949) suggested that the term "water level weathering" should be replaced with the "term water layer weathering", since the pools of water occurred in layers. The term "water layer weathering" has been used widely and is used subsequently in this study. Water layer weathering and the resulting morphology were described by Bartrum (1935:141):

> "... the general surface is characterised by shallow dimples, from a few inches to many feet in diameter, which are occupied by pools of water 1 or 2 inches in depth. Between the dimples rounded small ridges of rock project, which can be observed to become dry between periods of wetting by over-pouring waves and commonly to show distinct superficial disintegration, which may with confidence be ascribed to alternative wetting and drying, with conceivably some effect from crystallisation of salts from penetrating sea waters."

Wentworth (1938:13) noted that examples of water layer weathering showed "variations of level of less than 6 inches". The surfaces of platforms were characterised by pools that are "separated by an intricate network of dry topped ridges" (Wentworth 1938:18). These are clearly the same morphological features described by Bartrum (1935) as "rounded small ridges of rock". Water layer weathering produced horizontal surfaces at elevations between "2 and 20 feet above sea level". It was noted that water layer weathering operated at higher elevations on exposed headlands and at lower levels in sheltered coasts, due to larger waves producing splash at higher elevations. Platform surfaces must have pools of water that are replaced after drying out, "since the water layer weathering appears to go on most rapidly in the narrow zone which is wetted and dried most frequently" (Wentworth 1938:20). Wentworth (1938:28) attempted to describe the process of water level weathering:

> "...the attack on the rock is a physical process, akin to slaking of shales when exposed to water and with rock pressure released, which proceeds so much more rapidly with repeated submergence and emergence than with continuous immersion.... That surface tension phenomena, and colloidal and dilatation behaviours enter into the process is strongly probable..."

Wentworth (1938:28-29) also speculated:

> "that crystallisation of salts from the sea water may tend to break up the rock in the water-level zone. Occasionally, during quiet weather, there is a sufficient evaporation to concentrate the solution and leave residues of sodium chloride and other salts".

However, Wentworth (1938) questioned the effectiveness of these salts as a weathering agent since are they rapidly washed away.

The process of water layer weathering relies on the repeated wetting and drying of platform surfaces. It can therefore operate wherever sea water can accumulate and evaporate. Ongley (1940) proposed that ledges 17 and 24m above sea level resulted from spray weathering after observing pools of sea water on horizontal benches at Castle Point on the south east coast of the North Island of New Zealand. The physical process of water layer weathering remains to be fully explained but most writers consider salt weathering, wetting and drying, chemical weathering and the movement of solutions through rock capillaries to be important (Trenhaile 1987). Since water layer weathering involves drying, thermal expansion may also play a role. Sedimentary rocks such as shales and mudstones are particularly susceptible because clay minerals found in them expand on wetting and shrink on drying (Yatsu 1988). The relative contribution of each type of weathering will be dependent of environmental conditions, so that the importance of each will be different spatially and temporally. Seasonal variations are likely to be important in temperate environments.

2.4 THE DEVELOPMENT OF SHORE PLATFORMS

This section reviews studies that have attempted to explain the development of shore platforms. Those studies that identified weathering as the main agent of platform development are presented first, then those that identified waves as the principal agent are reviewed. Finally those that identified both marine and subaerial processes as being important are presented.

2.4.1 WEATHERING

Based on observations of Kaiaraara Island at Russell in the Bay of Islands, New Zealand, Bartrum (1916) advanced the theory that the development of the platform surrounding this island was due to subaerial weathering. "Subaerial weathering at the shoreline was progressive, and that as wave transport removes loosened spoil, fresh impetus is given to weathering..." (Bartrum 1916:134). He considered that the level to which weathering occurs is controlled by the level of the water table. This "... water table at the new shoreline is lowered to the level of high water and the zone of decomposition retrogresses cliff wards" (Bartrum 1916:134). The platform was described as being "...barely covered by mean high tides, and varying in width from a few feet to 30 yards or more. From the seaward margin there is a steep descent for a few feet. The surface is essentially horizontal but for very few minor irregularities..." (Bartrum 1916:133). Subsequently Bartrum referred to platforms developed in this way as Old Hat type platforms since Kaiaraara Island looks like a bowler hat.

Healy (1968a) proposed that subaerial weathering caused the development of shore platforms on the Whangaparaoa Peninsula north of Auckland on the North Island of New Zealand. Wetting and drying was thought to be the principal weathering process. Like Bartrum (1916) he considered that the level of saturation controlled weathering. Waves played a role only as a transporting medium (Healy 1968a).

2.4.2 WAVES

Dana (1849) was probably the first to propose a theory for the development of shore platforms which he based on observations made during travel through the Pacific, particularly Australia and at Russell, in the Bay of Islands of the North Island of New Zealand. He stated that "the existence of this platform [in reference to shore platforms in general] is due to the simple action of the sea" (Dana 1849:109) and "the water, in these cases, has worn away the cliffs, leaving the basement untouched" (Dana 1849:110). The action of the sea was "strongest from half to three fourths tide" and "it is apparent that the line of greatest wave-action, must be above low water level" (Dana 1849:110). He speculated that on a "tide of three feet" that "had risen to two out of the three" and with waves of "four feet", then "the wave, at the time of striking, would "stand three feet above high tide level". Therefore the "greatest force would be felt, not far from the line of high tide, or between that line and three feet above it" and added to this by noting that "under the influence of heavier waves, such as are common during storms, the line of wave-action would be at a still higher elevation" (Dana 1849:110). He also proposed that a height could be identified where wave action ceased entirely. This point could be found "somewhat above low tide" (Dana 1849 and 1880). The location was marked by the horizontal surface of the platform. The exact level depended on the range of the tide and "the usual strength of the waves". Therefore the elevation of a platform varied from location to location because of these factors. In New Zealand generally, this level was "above half tide" but in the Bay of Islands where the "Old Hat" is sheltered from the open ocean the elevation is "a little above low water" (Dana 1849:111). It was also proposed that tides and waves control the width of platforms. These two factors were not however considered to account totally for width.

From observations of shore platforms made on the west coast of the North Island near Auckland, New Zealand, Bartrum (1924) proposed that these platforms were the result of "attack" from storm waves. There shore platforms were narrow features with elevations "above mean high water" and they terminated at the seaward edge with a cliff. The elevations were reported as being "approximately 2 feet above mean high water" (Bartrum 1924:494). Storm waves "rise several feet above normal water-level as they travel onwards as mighty waves of translation in the shallower water near the coast. They are less impeded [than waves washing over Old Hat type platforms discussed above], and therefore more effective erosive agents, when the tide is nearing flood, and for this reason one may well expect them under special circumstances to maintain a cut bench of the character described, above the level of the normal zone of wave-attack" (Bartrum 1924:495).

Bartrum (1924, 1926) proposed that shore platforms in the Whangaroa Harbour on the west coast of the North Island near Auckland, were also the result of storm waves and he subsequently referred to them as storm wave platforms. The best developed platforms appeared in the most exposed locations although there was no evidence to support a relationship between platform width and exposure to waves. He also considered that these particular shore platforms were especially characteristic of "resistant" rock. Unlike the Old Hat type platform these platforms were influenced more strongly by differences in rock hardness, jointing and bedding. As a result the surface of them was more irregular.

Edwards (1941) discussed what he called "storm wave platforms" along the Victoria and Tasmania coasts of Australia. He considered these shore platforms to be identical in nature and mode of origin to those discussed by Bartrum (1924, 1926). Like those described by Bartrum they occurred a few feet above high tide, although the Australian examples appear to have greater lateral extent, with Edwards reporting widths up to "300 feet". Edwards considered that the continued survival of these shore platforms depended on the relative rates of retreat of the cliff backing the shore platform which he called the "high tide cliff" and the seaward edge of the platform, or the "low tide nip" as he termed it (also known as the low tide cliff or seaward cliff). For a shore platform to widen, the high tide cliff must retreat faster than the low tide nip. Conversely if the low tide nip retreats faster than the high tide cliff, then eventually the high tide cliff is overtaken and the platform ceases to exist. The erosion of the high tide cliff was thought to occur at high tide while the low tide nip was eroded at low tide. Edwards (1941) proposed that at high tide, larger, more powerful waves were able to reach the high tide cliff because of an increase in water depth in front of the platform. These waves were also "armed" with abrasive material supplied by the eroding cliff. Based on these two factors Edwards concluded that the high tide cliff would inevitably erode faster than the low tide nip. Edwards proposed erosion of the high tide cliff was caused by waves during storms, hence the term storm wave platforms.

Edwards (1951) added to his theory by noting that there was "maximum erosion above a defined level", such a level existed because tides and storm waves elevated the water level. This "defined level" was that of the platform. A defined level helped to explain the higher elevation of what are now called Type B surfaces compared with Type A, because of the occurrence of lower Type A platforms in sheltered embayments away from storm waves of the open coast. According to Edwards, the role of storm waves in platform development could not be doubted on the open coast. Edwards (1951) considered the amount of energy delivered by waves was an important control in platform initiation and development. He proposed that on the open coast there was an excess of energy that elevated the level at which waves erode. This excess energy was delivered by storm waves. He did make a concession to the role of weathering, by suggesting that as platforms widen with age the role of water layering increases in importance.

2.4.3 MARINE AND WEATHERING PROCESSES COMBINED

Bell and Clarke (1909) were the first to advance the notion that shore platforms developed as a result of the "co-operation of subaerial weathering, which causes the retreat of cliffs, with marine transport, which removes the waste so formed" (Bell and Clarke 1909). This idea was based on the observation of shore platforms on the Whangaroa Harbour, in the North Island of New Zealand. These same platforms Healy (1968a) later proposed resulted from subaerial weathering.

Bartrum and Turner (1928) published a description of the geology of the North Cape of New Zealand, in which a brief discussion on the origin of shore platforms along this coast was given. Bartrum and Turner proposed that the principal mode of formation was erosion by storm waves, but they also considered that subaerial weathering had played an important role. Bartrum and Turner (1928:104) wrote:

> "There appear to be grounds for the belief, however, that subaerial processes active upon the wave-cut platforms have contributed very materially to the remarkably level nature of the benches of the present area."

Bartrum and Turner (1928) proposed that shore platforms underwent a secondary planation due to subaerial weathering, but no description of this process was offered. Bartrum (1935) was the first to describe the phenomenon, but a name for the process was not published until Wentworth (1938) described what he termed "water level weathering". Bartrum (1935) introduced "A Hypothesis of Secondary Subaerial Planation of Certain Storm-wave Platforms". This was an attempt to explain the "suprisingly plane like surfaces" on "wave-cut" shore platforms on the North Cape of New Zealand. Although Bartrum (1935) considered wave erosion to be the formative process, water layer weathering was considered to be responsible for levelling the platform surface.

Jutson (1939, 1949a, 1949b, 1950, 1954) discussed those processes he believed responsible for the formation of shore platforms in Australia. He proposed that platforms could be grouped into three categories based on elevation. "High level" platforms were those with average heights of three feet but, could be found higher; "normal platforms" were found at elevations between mean low tide and mean high tide; and the "ultimate platform" was "well below low-water...". The general character of the platforms was that they appeared as a series of steps, with the high level platforms generally more narrow than the normal platform. Jutson (1939:248) proposed that the origin of these shore platforms was a result of the "sea up to the effective spray line". The sea cut these surfaces through the process of "marine abrasion" and through "spray erosion". A detailed description of how spray erodes was not given, but it was credited with removing the products of erosion at higher levels. In the upper portion of this zone "atmospheric and marine erosion combine to break down the rock, while the sea is the chief agent in their removal" (Jutson 1939:248). This idea appears quite similar to that offered by Bell and Clarke (1909). Above the spray line, platforms are formed by subaerial decay with the products of decay being carried away by wind, rain and gravity.

Hills (1949) presents a review paper of shore platform literature up to 1949. Hills was critical of the term "storm wave platform", noting that some platforms occur on coasts subject to "severe wave action in the normal course of events" and that the occurrence of storms is secondary. He considered that the term should not be applied to those examples cited by Edwards (1941). Hills considered that Bartrum's (1935) theory explaining the development of storm wave platforms was erroneous. The idea that waves could cut a horizontal surface was rejected. Hills considered such waves were responsible for the development of sloping wave ramps. For waves to cut a horizontal surface there would need to be a defined level of maximum erosion "which is not expectable with variation in wave height" (Hills 1949:149). He proposed that a sloping ramp develops because as waves shoal, energy is dissipated with maximum erosion occurring at the seaward edge of the platform and minimum erosion at the landward edge. Storm wave platforms as named by Bartrum (1924, 1926) and Edwards (1941) were not a result of waves according to Hills (1949). He proposed that such shore platforms with a horizontal profile were in fact modified wave ramps. Modification was as a result of water layer weathering; the evidence for this was in the fact that this process produced level surfaces and this type of platform was level. Waves were not considered to contribute much erosion on these platforms except at the cliff foot where the retreat of the cliff was a result of wave attack on it.

Mii (1962) examined the evolution of shore platforms in Tanabe Bay Japan. He classified the shore platforms of Tanabe Bay into eight categories based on morphology. These were; quarry type, cuesta type, valleyed-joint type, pooled-cuesta type, pooled type, holed type, sloping type and valleyed type. From these he inferred an assemblage of processes responsible for their origin. In his paper Mii makes a distinction between the "formation of the platform surface" and "cause of the horizontal surface." He considered that the formation of shore platforms was a result of both wave erosion and weathering. Mii presented four hypotheses to account for the horizontal surface of shore platforms. The first hypothesis was that shore platform development is a result of wave erosion down to a defined level. This level is variable depending on tidal range and sea conditions. Storm waves were considered important factors in the evolution of shore platforms, but were not solely responsible.

The second hypothesis proposed was that the level of permanent saturation controlled the level of subaerial weathering. Mii (1962) speculated on the role of the water table in permeable rocks and the possibility that it is affected by tides as in a sandy beach. He considered that variability in the level of ground water could not produce a level platform.

The third hypothesis was that the level of a platform surface was controlled by the level of water layering. It was recognised that this process could produce levelled platforms but because of sea conditions and tides it could operate anywhere in the inter tidal zone and several metres above it. Therefore, water layer weathering could not be solely responsible for the uniform elevation of shore platforms.

The fourth hypothesis was that the elevation of platforms was controlled by sea level. Platforms above the level of the sea were exposed to subaerial weathering and erosion by waves. Material is loosened by weathering and removed by waves. The lowest level to which this process can operate is sea level and hence that was termed "sea-level weathering" (Mii 1962). With the exception of the quarry type platform which was a result of wave erosion, the other seven types identified by Mii (1962) were formed by sea-level weathering and therefore were termed "sea-level shore platforms".

Mass Movement

McLean and Davidson (1968) introduced a detailed description of the role of mass movement in the development of shore platforms. They noted that previously Bartrum (1916, 1926, 1935, 1938) had recognised the role of subaerial weathering in cliff retreat, but had not clearly identified the processes operating. McLean and Davidson proposed that mass movement was one of the processes in Bartrum's theory. Observations were made along the Gisborne coast, north of Gisborne City on the east coast of the North Island of New Zealand. Here platforms were cut in banded mudstone and in banded mudstone and sandstones. From these observations McLean and Davidson (1968) identified three types of mass movements that were present. These were rock and soil falls, slides and flows. Rock and soil falls were subdivided into three groups depending on the size of material present; pebble falls, boulder falls or soil falls. These all were materials that had arrived at the base of cliffs by free falling from above. Slides were the most common type of mass movement reported by McLean and Davidson. They occurred as either slumps or debris slides. Flows were the third type of mass movement identified. These were characterised as "continuous plastic deformation of material along a shallow surface (McLean and Davidson 1968:20). All mass movements deposited material onto the landward edge of platforms and this material could be reached by the sea at high tide.

McLean and Davidson (1968) noted the role of structure, lithology and climate, especially high intensity rainfall, as important controls on mass movement. They also investigated the role of wave action as a control. Wave action was identified as the major transporting agent removing debris. Debris was either removed completely or redistributed over the platform surface. Mudstone debris broke down to be carried away in suspension, while sandstone provided material for embayed beaches along the coast. The effect of this removal was to truncate the toe of slides and flows. This reduced support at the toe and allowed more material to fall or flow into reach of wave action The continued removal of mass movement debris caused over steepening of the cliff slope and contributed to further mass movements leading to further retreat of the cliff and extension of the platform. Examples were cited where wave energy was not sufficient to remove debris and the accumulation of material had caused the extension of the platform to cease. In these cases McLean and Davidson identified secondary plantation of the shore platform surface to be occurring as a result of chemical, biological and mechanical agents. McLean and Davidson concluded by noting that in most respects their theory was not dissimilar to that of Bartrum (1916). This is clear, but they have added to Bartrum's theory by providing a detailed account of the processes implied by the term "subaerial" as used by Bartrum and many subsequent authors. Wider application of this theory may be difficult within different lithologies that are more resistant to land sliding, such as basalts.

Kirk (1977) proposed that both marine and subaerial processes could be responsible for the development of shore platforms. Unlike previous workers he did not consider one set to be more important than the other. He was able to measure the rate at which downwasting occurred on platform surfaces on the Kaikoura Peninsula on the South Island of New Zealand. This revealed that rates of erosion varied across the platform profile. On the inner landward side and the outer seaward side erosion rates were higher than on the middle of the platform profile. The interpretation given to this was that inner part of a platform was dominated by subaerial and supra-littoral processes and the outer part of a platform was dominated by marine processes. There was a grading of the two towards the middle of the platform. Thus there was a gradient across the platform from subaerial processes at the landward edge to true marine processes at the seaward edge. The measured erosion rates did not discriminate which processes caused this pattern. Evidence also came from tidal data and data on the elevation of platform morphology. Elevations of +1.0m above mean sea level represented 7 per cent of platform morphology and were covered by water 2.5 per cent of the time. Elevations up to +0.5m represented 21 per cent of platform morphology and were submerged 48 per cent of the time. Over half of shore platform morphology occurred above mean sea level. Twenty one per cent of platforms occur between mean sea level and -0.5m which is covered 63 per cent of the time. Platform morphology below -0.5m accounted for the remaining 22 per cent; this was covered 12 per cent of the remaining time. It was argued that because 20 per cent of the platform surface was above +0.5m and was covered for such a short period of time then subaerial processes must dominate. While 20 per cent of the platform surface below -0.5m was covered 88 per cent of the time then marine processes must dominate. The central part of the platform accounting for 60 per cent of the morphology was thus alternatively covered and exposed with neither marine nor subaerial processes dominant. The testing of this hypothesis is a goal of this study.

Sunamura (1978a) investigated the mechanisms of shore platform formation on the south eastern coast of the Izu Peninsula of Japan. The initial focus was on the role of waves in platform development. Because shore platform elevations were higher on headlands than in embayments Sunamura proposed different formative processes for the two types of platform. Those occurring on headlands were the result of wave erosion, principally erosion by breaking waves. Platforms in embayments resulted from broken waves and weathering, especially wetting and drying. According to Sunamura, weathering occurred down to the level of permanent saturation, which is mean low water level. Embayed platforms were lower than those on headlands because weathering had a significant role.

Section 2.4 has reviewed a number of previous studies into shore platform development and illustrated that three main ideas exist to explain that development. Wave erosion has been as a formative agent. In contradiction to this it has been argued that weathering is the principal agent of formation. The third argument was for a combination of both marine and weathering processes. No studies have as yet clearly identified which of the three best explains shore platforms development. How shore platforms develop is thus still an open question for research.

2.5 MORPHOLOGY

In their attempts to explain the development of shore platforms most researchers have considered the evidence offered by platform morphology as either supporting varying hypotheses or countering them. Debate has been centred on issues such as the relationship between platform elevation and exposure to wave energy or between platform gradient and tidal range. Investigations into morphology have resulted in part because of the problem of measuring processes directly. Investigators used morphology to identify processes operating on shore platforms, despite Mii's (1962) warning that morphology is a notoriously ambiguous indicator of process. Platform morphology is important when considering the equilibrium form platforms attain. Questions that have been raised include: How wide do shore platforms become? To what gradient do platforms develop? To what elevation do they tend? Why do platforms exist at all?

2.5.1 SHORE PLATFORM PROFILES

It has been recognised that two distinct morphologies of shore platforms exist, the sloping platform and the horizontal platform, although not all authors have accepted this classification. As noted earlier, Sunamura (1983) designated these Type A and Type B platforms respectively (Fig 2.1). Why do platforms develop two distinct morphologies? Are Type A and B platforms two distinct morphologies or two different stages in the evolution of shore platforms? Do these two profiles represent profiles of equilibrium?

Gill (1972) proposed that both what are now called Type A and B platforms were the products of an evolutionary shoreline process which continued until an ultimate state of equilibrium was attained. This was known as the "profile of equilibrium". Sloping platforms (Type A) were cut into soft rocks such as clay and siltstone or weathered basalt and granite. In fresh granites no platform was present, and a plunging cliff resulted. Horizontal platforms (Type B) were cut into a group of rocks of intermediate strength. Type B platforms or storm wave platforms were said to be in various stages of development, as was evident from the fact that they occurred at a variety of elevations with differing degrees of planation. Gill argued that since horizontal platforms occur in harder rock and sea level has only been at its present elevation for about 6000 years there has not been enough time for a sloping profile of equilibrium to have been achieved. He proposed that a second profile of equilibrium existed in platforms cut into aeolianite and calcarenite. The profile was a horizontal platform (essentially a Type B platform) and inter-tidal. Gill considered the soluble nature of these rocks to be important, although he never stated why. Therefore any Type B platform in soluble rock was a profile of equilibrium, but Type B platforms in insoluble rock were an evolutionary stage, the end result of which would be a Type A profile. Gill and Lang (1983) also proposed that Type A and B profiles are different stages of development towards an ultimate profile of equilibrium and concluded that Type A and B platforms were not two distinct morphologies but rather two stages in one evolutionary process. Others proposed that they are two distinct morphologies that can be explained in terms of differences in processes and lithology (Edwards 1941; Tsujimoto 1987; Sunamura 1992).

Tsujimoto (1987) provided a quantitative relation that showed that a demarcation existed between shore platforms and plunging cliffs and that a critical condition for the initiation of a shore platform could be identified. This work also addressed the question as to whether Type A and Type B are distinct morphologies or different stages of one evolutionary process. Since shore platforms form at the base of a cliff a critical condition for their initiation can be identified based on whether or not erosion will occur. Cliff erosion occurs when the resisting force of the rock F_R is less than the erosive force of the waves F_W. Therefore the critical condition for the initiation of a shore platform is given by:

$$F_R = F_W \qquad \textbf{2.7}$$

where:

F_R = resisting force of rock

F_W = erosive force of waves

Tsujimoto (1987) proposed that F_W in front of a cliff could be represented by wave pressure so that:

$$F_W = Ap \qquad \textbf{2.8}$$

where:

A = is a nondimensional constant representing abrasion

p = pressure.

The calculation of wave pressure was dependent on the type of wave in front of the cliff, either standing, breaking or broken waves. The maximum wave pressure exerted by a standing wave was calculated from Sainflou (1928) using equation 2.1. The maximum pressure exerted by a breaking wave was calculated using equation 2.2. Maximum wave pressure in a broken wave was calculated using equation 2.3. The maximum value for p from equations 2.1, 2.2 and 2.3 were used as an index for F_W.

F_R is the resisting force of the rock and is calculated by multiplying a discontinuity index (Suzuki 1982) by the compressive strength of the rock, F_R is given as:

$$F_R = BS_c(Vpf / Vpc)BS_c^* \qquad \textbf{2.9}$$

where:

B = a nondimensional constant representing reduction in strength due to weathering

$$S_c^* = S_c(V_{pf} / V_{pc}) \qquad \textbf{2.10}$$

S_c = compressive strength of the rock and (V_{pf}/V_{pc}) = discontinuity index where V_{pf} is the longitudinal wave velocity measured in situ and V_{pc} is the longitudinal wave velocity measured in a specimen without visible cracks.

So that:

$$F_R = BS_c^* \qquad \textbf{2.11}$$

and from equation 2.8:

$$FW = Ap$$

Tsujimoto (1987) proposed that a dynamic condition for delimiting shore platforms could be obtained from equations 2.7, 2.8 and 2.9 so that:

$$p = cS_c^* \qquad \textbf{2.12}$$

where:

$$c = B / A \qquad 2.13$$

Equation 2.13 indicates that a demarcation should be expressed by a straight line inclined at 45° on logarithmic graph paper. Tsujimoto (1987) collected field data from 25 sites around Japan in order to calculate values for p and S^*_c. Values for p range from 5.8 to 220t/m^2 and S^*_c ranged from less than 13 to 5600t/m^2. Data were then plotted on logarithmic graph paper (Fig 2.11).

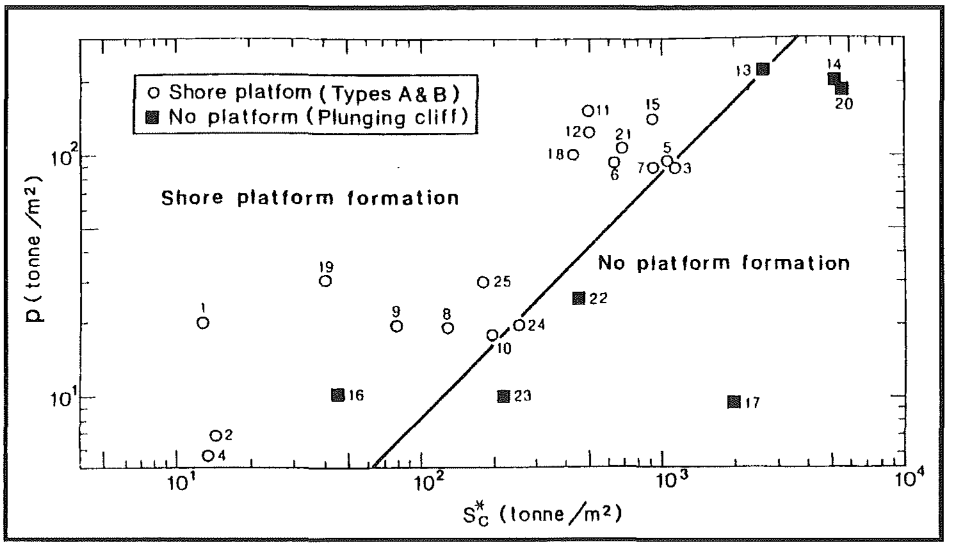

Figure 2.11 Demarcation between shore platform and plunging cliff (Tsujimoto 1987).

It was found that a line inclined at 45° clearly separated plunging cliffs and shore platforms. There was one exception to this which Tsujimoto explained as a problem in over estimating maximum wave height at the study site. From this line the critical condition for the formation of a shore platform is given by:

$$p = 0.081 S^*_c \qquad 2.14$$

What is remarkable is that p does not have to exceed S_c^* as described in equation 2.7. On the left hand side of the line, F_W is greater than F_R and shore platforms are formed. Shore platforms are not formed on the right hand side of the line since F_R is greater than F_W. Sunamura (1994) noted that if shore platform development depended only on rock characteristics then the line in Figure 2.11 would be vertical. Of course if shore platform development was dependent solely on waves then the line would be horizontal. Tsujimoto (1987) has clearly demonstrated that a boundary condition for the development of shore platforms exists. This provides strong evidence that waves are responsible for the initiation of shore platform development.

Tsujimoto (1987) also provided a quantitative relationship that was able to distinguish between Type A and Type B profiles; when the condition for platform initiation is satisfied as described by equation 2.14, a notch is formed at or near still water level. He proposed that the critical condition for demarcating Type A and Type B platforms is determined by whether or not the initial seaward cliff is preserved or destroyed, if it is destroyed, then a Type A platform results, but if it remains, then a Type B platform is formed. The destruction of the seaward cliff results from surface lowering of the floor of the notch not from direct wave attack on the bluff. This implies that the seaward cliff of Type B platforms represents the original position of the shoreline; this point will be discussed later. The critical formative condition between Type A and Type B is dependent on the occurrence of surface lowering and can be expressed as:

$$F_{WS} = F_{RS} \qquad \textbf{2.15}$$

where:

F_{WS} = the resisting force of rock against surface lowering

F_{RS} = the wave assailing force causing surface lowering.

For the relationship demarcating Type A and Type A platforms, F_{WS} is represented by the shear force of waves since it is this force that is most effective in notch cutting. The wave assailing force acting on the notch bottom is given by:

$$F_{WS} = a\tau \qquad \textbf{2.16}$$

where:

a = a nondimensional constant representing abrasion

τ = shear force

and

$$\tau = C_f \rho U^2 \qquad \textbf{2.17}$$

where:

C_f = a nondimensional coefficient of friction

ρ = density of water

U = water velocity

C_f is required to calculate the shear stress and Tsujimoto used a value of 0.15 which was determined by Kohno et al. (1978) who measured the reduction of wave height across a coral reef.

U is obtained through solitary wave theory. The velocity of a solitary wave, C, is given by:

$$C = \sqrt{g(H+h)} \quad \textbf{2.18}$$

where:

H = the wave height

h = the water depth.

h is approximately zero in the situation where a broken wave rushes into a notch, so that C is given as:

$$C = \sqrt{gH} \quad \textbf{2.19}$$

Tsujimoto assumed that in very shallow water, particles move only horizontally and the velocity distribution is uniform. Further, he assumed that the velocity of water particles was the same as wave velocity so that the velocity of water particles at the bottom could be given by:

$$U = \sqrt{gH} \quad \textbf{2.20}$$

Equation 2. 17 was re-written:

$$\tau_{MAX} = 0.15\rho H_b \quad \textbf{2.21}$$

where:

H_b = height of breaking wave

This equation returns the maximum shear stress since breaking waves exert the highest pressures.

F_{RS} was represented by:

$$F_{RS} = b(Vpf\ /\ Vpc)BS_s \quad \textbf{2.22}$$

where:

b = a nondimensional constant representing a reduction in strength dur to weathering

$S^*_s = (V_{pf}/V_{pc})\ S_s$

Tsujimoto (1987) proposed then that a demarcation between Type A and Type B platforms could be determined from equations 2.15, 2.16 and 2.22, so that:

$$\tau = c' S_s^* \qquad \textbf{2.23}$$

where:

$c'=b/a$

c' = an unknown dimensionless constant

This equation indicates that a demarcation should be given by a straight line inclined at 45° on logarithmic graph paper. Again Tsujimoto (1987) plotted values for τ and S^*_s calculated from field data (Fig 2.3) This clearly showed a separation of Type A and Type B shore platforms by a line inclined at 45° (Fig 2.12). The straight line is given by:

$$\tau = 0.005 S_s^* \qquad \textbf{2.24}$$

That is, when wave induced shear stress is greater than 0.5 per cent of the compressive strength of a rock a Type A platform will develop. On the left hand side of the line in Figure 2.12 F_{WS} is greater than FS_R and Type A platforms result. On the right hand side of the line F_{RS} is greater than F_{WS} so that no surface lowering occurs and Type B platforms are formed. Tsujimoto's (1987) results are summarised in Table 2.1.

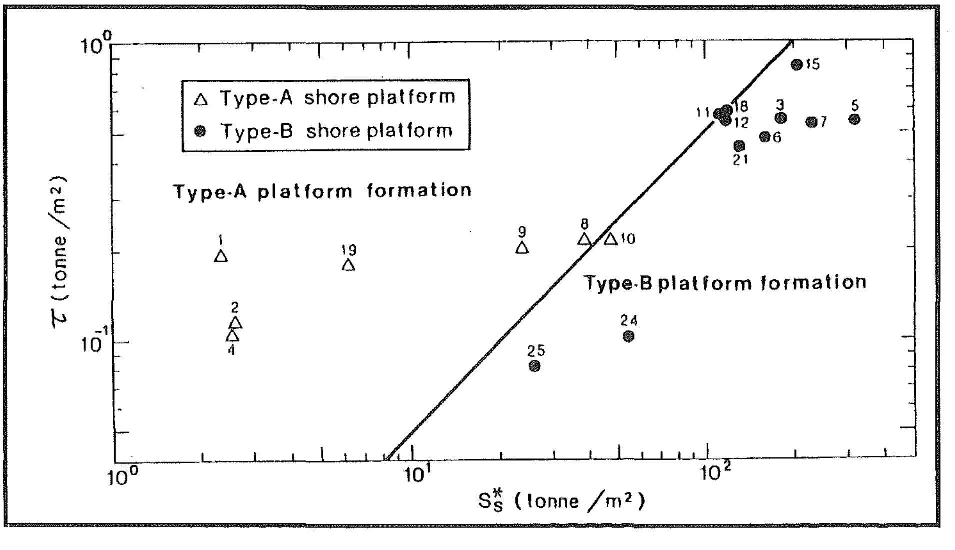

Figure 2.12 Demarcation between Type A and Type B shore platform (Tsujimoto 1987).

Table 2.1 Conditions for shore platform initiation and demarcation between Type A and Type B (Tsujimoto 1987:89).

Type A Platforms	Type B Platforms	Plunging Cliffs
$p > 0.081\ S^*_c$	$p > 0.081\ S^*_c$	$p < 0.081\ S^*_c$
$\tau > 0.005\ S^*_c$	$\tau < 0.005\ S^*_c$	

The assumption that no surface lowering occurs on Type B shore platforms must be questioned. Studies utilising the micro-erosion meter have shown platform lowering does occur. This suggests that some other mechanism is responsible for the preservation of the seaward cliff if it does in fact represent the position of the initial coastal line. Some researchers have argued that it does while other disagree. A review of that debate will occur in a later section. While doubt is expressed about the assumption that no surface lowering occurs on Type B shore platforms it would seem more reasonable that surface lowering rates on Type B platforms are slower than on Type A platforms, given that Tsujimoto (1987) has shown Type B platforms occur in rock with compressive strengths greater than Type A platforms. This point will be tested later with measured erosion rates. Tsujimoto (1987) has clearly shown that Type A and Type B platforms are two distinct platform profiles based on the relationship between the assailing force of waves and the resisting force of the platform rock. There is little room for debate over the difference in platform profiles. Type A and Type B are clearly two different morphological expressions of a shore platform. According to Sunamura (1992) the difference between the two types of platforms can be attributed to the relative difference in the magnitude of the relationship between wave assailing force and resisting force of the rock. This demarcation would appear to offer compelling evidence supporting the view that shore platforms result because of wave action. A question that does arise is, are Type A and B universal morphologies, can all platforms be designated as either type?

2.5.2 PLATFORM GRADIENT

Platform gradient has been most often studied in association with tidal range. The two have been thought to be closely linked. Trenhaile (1974a) found a correlation of 0.92 between platform gradient and tidal range in a macro-tidal environment. The correlation decreased to 0.88 when data from eastern Québec were included where the tidal range is meso-tidal. This suggests that as tidal range becomes smaller so does its influence on platform gradient. Williams (1986) showed that these correlations may be doubtful because data were combined from two different rock types, limestone and shale at two different locations in Yorkshire and Glamorgan. The question was, should each rock type be treated as a separate population? When this was done correlations reduced to 0.68 and 0.46 respectively. A significance test showed P = 0.76, and Williams (1986) concluded that H_o could not be accepted or rejected. This means there is uncertainty concerning correlations between platform gradient and tidal range.

Trenhaile (1987) proposed that platforms in tidal environments with a range of less than 2.5m should be almost horizontal. He cited an example from Japan where platform gradients are between 0.2 and 0.5° and the tidal range is between 0.4 and 2.7m. Trenhaile (1987) speculated that near horizontal platforms in Australia and New Zealand are a result of the small tidal range, but noted that sloping platforms do occur. If we accept Trenhaile's (1987) proposition that small tidal ranges produce near horizontal platforms then we can reconsider Hills (1972) who argued that waves could not cut a horizontal surface. The horizontal platforms Hills studied were in the meso-micro-tidal range of Australia. According to Trenhaile (1974a, 1978, 1987) these platforms could have been cut by waves.

Trenhaile (1974a) suggested that the relationship between tidal range and platform gradient has important genetic implications. Two points were made in regard to this. First, if some platforms are developed by weathering then why do their gradients vary with tidal range? Second, if some platforms are cut by waves then the relationship between tidal range and gradient must be attributable to the distribution of wave energy in the inter-tidal zone (Trenhaile 1987). Evidence for a stronger link is contradictory. Hills (1972) identified sloping platforms in sheltered embayments and horizontal platforms exposed on headlands, as did Duckmanton (1974) on the Kaikoura Peninsula. In the absence of wave data Trenhaile (1974a) used fetch length as a surrogate and found gradient decreased as fetch increased. This was supported by modelling (Trenhaile and Layzell 1980, 1981). Trenhaile (1987) proposed that this contradiction most likely reflects differences in lithology and geology. He also proposed that offshore gradients were important for the amount of energy arriving on a platform.

2.5.3 SHORE PLATFORM WIDTH

The width of shore platforms have been considered by a number of authors (Dana 1849; Johnson 1919; Edwards 1941; Trenhaile, 1972, 1978, 1983; Trenhaile and Layzell 1981; Sunamura 1992). Johnson (1919) proposed that width increased through time, but the rate of extension decreased over time. Edwards (1941) considered the width of a platform to be controlled by the relative difference in the rate of retreat of the low and high tide cliffs. The rates of retreat of each was controlled by, among other factors, the tidal range. Trenhaile (1972, 1978) did not find a relationship between tidal range and width. Modelling by Trenhaile and Layzell (1980, 1981) did indicate a direct relationship between tidal range and platform width.

Attempts to establish a relationship between platform width and wave intensity have also proven difficult. Some field data do support a relationship, for example, in Japan platform widths of 60m are found on the open Pacific coast, 50m on the less exposed Japan Sea coast and 40m on the Inland Sea coast (Takahashi 1977). Contrary to this, Bartrum (1935), Edwards (1941), Hills (1949 and 1971), Duckmanton (1974) and Kirk (1977) found the widest platforms in sheltered embayments. Trenhaile (1987) considered it a logical assumption that there should be a direct relationship between platform width and wave energy, but noted that it was difficult to test because of a lack of wave data on rocky coasts. This logical assumption was also based on accepting that only waves erode shore platforms. The difficulty in establishing relationships between tidal range, wave exposure and platform width suggests that other factors such as rock hardness, lithology and structure may also be significant controls (Trenhaile 1978, 1980, 1987).

Width is also important if one accepts the view that the seaward edge of a platform retreats. If it does not, then the seaward edge marks the original position of the shoreline when platform development began. This point is important for modelling platform development, and for the type of equilibrium that platforms attain. In the views of Sunamura (1975, 1978a, 1990, 1991, 1992) and Tsujimoto (1987) the seaward cliffs of Type B platforms do not retreat. Laboratory modelling by Sunamura (1975, 1978a, 1990, 1991, 1992) showed that the original shoreline position was maintained after the development of a seaward cliff. Sunamura (1992) noted that the seaward cliff is often covered with a marine flora and fauna even after severe storms. He argued that this is clear evidence for a lack of seaward cliff erosion. In contrast, Bartrum (1926), Jutson (1939), Edwards (1941), Gill (1972), Trenhaile (1974a, 1978, 1983a, 1987) and Trenhaile and Layzell (1980, 1981) proposed that the seaward cliff does retreat. The evidence they offered is the large blocks and boulders found on platforms after storms. These have been eroded from the seaward cliff and thrown up by waves. Gill (1972) offered one of the few explanations for the process: in aeolianite platforms solution processes undercut the cliff to the point where the resulting over hang can be broken off by waves.

Sunamura (1990, 1991, 1992) offers the first discussion of this issue made on the basis of wave dynamics in front of a Type B platform. From Sunamura (1990) the dynamic pressure,

p, of breaking waves acting on a vertical wall decreases exponentially with depth, and is expressed:

$$p = p_o e^{a_p(z/h)} \qquad \textbf{2.25}$$

where:

p_o = pressure at still water level

a_p = is a reduction coefficient

z = increase in water depth

h = depth of water at base of the cliff taken from still water level

Sunamura (1990) assumed that the assailing force of breaking waves is linearly related to the intensity of this dynamic pressure, therefore the wave assailing force also decreases exponentially with increasing depth and can be described by equation 2.26:

$$F_W(z) = F_W e^{a_f(z/h)} \qquad \textbf{2.26}$$

where:

F_W (z) = the assailing force of waves at depth z (negative value) measured from still water level (SWL)

F_W = assailing force of waves at SWL

a_f = is a reduction coefficient of F_W

The strength of the cliff is space-independent so that the resisting force of the cliff is written:

$$F_R(z) = F_R = \text{constant} \qquad \textbf{2.27}$$

Figure 2.13 shows the vertical distribution of F_W (z) and F_R(z). No erosion will occur where F_W (z) < F_R(z). The lower part of the cliff does not therefore erode (Sunamura 1992). Based on this theoretical illustration Sunamura (1992) argued that the seaward cliff of Type B platforms does not retreat. Sunamura cited Cotton (1963) who suggested that the seaward cliff of Old Hat platforms marks the original position of the shore, and Gill (1950) who suggested the same for platforms on the east coast of New Zealand as field evidence. The existence of sub-tidal notches as described by Gill (1972) is attributed to undercutting on lower stands of sea level.

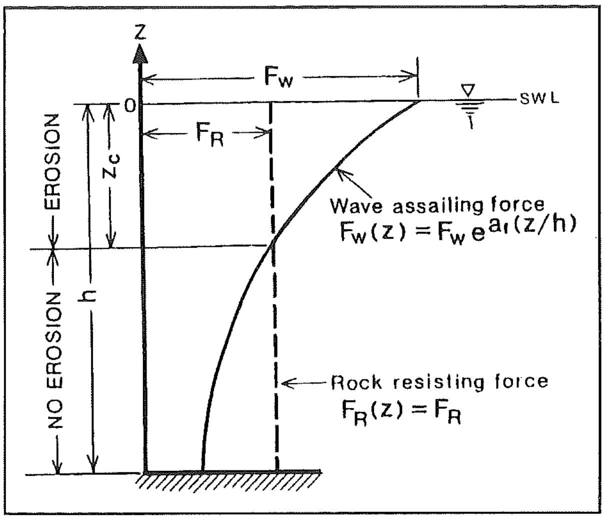

Figure 2.13 Vertical distribution of assailing force of waves and resisting force of rocks (Sunamura 1991:763).

Establishing whether or not the seaward cliff does retreat has important implications for modelling shore platform development. If the original position of the coast can be identified, then rates of development can be more accurately attained. Models such as the parallel retreat model (presented in Chapter Three) become invalid if the seaward cliff does not retreat. Clearly not enough attention has been directed to this important issue. There are many published rates of backshore cliff retreat but none for seaward cliff retreat. If the cliff does retreat then clearly it must be at a much slower rate than that of the backshore cliff.

2.5.4 PLATFORM ELEVATION

There are a number of different propositions as to the level to which shore platforms may tend. Elevation has often been cited as an important genetic indicator but little agreement exists between workers as to exactly what it indicates. One important question is, do shore platforms develop at one elevation in relation to one sea level? This question is important since shore platforms are often used to reconstruct paleo-sea levels. The elevation at which shore platforms develop remains a contentious issue. The classical view was that platforms develop as a result of single sea level down to low tide (Davis 1896, and Johnson 1919).

Bartrum (1916, 1924, 1926, 1935) distinguished between platforms of the Old Hat type with an elevation slightly below high tide and storm wave platforms with elevations several metres above high tide. Jutson (1939) considered whether the elevation of platforms above high tide on the New South Wales Coast between Botany Bay and Broken Bay was due to the emergence of the coast or due to formative processes operating at higher levels. He concluded that they resulted from salt spray weathering and were in fact modern features. Gill (1972) also concluded that higher platforms were a result of contemporary processes and were being lowered to an equilibrium profile at low tide.

So (1965), Trenhaile (1972, 1974a), Duckmanton (1974) and Sunamura (1978a) have cited platforms that are higher in mean elevation on exposed headlands than in sheltered bays. This suggests a possible relationship between exposure to wave energy and elevation. Gill and Lang (1983) on the other hand did not find changes in elevation between headlands and embayments along the Otway coast of Victoria, where platforms were cut in greywacke. Trenhaile (1971) concluded that high water rock ledges in the Vale of Glamorgan were the results of lithological control and higher stands of past sea level. Duckmanton (1974) did not find any correlation between platform elevation and lithology on the Kaikoura Peninsula.

Based on laboratory modeling Sunamura (1990, 1991) found a direct relationship between Type B platform elevation and rock strength, if other factors remained the same. Considerable variation was shown to occur with variations in breaker height and rock strength. Using z_c to denote elevation, Sunamura (1991) wrote:

$$F_W(z_c) = F_R(z_c) \qquad \textbf{2.28}$$

based on:

$$F_W = A\rho g H_b \qquad \textbf{2.29}$$

and:

$$F_R = BS_c \qquad \textbf{2.30}$$

the elevation of a platform was described by the equation:

$$\frac{Z_c}{h} = \frac{1}{a_f}\left[\Gamma + \ln\left(\frac{\rho g H_b}{S_c}\right)\right] \qquad \textbf{2.31}$$

Values for z_c were obtained experimentally, and analysed using equation 2.31. The results are shown in Figure 2.14.

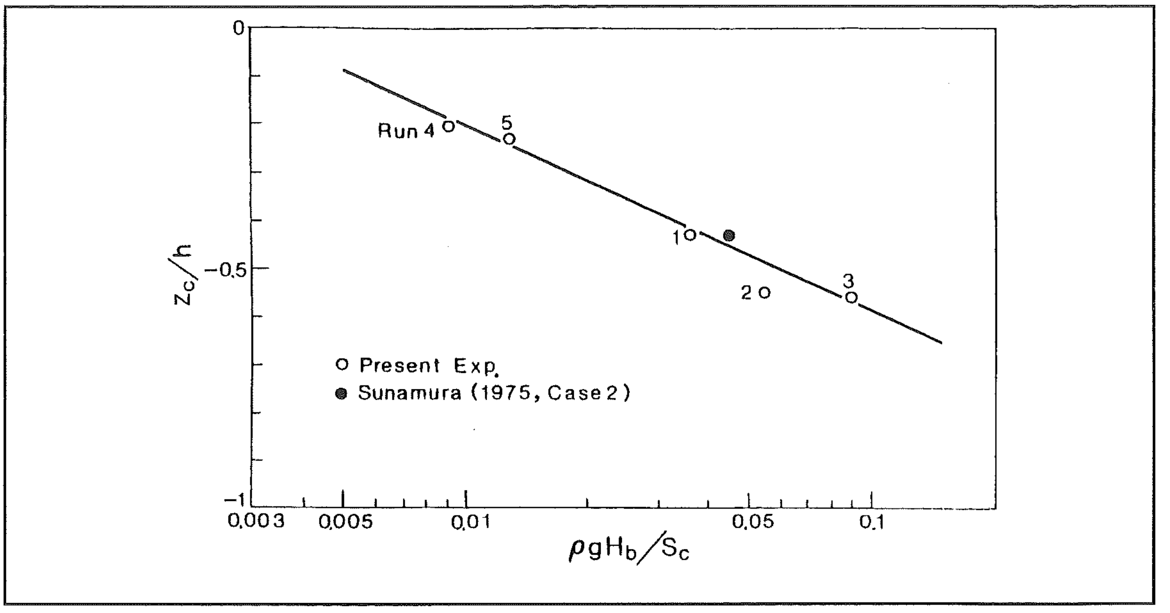

Figure 2.14 Normalized platform elevations z_c/h, plotted against dimensionless wave-rock parameter, $\rho g H_b/S_c$ (Sunamura 1991:764).

The straight line in Figure 2.14 can be described as:

$$\frac{Z_c}{h} = -0.17\left[5.8 + \ln\left(\frac{\rho g H_b}{S_c}\right)\right] \qquad 2.32$$

where

Z_c = critical depth of erosion, that is, the elevation of a platform.

A comparison was made between equations 2.31 and 2.32 to yield a_f = 5.9 and Γ = 5.8.

Sunamura (1991) then attempted to apply these results to field scale examples. He considered two sites where the only difference was in the values for rock strength. So that at Site one:

$$\frac{Z_{c1}}{h} = \frac{1}{a_f}\left[\Gamma + \ln\left(\frac{\rho g H_b}{S_c}\right)\right] \qquad 2.33$$

and at Site two:

$$\frac{Z_{c2}}{h} = \frac{1}{a_f}\left[\Gamma + \ln\left(\frac{\rho g H_b}{S_c}\right)\right] \qquad 2.34$$

From equations 2.33 and 2.34 the difference in elevation is given by:

$$\Delta z_c = z_{c1} - z_{c2} = -\frac{h}{a_f}\ln\left(\frac{S_{c2}}{S_{c1}}\right) \qquad 2.35$$

Because the height of breaking waves in front of a cliff is controlled by the depth of water Sunamura (1992) assumed that:

$$H_b = h \qquad 2.36$$

Sunamura (1991) also assumed that the values for a_f obtained in the laboratory could be applied in the field so that:

$$a_f = 5 \cdot 9 \qquad 2.37$$

Based on these two assumption equation 2.35 reduces to:

$$\Delta Z_c = -0.17 H_b \ln\left(\frac{S_{c2}}{S_{c1}}\right) \qquad (S_{C1} > S_{C2}) \qquad 2.38$$

Three calculations were made using equation 2.38 using values of 3, 5, and 7m for H_b. The results of this are shown in Fig 2.15.

It was found that differences in platform height increased as the strength ratio S_{c2}/S_{c1}, decreased. A platform cut by a wave H_b = 5m, differed 0.6m in elevation when S_{c2}/S_{c1} was halved. Figured 2.15 shows that large variations in elevation result from variations in breaker height and rock strength (Sunamura 1991). Clearly softer rocks have lower platforms. Sunamura (1991) found Δz_c was directly related to h, the water depth in front of the cliff, and that this factor had been ignored in previous research as a control of platform elevation. He also argued that the absolute elevation of a platform in the field could be obtained using equation 2.37 and Γ. For this, the values for Δz_c, h, and S_c were required from the field and a_f = 5.9.

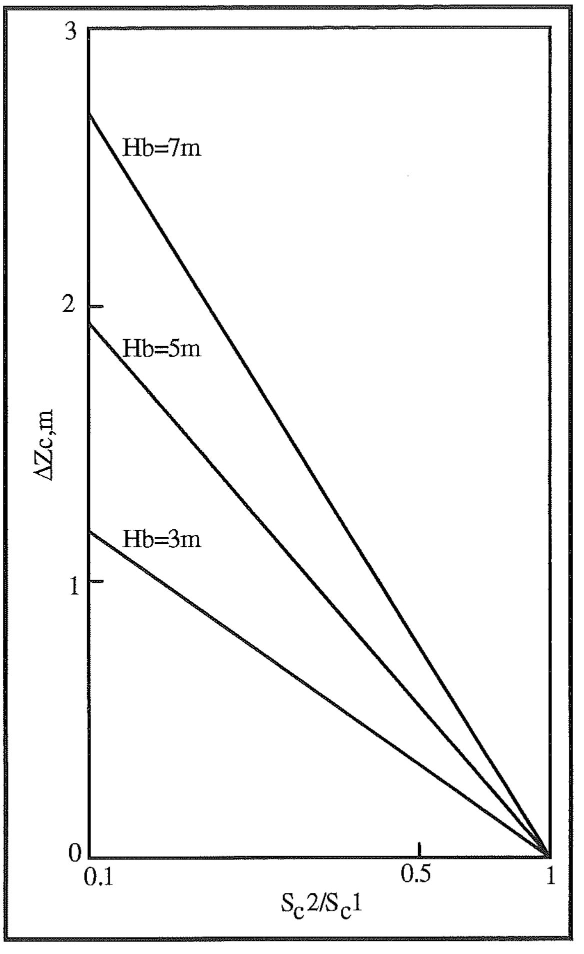

Figure 2.15 Relationship between differences in platform elevation Δz_c, and strength ratio, S_{c2}/S_{c1}, at two sites for three breaker heights H_b = 3, 5, and 7m. (Sunamura 1991:764)

2.6 GEOLOGY AND LITHOLOGY

Dana (1849) noted that the "natures of the rock material" played an important role in the development of shore platforms. Evidence for this was to be found on basaltic shores where it was unusual to find shore platforms, while on sandstone shores platforms of uniform width were maintained. He also suggested that the width of shore platforms was controlled by rock hardness. A quantitative consideration did not come until Edwards (1941) measured and discussed the role of rock hardness affecting platform development. Edwards used compressive strength to represent rock hardness. Values for compressive strength for different rock types found on the Victorian and Tasmanian coast were presented; a relationship was discovered between rock hardness and platform width. These results are shown in Table 2.2. The best developed platforms occurred in rock with compressive strengths between 3000 to 7800 p.s.i. They were also well developed in rock with compressive strengths between 11000 and 16000 p.s.i. At compressive strengths of 27000 they were absent or incipient. In weak rock between 1500 and 3000 p.s.i they were narrow, absent or incipient.

Table 2.2 Relationship between rock strength and width of shore platform (Edwards 1941:231).

Rock Type	Compression Strength (lbs. per sq.in)	Nature of Platform
Woolamai granite	27000	absent or incipient
Tertiary Basalt	11000 - 16000	well developed, with widths up to 100 feet
Jurassic felspathic sandstone	3000 - 7800	best developed, with widths up to 300 feet
Tertiary limestone	1500 - 3000	narrow with widths up to 15 feet; generally absent or incipient.

It was not until the work of Tsujimoto (1985 in Sunamura 1992, 1987) that rock strength was used again in an investigation of platform development. It was found that a demarcation between plunging cliffs, and Type A and B shore platforms existed based on rock hardness. According to Sunamura (1994), Edwards (1941) had unknowingly made the same demarcation (Table 2.3). Many authors have noted the role geology and lithology play in platform development and the effects on the resulting morphology, but with the exception of Edwards (1941), Sunamura (1973) and Tsujimoto (1985, 1987) none have explored this quantitatively.

Trenhaile (1980, 1987) summarised the role of geology into three parts:

1) *Lithology, structure and mineralogy control the efficiency of erosional process.* Rock that is thinly bedded and well jointed will be eroded dominantly by wave quarrying. Rocks that absorb large amounts of water are probably more susceptible to chemical weathering. The amount and type of debris that accumulates at the cliff base is controlled by geological factors (Robinson 1977b) which in turn affects the rate of cliff retreat.
2) *The platform profile is influenced by structural and lithological factors.* Rock dip affects surface roughness. Washboard relief develops in steeply dipping, thinly bedded strata. Alternatively, smooth surfaces result when dip is shallow or horizontal.
3) *The degree of inheritance from past sea level depends of the susceptibility of the rock to erosion.*

Table 2.3 Compressive strength values for Type A and Type B platforms.

Study	Type A	Type B	Plunging Cliff
Edwards (1941)	10294-20588 KN/m^2	20588-109804 KN/m^2	186079 KN/m^2
Tsujimoto (1985)	<2941 KN/m^2	2941-14706 KN/m^2	>14706 KN/m^2
Tsujimoto (1987)	127-3824 KN/m^2	1471-25498 KN/m^2	5982-196140 KN/m^2

Trenhaile (1987) cited examples where platform gradient increased with resistance to erosion (Trenhaile 1972, 1974a, 1978), and developed models that reproduced this (Trenhaile and Layzell 1980, 1981, and Trenhaile 1983b). This is contrary to Gill and Lang (1983) who found horizontal platforms in greywacke and sloping ramps in softer siltstone. Tsujimoto (1987) and Sunamura (1992, 1994) found that platform gradient decreased with rock hardness. Such contrary evidence may reflect the role of tidal range and the possibility that rock hardness does not necessarily control susceptibility to erosion.

The relationship between platform width and geology is also a complex one. Everard et al. (1964) found that softer rocks give rise to wider platforms than hard rocks on the Cornwall coast, as did Takahashi (1977) in southern Japan where platforms are absent in igneous rock. Wider platforms were found on the sheltered sides of islands and sheltered locations on the eastern side of the Vale of Glamorgan, Wales. Trenhaile (1972) proposed that this testified to the role of wave energy in controlling platform width. The relationship between platform width and geology is further complicated when Australian examples are considered. According to Edwards (1941) very narrow platforms result in soft limestone because the seaward cliff of platforms is more easily eroded and this is also why wider platforms are found in more resistant sandstones. However, platform widths decreased again in the harder basalts and were almost absent in granites (Edwards 1941). On the Vale of Glamorgan wider platforms occur in shaley Liassic *angulata* than in the more resistant *bucklandi* limestone (Trenhaile 1987). On the Cornwall Peninsula Everard et al. (1964) found that in steeply dipping rocks, platforms are widest when the strike is perpendicular to the cliff face, and in gently dipping strata they are widest when the strike is parallel to the cliff. Platform elevation has also been linked to rock hardness such that elevations are generally higher in harder rock (Gill 1972; Hills 1971; Kirk 1977; Takahashi 1977; Gill and Lang 1983; and Sunamura 1978, 1991).

2.7 BIOLOGICAL CONTROLS

Biological activity on shore platforms has two effects: 1) it causes erosion, which can be separated into biomechanical and biochemical components and; 2) it retards or prevents other erosional processes. Neumann (1966) defined bioerosion as the removal of the lithic substrate by direct organic activities. Emery (1946) and Revelle and Emery (1957) proposed that in tropical regions, nocturnal falls in temperature and the production of carbon dioxide by marine algae and animals through respiration increases the solution of calcite at night. Everard et al. (1964) thought the chemical effects of plants and animals contributed to erosion on the Cornwall coast. Marine algae and animals increase the pH of sea water in rock pools and expel carbon dioxide during darkness causing the disintegration of rock. During the warmer summer months this effect is enhanced as temperatures in rock pools increase. Water becomes saturated with calcium and magnesium which is flushed out on the next high tide (Everad et al. 1964). Trudgill (1976a) investigated the role of biochemical and biomechanical weathering on Aldabra Atoll. He found that the solution of limestone from biological activity accounted for 10 per cent of all erosion.

Many studies have attempted to quantify biomechanical erosion. This form of erosion takes place in two main ways, either as animals bore or as they graze. Endolithic algae are important on rocky shores in two ways. First, they bore into the rock surface with fine filaments. Endolithic cyanophyta bore to depths ranging from 500 to 900 microns and have population densities of between 150,000 to 1,000,000/cm^2 (Trenhaile 1987). Secondly endolithic algae and epilithic algae are a primary food source for grazing animals. However, organisms that graze on epilithic algae probably achieve little erosion. Organisms such as patelliform molluscs erode material through grazing and through boring of a home scar. Different species also graze to different depths in an attempt to reduce competition (Trudgill 1976a). Depths of home scars vary depending on individuals' size and from species to species. The role of excavated home scars in erosion is ambiguous. Obviously material is removed by excavation but Trenhaile (1987) speculates that vacated home scars render rock more susceptible to mechanical wave erosion and this factor may be more important than direct removal by boring.

In Barbadoes, West Indies, McLean (1967) investigated bioerosion on limestone by marine gastropods which remove rock by scraping the surface with their radular teeth to feed on algae. He found that over 80 per cent of faecal pellets contained carbonate material, clear evidence for bioerosion by gastropods. Erosion rates ranged from 0.2 to 2.4 g/yr depending on species, animal size, depth of penetration by algae, and hardness of the rock. By determining the population density and average size of *Nerita tesselata* in an area of $110m^2$ the erosion data were then extrapolated to calculate that $154g/m^2/yr$ was removed and a total of 17kg/yr was removed over the total area.

Healy (1968b) estimated that bioerosion on sand and siltstone platforms near Auckland, New Zealand was in the order of 10mm/yr, although this was not actually measured. Trudgill (1976a) measured rates of boring organisms on Aldabra Atoll, where rates varied from 0.9cm/yr to 4.5cm/yr. Erosion due to grazing was measured at 0.45mm/yr at sandy locations and 0.61mm/yr where sand was absent. The contribution to total erosion was 36 per cent and 64 per cent respectively. Trenhaile (1987:77-79) presents a summary of 42 investigations of bioerosion rates which range from 30 to 50 microns in three to four weeks by algae on carbonates, to 1m/yr on limestone by boring *Paracentrotus lividus*.

Hills (1949) described the effects of marine organisms on shore platforms. The role of boring sea urchins was noted briefly by Wentworth (1938) but Hills (1949) provides a more detailed account of the effect of marine organisms. He reported that the "growth of marine plants and animals is so profuse as to form an almost uninterrupted cover to rock surfaces below a certain level ... the level concerned is usually about mean sea level, although it may vary according to local conditions..."(Hills 1949:143). He considered that the growth of marine organisms in such dense mats prevented abrasion and wave quarrying. Another effect is that marine growths prevent surfaces from drying out and thus limiting the extent of water layer weathering. Everard et al. (1964) also noted "marine algae form an almost complete blanket and this indicates that wave-quarrying and abrasion is limited" (Everard et al. 1964:300). However, they did not suggest algae prevent wave quarrying or abrasion. They also noted how seaweeds attach to rocks with a hold fast. During severe storms seaweeds are dislodged and remove slivers of rock, which makes an albeit small contribution, to erosion. More importantly, the removal of seaweed exposes fresh rock to waves. Kirk (1977) noted how dense growths of kelp on the Kaikoura Peninsula protect platforms since as much as 20 per cent of a wave energy is required to bend artificial sea grass (Wayne 1974).

2.8 MICRO-EROSION METER STUDIES

The foregoing has amply demonstrated how much of the research into shore platform development lacked quantitative data. This occurred because suitable means to measure cliff recession and surface lowering did not exist during early investigations. Sunamura (1994) noted that the first published rates of cliff recession were probably by Johnson (1925) from surveys. Maps were used widely from the 1950s to calculate cliff retreat. The advent of aerial photography saw a leap in the number of attempts to calculate cliff retreat rates from the late 1960s (see Sunamura 1994:265-276).

Prior to 1970 attempts to calculate rates of surface lowering on platforms relied on techniques such as weathering of dated inscriptions (Emery 1941), chemical analysis of pool water (Revelle and Emery 1957) and the use of scour pins (Hodgkin 1964). Obviously such techniques lacked the precision to measure rates of erosion that were measured in millimetres per year. In 1970 however, a new technique was introduced that enabled very accurate measurements. The micro-erosion meter (MEM) was introduced by High and Hanna (1970) as a technique for measuring small rates of erosion on bedrock. It was modified by Trudgill et al. (1981) to allow a greater number of measurements to be made. The modified meter is known as the traversing micro-erosion meter (TMEM). The adaptation of this technique for shore platform studies and published rates of erosion soon followed (Table 2.4).

Investigators saw the potential to answer questions concerning the age and rate of development of shore platforms and to investigate the processes operating on shore platforms. Questions such as, how old are shore platforms, and how fast do they develop? Both questions have become important as it has been demonstrated that some shore platforms are relict features from previous interglacials that had been reactivated following Holocene sea level rise (Phillips 1970a, 1970b). Thus some platforms have undergone more than one episode of cutting. If rates of development could be measured then interpolation of these rates could elucidate possible ages of shore platforms and answer questions concerning inheritance. While the MEM has aided in such investigations it has also provide insight into processes operating on shore platforms and helped identify new ones.

Table 2.4 Summary of published erosion rates measured using the MEM and TMEM

Authors	Mean annual erosion rate mm/yr	Lithology and Morphology	Location
Stephenson and Kirk (1996)	1.48	Intertidal limestone and mudstone	Kaikoura Peninsula New Zealand
Mottershead (1989)	0.625	Supratidal Green schist	Start-Prawle Peninsula Devon, U.K
Viles and Trudgill (1984)	1.97	Limestone, raised coral reefs	Aldabra Atoll Indian Ocean
Gill and Lang (1983)	0.37	Greywacke inter-tidal platforms	Otway Coast Victoria Australia
Spencer (1981)	0.38	Limestone, raised coral reef	Grand Cayman Islands West Indies
Spencer (1985)	0.09 to 1.77	Limestone, raised coral reefs	Grand Cayman Islands West Indies
Kirk (1977)	1.53	Intertidal limestone and mudstone	Kaikoura Peninsula New Zealand
Robinson (1977a,b,c,)	0.0 to 0.9	Intertidal shale ramp and platforms	Yorkshire U.K.
Trudgill (1976a, 1976b)	1.01 to 1.25	Limestone, raised coral reefs	Aldabra Atoll Indian Ocean

Trudgill (1976a, 1976b) used a MEM as part of an investigation into marine and terrestrial erosion of limestone on Aldabra Atoll in the Indian Ocean. Marine erosion was caused by solution of limestone, biological erosion in the form of boring and grazing, salt spray weathering, spray action and abrasion. The MEM was used in conjunction with weight loss tablets. These tablets were made of limestone in fine mesh bags and placed in the inter-tidal zone. The mesh had the effect of excluding processes such bioerosion and abrasion but permited weathering processes to occur. By isolating particular processes with variations in the design of weight loss tablets Trudgill was able to quantitatively assess the relative contributions of bioerosion, abrasion and weathering to the total erosion measured with the MEM. Although a direct comparison of results between the two techniques was questioned by Trudgill, results showed that erosion rates were comparable to one significant figure.

Trudgill (1976b) found that inter-tidal erosion at a site where sand was present was 1.25mm/yr. When tablets were used to exclude grazing, the erosion rate dropped to 0.80mm/yr and when grazing and abrasion were excluded erosion was 0.39mm/yr. This meant that abrasion accounted for 0.41mm/yr or 32.8 per cent of the total, grazing 0.45mm/yr or 36 per cent and other processes 0.39mm/yr or 31.2 per cent of total erosion. Other processes included solution, salt weathering, wetting and drying, spray and wave action. At a MEM site where there was no sand present the total erosion was 1.01mm/yr; when grazing was excluded this became 0.40mm/yr. Therefore grazing accounted for 0.61mm/yr or 64 per cent of the total erosion and other processes caused 0.40mm/yr erosion or 36 per cent of the total. While Trudgill was able to quantify the contribution of bio-erosion he did not separate out weathering processes from wave quarrying. Trudgill (1976a) also found that measured erosion rates increased around Aldabra Atoll with increasing exposure to the dominant southeast Trade Winds. Rates of erosion on sheltered sites ranged from 0.60 to 1.0mm/yr and on exposed southeast facing sites ranged from 2 to 4mm/yr. Further to this the zonation of marine organisms did not correspond with these higher erosion rates, suggesting that on the exposed coast physical process (salt spray impact, wave quarrying and wetting and drying) were dominant.

Kirk (1977) used a MEM on the Kaikoura Peninsula to investigate rates and processes of erosion. Seven profiles were established around the Kaikoura Peninsula, with between 2 and 8 MEM bolts sites on each depending on the width of the platform. Two profiles were on limestone and the rest on mudstone. The grand mean lowering rate was 1.53mm/yr; this was calculated by averaging mean rates for all profiles means, which were calculated from the mean for each MEM site. The minimum mean for a profile was 0.38mm/yr and the maximum was 2.50mm/yr. The minimum mean for an individual bolt site was 0.35mm/yr and the maximum was 7.03mm/yr. Based on these erosion rates Kirk (1977) concluded that the platforms on the Kaikoura Peninsula were contemporary features no older than the amount of time sea level had occupied its present level. Another result was variation in erosion rates across the platform profile. Rates were higher on the seaward margin and landward margins than on the central part of platforms. How this finding and these data were used to formulate a hypothesis for shore platform development has already been discussed.

Robinson (1977a, 1977b) used the MEM technique to investigate erosion processes at the foot of a cliff on a shore platform on the northeast Yorkshire coast. MEM readings were taken approximately every two weeks. From this he was able to calculate a mean erosion rate per tidal cycle. Robinson assumed that four processes identified by King (1972) might be responsible for erosion:

1) corrosion, chemical weathering of rocks;
2) attrition, the break up and abrasion of material derived from the cliff;
3) corrasion, erosion and smoothing of the cliff foot by waves armed with sediment; and
4) hydraulic action (quarrying), the removal of blocks as water is forced into joints and fissures.

Robinson rejected the first process, corrosion, because the cliff was cut in shale and the second, attrition, because it was "not relevant to the cliff foot". He considered corrasion and quarrying likely to be present as the environment was a storm wave one with sediment was present at the cliff foot.

It was necessary to identify variables that could be used to recognise processes operating between measurement periods without actually using erosion data. The parameters used were,

1) *The coefficient of variation of erosion,* Robinson assumed that corrasion would produce erosion rates that were relatively uniform spatially; whereas quarrying of small blocks would produce very high rates as well as very low rates. Therefore it would be possible to distinguish between the two processes by measuring spatial variations in the erosion rates.
2) *Wave energy*, quarrying was thought to only be effective during high energy events.
3) *Distance from beach of MEM sites,* since corrasion requires sediment to be available, the proximity of a beach wass important.

Further statistical analysis enabled Robinson to group erosion periods according to the three classes above. Robinson used the divisive-monothetic method of association analysis since this allows the cause of division between classes to be attributed to one variable. As a result Robinson proposed that he could identify which process dominated the measurement period.

This analysis revealed that quarrying was the major process at a cliff foot where it does not have a beach in front of it. He considered that quarrying operated at two scales; large scale quarrying which equates to recession rates in cm/yrs, and micro quarrying which can be measured in mm/yr. The second was thought to be insignificant compared to the first. Since quarrying was dependent on wave energy it was considered to be most significant during winter months when storms were more prevalent. Lower erosion rates during summer months were thought to as a result of weathering processes such as wetting and drying. This caused continued expansion and contraction of the shale laminae, and cracking along bedding planes. The role of weathering was not determined through the statistical analysis.

Robinson noted that in a narrow zone approximately 10cm above the beach, sediment erosion of the cliff was significantly higher than at the higher elevations of 20cm. He proposed that while quarrying was at work at both elevations up to 10cm there was another process in play. In part Robinson proposed that both corrasion and quarrying worked together in this lower zone. Sediment was not carried to higher elevations to enable corrasion to work. He noted that when quarrying loosened material, it was not always completely removed, but remained to be picked up by waves. One result was for fine grained material to be washed into the gap between the dislodged material and the cliff, thus aiding the process of quarrying. Robinson believed he had identified a new process of erosion, which he termed "wedging".

Where beach sediment was present corrasion occurred. It was limited to a narrow band related to the location of beach sediments and caused the formation of a shallow depression in which sediment remained. However, this depended greatly on the amount of sediment present. Significantly, two thirds of erosion from corrasion occurred during the winter months. This related to the occurrence of higher wave energy.

Overall, Robinson (1977b) found that micro-quarrying and weathering lowered platform surfaces at a rate of 0.144cm/yr compared to 2.3cm/yr caused by quarrying. If a beach was present then quarrying was the dominant process at a height of 19.8cm above the beach with erosion occurring at a median rate of 0.91×10^{-3}cm tide^{-1}. In the zone 10cm above the beach, corrasion was dominant and caused erosion at a median rate of 5.79×10^{-3}cm tide^{-1}. Wedging aided by some corrasion produced a median erosion rate of 11.05×10^{-3}cm tide^{-1}. The primary control of erosion at the cliff foot was wave energy which was greater in the winter; although at some study sites erosion rates were higher in summer when wetting and drying dominated. Tides were not considered to be an important factor. By comparison, where a beach was present in front of a cliff, erosion rates were 15 to 18.5 time higher than those where a beach was absent.

Robinson (1977c) identified four classes of shore platforms on the coast of northeast Yorkshire. These classes were based on morphology and rates of erosion measured using the MEM. Class 1 was a platform with a sub-horizontal plane with erosion rates in the order of 0.01 to 0.20 cm/yr, although these can be higher closer to the foot of the backshore cliff. Class 2 had a ramp with a slope greater than 2.5° at the cliff foot and a plane seaward of this. The ramp was covered with sediment that was subject to movement by waves. Rates of erosion varied from 0.10 to 3.00 cm/yr depending on the amount of sediment present. A class 3 platform consisted entirely of a ramp which may be covered by boulders. Erosion rates on this type of platform were negligible. Changes in the nature of debris on the platform may lead to change to another class of platform. Class 4 platforms were dominated by geological factors, and the identification of a ramp or plane was difficult.

Spencer (1981, 1985) used the traversing micro-erosion meter (TMEM), which enabled more than three readings to be taken at a bolt site; in this case either 20 or 21 readings per site. The traversing micro-erosion meter is described fully in Chapter Four. In Spencer's study the TMEM was used to investigate changes in the micro-topography on calcarenite on Grand Cayman Island in the West Indies. Three study sites were located on a littoral platform with an elevation between 0.4 and 1.1m above mean sea level. The grand mean lowering rate was 0.38mm/yr between 1977 and 1978 (Spencer 1981). This compared with 0.39mm/yr reported by Trudgill (1976a) on similar rocks on Aldabra Atoll. Spencer (1981) noted that the islands share similar climates, particularly in regard to rainfall. The cause of surface lowering was attributed to subaerial processes, Spencer did not discuss marine processes at all.

Spencer was able to undertake a form of analysis not previously available to researchers using the MEM. He ranked erosion rate data for each measurement position at a bolt site and grouped them into quartiles. An isopleth map was produced to illustrate where rates of erosion were high or low. This revealed that high points eroded faster than lower ones so that the surface was losing its micro-relief. The explanation offered was that these changes were a function of the mineralogy of the rock. The calcarenites contained pockets of highly concentrated magnesium which are more susceptible to chemical erosion that the surrounding matrix. This leads to preferential erosion.

Spencer (1981) concluded that the TMEM allowed micro-topographic changes to be monitored and related in a dynamic way to rock mineralogy. He sounded a warning about possible misinterpretation of results from too short a study period. The number of TMEM sites required to gain representative results was unknown. Spencer's (1981) results showed that a great deal of variability existed within a single TMEM site and between sites. He questioned the usefulness of calculating an average erosion rate as this had the effect of obscuring the variability which gave clues to the processes operating. The grouping of data into classes probably had the same effect. It was proposed that using the median may be a more sensible procedure.

Furthermore, Spencer's data showed positive skewness. He noted that Robinson (1976a) had pointed out the danger of comparing means and standard deviations from sites with non-normal sampling distributions, and the use of non-parametric tests of differences was advised. Finally Spencer cautioned against extrapolating from the small area of a TMEM site to a larger scale where structural controls became important, but did not explain why caution was needed.

Gill and Lang (1983) used a MEM to investigate the origin and evolution of shore platforms on the Otway coast of Victoria in South Australia. These platforms are cut in greywacke and siltstone, and are exposed to a swell wave environment. In a similar fashion to Kirk (1977), Gill and Lang (1983) installed bolt sites along profiles normal to the shore. A total of 62 bolt sites were installed on 9 profiles along a 50km stretch of coastline. By the end of the study period readings were being taken from only 50 bolt sites as some could not be reached because of swell waves, sand covering some sites, or the growth of biota. The mean annual erosion rate for the Otway shore platforms was 0.37mm/yr. The highest mean annual rate for a profile was 0.9mm/yr and the minimum was 0.2mm/yr. Mean annual rates between individual bolt sites ranged from 0.02mm/yr on greywacke to 1.8mm/yr on a siltstone platform.

Viles and Trudgill (1984) present erosion rates from Aldabra Atoll, based on an eleven year period. On the inter-tidal surfaces of a raised coral reef the mean lowering rate was reported to be 1.97mm/yr. Viles and Trudgill (1984) also attempted to test the validity of extrapolating shorter term data to longer periods. To do this, they predicted the total erosion that would occur in eleven years by extrapolating from a two year data set and compared this result with erosion measured over the eleven year period. The shorter term measurements were within an order of magnitude of the long term rates with a 10 per cent difference in mean rates. Viles and Trudgill (1984) concluded that the use of a "small" number of sites was suspect and that a "larger" number of MEM sites was needed to gain acceptable data. They did not suggest the number required. Attempts to extrapolate shorter term data were thought to be invalid, except to establish an order of magnitude, and extrapolation should be done with a degree of caution.

Using the MEM, Mottershead (1989) calculated a mean lowering rate of 0.625mm/yr on supratidal greenschist, on the Start-Prawle Peninsula, of the south Devon coast of the United Kingdom, based on a seven-year time period. The principal agent of erosion was salt spray weathering. Mottershead (1989) concluded that measurements taken from 30 individual positions were sufficient to calculate a representative mean annual lowering rate on the Start-Prawle Peninsula and that year to year variations in total lowering were not statistically significant.

As part of the present investigation Stephenson and Kirk (1996) (Appendix One) remeasured MEM bolt sites at Kaikoura that were installed in 1973 by Kirk (1977). This allowed erosion rates to be calculated from an elapsed period of 20 years from 15 of the original 31 bolt sites, some 16 sites could not be found or were unusable. Stephenson and Kirk found that the grand mean erosion rate for both lithologies was 1.43mm/yr. This compared with 1.53mm/yr from the two years of data from Kirk (1977). The mean erosion rate for all mudstone platforms was 1.48mm/yr, and 1.10mm/yr for limestone. Lowering rates on individual MEM bolt sites ranged from a minimum of 0.66 mm/yr on a limestone platform to a maximum of 2.53 mm/yr on a mudstone platform. This compared with a range from 0.38mm/yr to 2.98mm/yr for the same 15 bolt sites from Kirk (1977). Student's *t*-tests revealed that data from both the short term study of Kirk (1977) and that collected in 1994 were derived from the same population. It was argued that since this was the case, mean annual erosion rates derived from shorter term studies were equally valid as those from longer term ones, certainly at the scale of decades, at Kaikoura. Stephenson and Kirk (1996) also tested Mottershead's (1989) proposition that 30 individual measurements provide a valid erosion rate. Again using Student's *t*-tests they showed that this was statistically valid for the shore platforms on the Kaikoura Peninsula.

This section has reviewed a number of studies that have utilised the TMEM and MEM to measure erosion rates on shore platforms. Table 2.4 summarised published erosion rates from around the world that were calculated using the technique. A number of published erosion rates are now available. However, there are still few published results from use of the traversing micro-erosion meter. This modified version of the MEM allows a greater number of measurements to be collected and this is useful as the MEM has a limited spatial coverage. The TMEM may provide greater insight into erosive processes with the improved volume of data it yields. Platform erosion will be measured with the TMEM in this study. The MEM and TMEM are still the only instruments that allows precise measurement of surface lowering rates on shore platforms. Measured rates of erosion are required to assess the age and rate of development of shore platforms and to gain evidence for the processes of erosion that occur on these features. Measured rates of erosion are also necessary to assess a number of models of shore platform development that will be reviewed in Chapter Three.

2.9 FUTURE RESEARCH

This chapter began by illustrating that the term "shore platform" is the most appropriate term for near horizontal rock surfaces at the shoreline as it has no genetic meaning. A non-genetic term is important since the precise roles of weathering and marine processes are still not fully understood in shore platform development. A detailed description of how marine and weathering processes are thought to cause erosion was presented. Because of a lack of investigation of wave dynamics on shore platforms, explanations of how wave erosion is thought to occur are "borrowed" from engineering literature. A review of investigations that attempted to explain the processes responsible for the evolution of shore platforms followed. It was shown how a number of different views are available to explain the development of shore platforms. Some investigations proposed weathering was the sole process responsible while others proposed wave erosion as the only process. A larger group of investigators identified wave erosion as the dominant process and assigned weathering to a secondary role. Only Bell and Clarke (1908) and Kirk (1977) considered both wave erosion and weathering to be equally important. This difference in thought as to how shore platforms develop results from a lack of quantitative research. Few studies have attempted to directly measure the efficiency of either process to cause erosion. Quantitative data on both marine and weathering processes is required to critically review theories of shore platform development.

Sunamura (1983) proposed that there are only two shore platform morphologies, the sloping platform designated Type A and the near horizontal platform with a marked seaward cliff designated Type B. Tsujimoto (1987) provided a way to consider the difference between Type A and Type B platforms based on rock strength and the wave environment. It was argued that the assumption that the surface of a Type B platform does not undergo lowering is inconsistent with the field evidence. A question that arises from Tsujimoto's work is: whether erosion is linked to the compressive strength of the rock a platform is formed in? A better explanation for the development of Type B platforms was offered by Sunamura (1990, 1991, 1992) based on wave dynamics. This led to the contentious issue of the importance of the seaward cliff and whether or not it retreats. Clarification of this issue will be attempted in this study.

Morphological evidence offered some insights into the roles of waves and weathering but generally there has been difficulty in establishing clear relationships with processes. This is not surprising given that the lack of attention paid to the role of geology. Geological factors have been investigated in isolation, the exception being Tsujimoto (1987) and Sunamura (1990, 1991, 1992). Future investigations of morphology must incorporate the role of geology with process studies, and the value of doing so has already been demonstrated by Tsujimoto (1987). Studies that have looked to establish links between platform morphology and the process environment are fundamentally flawed if they have not considered feed back mechanisms imposed by geological factors. Platform morphology has been shown to be dependent on both processes and geology. There is then a need to quantitatively assess geological factors influencing shore platform development at Kaikoura.

A number of conclusions can be drawn from studies that have utilised the MEM and TMEM. The MEM and TMEM technique generate data that display a high degree of variability. Results revealed the variable nature of the process environment in which shore platforms are formed and allow a semi-quantitative analysis of the relative contribution of bio-erosion, abrasion, wave quarrying and weathering. It has been shown how exposure to higher wave energies yields higher erosion rates and reduces the importance of bio-erosion. The role lithology has in influencing erosion rates has clearly been identified. Not surprisingly, erosion rates are lower on harder lithologies and higher on softer ones. There is a notable lack of data from TMEM studies, suggesting that the technique is open to advancements, especially in analysis and presentation of data. However, the warning sounded by Kirk (1977) and Trenhaile (1980, 1987) that this technique does not provide data on mass wasting rates must be remembered when drawing conclusions from the data.

3. MODELING SHORE PLATFORM DEVELOPMENT

3.1 INTRODUCTION

In Chapter One a problem associated with attempts to model shore platform development was identified. This chapter advances the examination of those models and discusses in detail the apparent contradictions noted in Chapter One. Three types of models are considered, 1) conceptual models that provide a descriptive explanation of how shore platforms develop, or some means of organisation of a wide variety of ideas that contribute to understanding shore platform development, 2) a geometric model where platform geometry is used to predict rates of development and 3) functional models that are constructed mathematically. These models were designed to predict the outcomes of a number of relationships between factors involved in shore platform development.

3.2 CONCEPTUAL MODELS

Johnson (1919) proposed a model (Figure 3.1) to account for the development of the shore profile based on the Davisian concept of the cyclic evolution of coasts. The slope of a shore platform progressively declined as width increased, although this change was quite slight at the initial stages of development. Eventually the width of the platform became so great that waves could no long erode the cliff foot. This model predicted that shore platforms would reach a static state of equilibrium. The platform remained in that state until the system was rejuvenated by a change in base level..

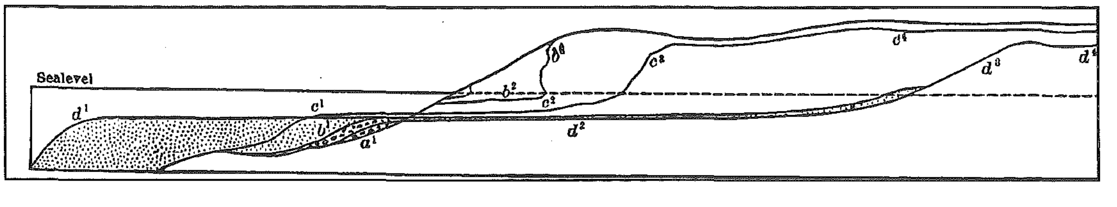

Figure 3.1 Stages in the development of the shore profile (Johnson 1919 Fig 32).

Challinor (1949) rejected Johnson's idea that the slope of a platform gradually decreased, and proposed instead that as platforms developed the width and gradient remained constant so that shore platforms retreated in a parallel fashion. This was because the down cutting of the platform was fast enough to allow waves to continue to reach and erode the backshore cliff. The profile that resulted (Fig 3.2) was a horizontal platform with a sloping ramp immediately in front of the cliff. The platform was therefore in a state of dynamic equilibrium maintaining gradient and width as it retreated. Both Challinor's and Johnson's models are important to modern shore platform studies because the differences in views as to the form of equilibrium attained by shore platforms have not yet been resolved. This is discussed further in Section 3.3.

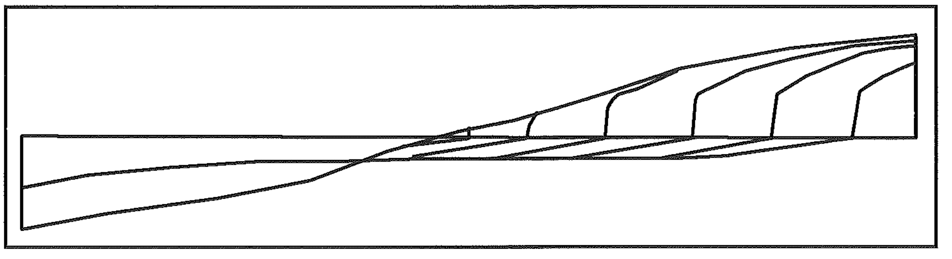

Figure 3.2 Challinor's diagram explaining the consistency of form of the coast profile as the sea advances landward (Challinor 1949 Fig 1).

Sunamura (1974, 1983, 1992, 1994) developed and presented a model (Fig 3.3) in an attempt to explain the relationship between the forces that cause erosion and those factors that represent resistance to it. This model has been used to explain bed rock lowering, the erosion of coastal cliffs and the development of shore platforms. The development of shore platforms was seen as dependent on the relationship between an assailing force of waves (F_W) and a resisting force of rock (F_R). If F_W is larger than F_R then erosion will occur. Conversely if F_R exceeds F_W no erosion will occur. The model illustrates those factors that increase or reduce these two variables and the relationships between them.

The assailing force of waves was represented using deep water wave energy. Nearshore bottom topography was identified as being an important influence on that energy as it arrives at the shore. The force applied by waves was characterised as either hydraulic or mechanical. Hydraulic action includes compression, tension and shearing under waves. When bores travel across a platform a hydraulic shear force due to oscillatory water movement is imparted. Hydraulic action also include the effect of air being compressed in rocks crevices as water rushes into them. Mechanical action results from waves carrying sediments that act as abrasives. If the sediment cover is too thick then it protects the bedrock from hydraulic action, but this protective role was not accounted for in the model.

The resisting force of rock was more simply defined with the result that it can quantified. It was defined as the mechanical strength of rock, measured using compressive, tensile and shear strengths. Mechanical strength is strongly influenced by lithology and structure. Discontinuities that result from cracks, joints, faults and bedding plains reduce F_R. F_R is further reduced by weathering. In considering mechanical strength Sunamura (1994) recognised the role of wetting and drying, chemical weathering and frost action, although attempts to quantify F_R have not been able to account for weathering. The role of biological activity, which can serve to increase or decrease F_R was also recognised. Encrusting organisms increase F_R by providing a protective layer over rock surfaces. This model served to illustrate how F_W and F_R are controlled but it did not illustrate how shore platforms developed.

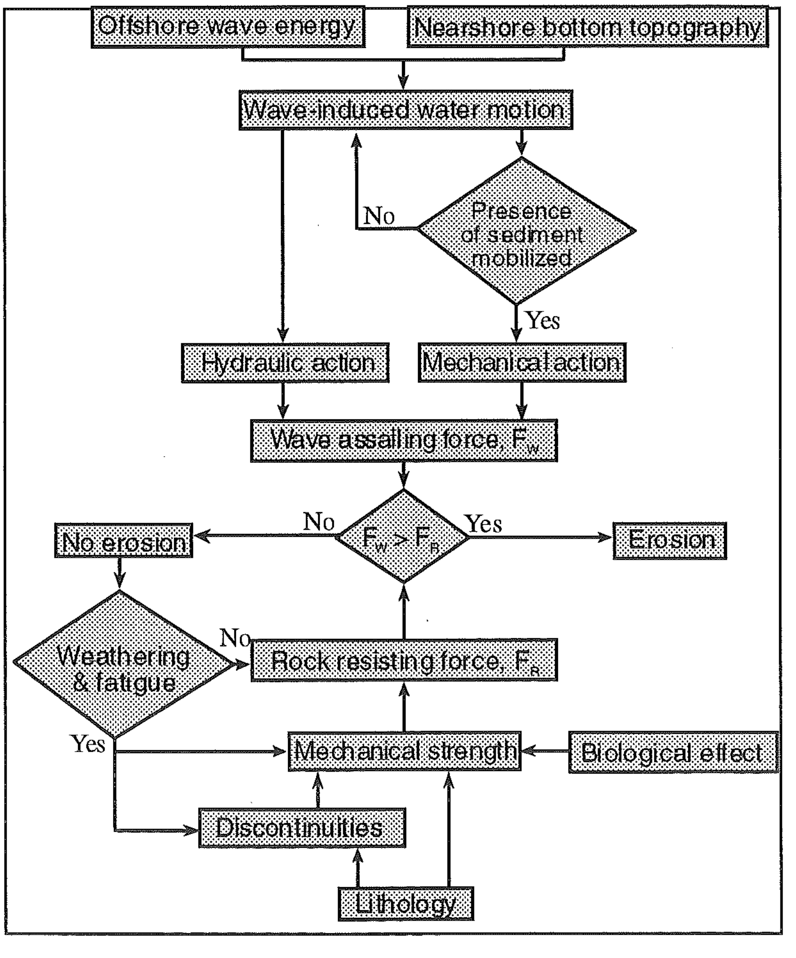

Figure 3.3 Factors affecting erosion of rocky coasts. Ultimate factors are wave assailing force, F_W, and rock resisting force, F_R. Erosion occurs when F_W is greater than F_R (Sunamura 1994 Fig 1).

3.3 THE PARALLEL RETREAT MODEL

Because Challinor (1949) raised questions about the gradients displayed by shore platforms and the form of equilibrium that might be reached, Trenhaile (1974a) investigated the geometry of shore platforms in England and Wales. This work was intended to establish the degree of adjustment of the platform gradient to contemporary processes. It was also intended to establish whether relationships between platform gradient and aspects of the morphogenetic environment exist. Based on Challinor's (1949) proposition of parallel retreat, Trenhaile (1974a) developed a specific parallel retreat model. If parallel retreat is to occur (Fig 3.4), then:

$$dD = dW \tan \alpha \qquad \textbf{3.1}$$

where:

dD = increment of platform down cutting in time

dW = increment of cliff retreat in time

α = platform slope.

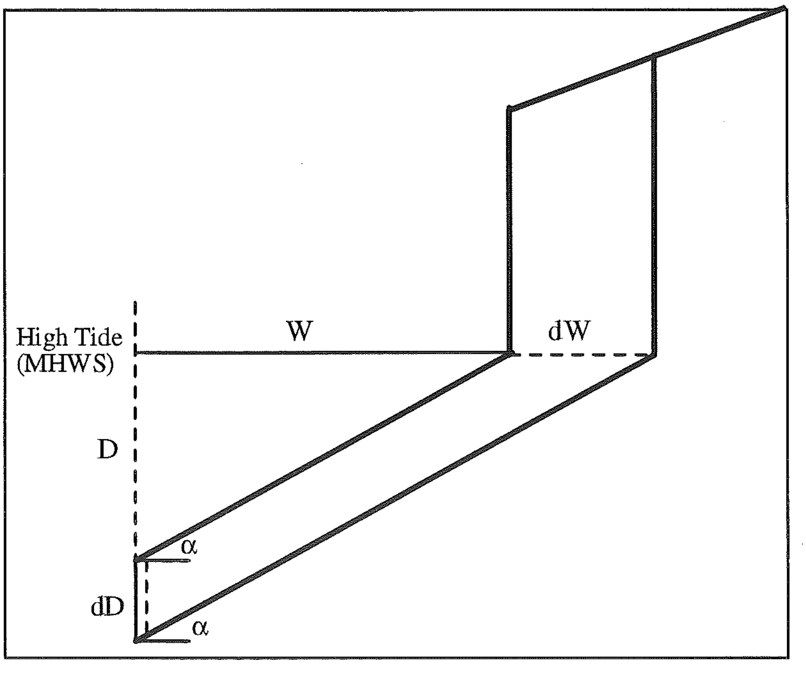

Figure 3.4 The parallel retreat model (Trenhaile 1974a Fig 6).

Trenhaile (1974a) used this model to predict platform lowering rates based on known cliff retreat rates in the Vale of Glamorgan. Using a cliff retreat of 1.27cm/yr and $\alpha = 0.05$, platform lowering was predicted to be 0.0635cm/yr in chalk cliffs. Unable to measure actual down lowering rates, Trenhaile estimated them from the height of the scarp at the base of the eroding cliff. Values were in the range of 0.0533 to 0.36cm per year. While the predicted value was at the lower end of the estimated range it was concluded that the results showed that lowering was within a general order of magnitude of the cliff recession rates and that these rates were sufficient to facilitate parallel retreat. Trenhaile (1974a) concluded that platform gradient was maintained in dynamic equilibrium with the process environment. Clearly, more accurate rates of surface lowering are required to assess the model. The values estimated for down lowering have a range of two orders of magnitude which makes it easier to validate the model.

A number of points need to be addressed in order to validate the parallel retreat model.

1) The model requires that the rate of surface lowering is constant across the platform. In fact it must be so, in order to maintain parallel retreat. Any variations in lowering rates across the platform cause a change in gradient. The present study will examine patterns of cross shore surface lowering rates on platforms on the Kaikoura Peninsula and will use the data to assess this problem.
2) There should also be some morphological evidence to support parallel retreat. The slope profile below the low tide level should appear as in Challinor's (1949) model (Figure 3.2). Investigation of the off shore topography of shore platforms may also show whether or not parallel retreat occurs. Later in the thesis a survey of off shore topography is presented in order to address this issue.
3) Clearly the parallel retreat model is inconsistent with Sunamura's (1990, 1991, 1992) view that the low tide cliff on a Type B platform does not retreat. If Sunamura is correct and the position of the low tide cliff is preserved, parallel retreat cannot occur. The slope of the platform would have to decline as the platform is extended. This highlights the importance of establishing whether or not the low tide cliff on Type B platform retreats. It is also necessary to establish whether or not the seaward edge of Type A platforms also retreats.

Kirk (1977) tested the parallel retreat model using both measured surface lowering and cliff erosion rate data from Kaikoura Peninsula. Cliff recession rates were found to be at least two orders of magnitude faster than surface lowering rates. Annual lowering rates averaged 3% of cliff recession rates. A logarithmic best-fit relationship between observed lowering rates and predicted cliff retreat gave better results ($r = 0.89$ significant at $p = 0.01$). According to Kirk (1977) this reflected the strong influence of platform gradient in the model. Kirk concluded that the model was only in moderate agreement with the data, in part due to the inherited nature of the inner margins of the Kaikoura shore platforms. However, the platforms in the Vale of Glamorgan were thought to contain inherited morphology. Kirk (1977) suggested that future modelling should investigate power and logarithmic relationships between platform lowering and cliff retreat. It is still an open issue as to whether or not platforms retreat in a parallel way. The central question is: whether or not a parallel retreat model is appropriate? Studies so far have not answered this question.

3.4 FUNCTIONAL MODELS

Based on work by Trenhaile (1974a, 1978) which presented a positive correlation between increasing platform gradient and higher tidal range, Trenhaile and Layzell (1980, 1981) and Trenhaile (1983a) developed and tested a model that specified how the tidal distribution of wave energy was thought to erode shore platforms. The model was used to predict platform erosion and cliff retreat, and platform gradient and width. Predictions of these properties were tested against examples from Canada, Australia, New Zealand and Britain. In the model it is assumed that the rate of platform erosion is determined by the period of time still water occupies a given elevation on the platform. Other factors that determine platform erosion and that were incorporated into the model are wave energy, rock hardness, platform gradient and the rate of submarine erosion. The model takes the form:

$$R_{n,t} = tAF_n \tan\alpha_{n-1} \qquad \textbf{3.2}$$

where:

R = erosion (cm/yr)

n = platform level 1,2,3...

t = time (years)]

$tan\ \alpha_{n-1}$ = submarine slope at each time interval

A = erodibility factor (cm/hr) This is derived by

$$A = FW \tan\alpha \,/\, V \qquad \textbf{3.3}$$

where:

F = still water level

W = deep water wave energy delivered per hour

V = amount of energy required to erode 1cm of rock.

F_n = tidal duration factor given by:

$$F_n = \sum(D_e N_e) + \sum(2D_i N_i) \qquad 3.4$$

where: F_n = tidal duration (hrs/yr)

n = platform level 1,2,3...

D_e = duration (hrs/yr)

N_e = number of high or low tide levels at n

D_i = the duration in (hrs/yr) of the tide at n at an intermediate point on the tidal cycle.

N_i = the number of high and low tides above or below n.

Platform profiles were simulated using equation 3.2 to calculate erosion at vertical intervals of 91.44cm along each profile (Fig 3.5). Profiles consisted of a number of segments, the size of each determined by the tidal range. The initial profile was assumed to be a slope of 30° inherited during postglacial sea level rise.

Trenhaile and Layzell's (1981) results showed that initial erosion rates were strongly influenced by the tidal duration factor. This causes erosion to vary along each profile because of the length of time the tide occupies a particular level varies. The gradient of each segment is controlled by the difference in erosion at the top and bottom of it. If erosion is higher at the top then the gradient is reduced. This impacts on the segment above by reducing the amount of wave energy reaching it. Conversely, higher erosion on a lower part of a segment steepens it and allows more wave energy to reach the segment above it. This negative feedback arrests the increased gradient of segments on the upper part of the profile. As time progresses erosion rates became constant along the profile. According to Trenhaile and Layzell (1981) a state of dynamic equilibrium was reached once erosion is the same across the profile and from this point the geometry of the platform was preserved.

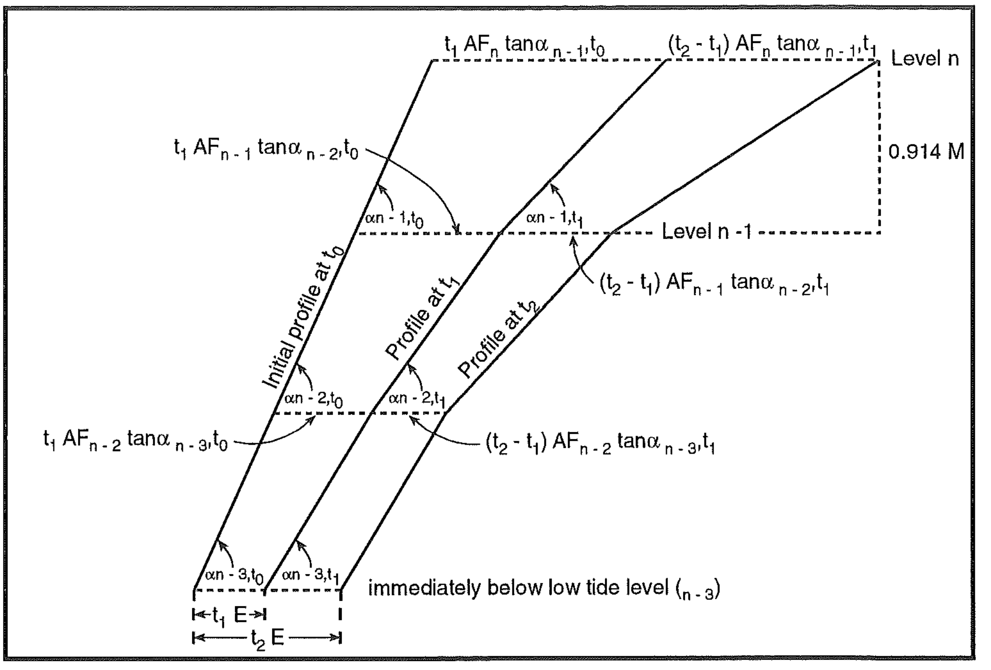

Figure 3.5 Model construction (Trenhaile and Layzell 1981, Fig 3).

Trenhaile and Layzell (1980) concluded that the model simulated platform geometry and demonstrated the importance of the tidal duration factor (F_n) in determining platform gradient. It was proposed that platform development is initially rapid but declines as width increases and equilibrium is reached. However, some important restrictions on the model performance were noted. In particular, there was a lack of data with which to test the model predictions. Data on both the rates of platform lowering and back wasting are required to fully test the model, but were not available for the sites chosen in the study. The success of the model was therefore judged on the basis of similarity between the predicted and the observed platform profile. Trenhaile and Layzell (1980) noted that this does not prove the validity of the model. Trenhaile (1983a) concluded that the model indicated that enough time has elapsed since sea level rise for contemporary shore platform to be in a state of dynamic equilibrium.

Trenhaile (1983a) developed a second model in which rates of erosion at the cliff platform junction and the low tide cliff are specified. The model was structured such that cliff recession occurs in two stages, a) undercutting to the point of collapse and b) the removal of debris. A notch is cut by mechanical wave erosion until a critical depth is reached when the overhang becomes unstable and collapses. Undercutting cannot resume until the collapsed debris is removed by waves. The total time taken for these two stages to occur was given by:

$$T_{n,x} = \left(T_r \cot\beta + nx - E \sum_{T_0}^{T_{n-1}} T \right) (C_1 + C_2 nx) x \qquad 3.5$$

where:

$T_{n,x}$ = total time taken to undercut cliff and remove debris

T_r = tidal range

β = gradient of the inherited slope

n = number of times the cliff has collapsed and debris removed

x = depth of notch at point of collapse

$E\sum_{T_0}^{Tn-1} T$ = total erosion that has occurred at the low tide level

C_1 = tan α/UT

where: U = amount of cliff undercutting in a year

α = gradient of the platform

C_2 = tan α/ST

where: S = amount of debris removed in a year

An attempt to operationalise the model was made using field data collected in the Vale of Glamorgan in Wales and in Gaspé eastern Québec, Canada. Not all values were obtained through direct measurement. Rather, some were obtained from proxy estimates made from sources such as old photographs. Rates of low tide cliff retreat were not directly measured but rather, these were "estimated from rates of cliff and scarp retreat assuming that sub-equilibrium states prevail" (Trenhaile 1983a:151).

Results indicated that platform width increases rapidly during initial stages of development but the rate of erosion declines over time. The overall trend for the model was the development of a profile of dynamic equilibrium. This occurred when the time required to undercut the cliff and remove the debris so formed, was the same as the time required to cause recession at the low tide level by the same amount as the undercutting of the cliff (Trenhaile 1983a). It was found that if the rate of erosion of the cliff foot decreased below that at the low tide level then the increase in platform gradient would cause the erosion rate of the cliff to increase, causing the restoration of the equilibrium gradient. Thus platform development was in a state of dynamic equilibrium similar to that described by Edwards (1941) as discussed in Chapter Two (page 25). This condition would endure so long as the low tide erosion rate remained constant. If however, the low tide erosion rate decreased with time a state of quasi-equilibrium could be reached. Given enough time, a state of static equilibrium would be reached similar to that proposed by Davis (1896) and Johnson (1919). But this state of equilibrium could only be reached if sea level was stable for an "extremely long period" (Trenhaile 1983b:151).

The issue as to what equilibrium state shore platforms tend to, has not been resolved by the study. The design of the model predetermines the outcome of a state of dynamic equilibrium. This is because low tide cliff recession is built into equation 3.6 and so long as a positive rate is entered then dynamic equilibrium will always result. If zero is used as a value for $E\sum_{T_0}^{Tn-1}T$ in equation 3.6 then a static state of equilibrium will result. It will be recall from above that low tide cliff recession was estimated from cliff and scarp recession based on Edward's (1941) notion that the low tide cliff must retreat in order to maintain a platform. The model construction and outcomes are based on a circular argument. Shore platforms are in a state of dynamic equilibrium because low tide cliff retreat occurs, but low tide cliff retreat is already factored into the model and the model then shows shore platform are in state of dynamic equilibrium. Questions as to equilibrium tendency cannot be tested using this model. Rather, direct field evidence of low tide cliff recession is required.

Sunamura (1977) investigated the relationship between cliff erosion and the erosive force of waves. He proposed that cliff erosion was controlled by the relationship between the erosive force of waves and the resisting force of rock, but the obvious difficulty of quantification of these variables was noted. This is because waves cause erosion by a number of different means including: hydraulic action, (encompassing compression, tension, cavitation and wear); abrasion by sediments moved in waves; and air compression in fissures by waves. The resisting force of rock is controlled by mechanical properties such as compressive and tensile strength, resistance to wear, and the occurrence or absence of joints and faults. Sunamura (1977) empirically described the relationship between cliff recession and the eroding force such that:

$$\frac{dX}{dt} \propto F \qquad \textbf{3.6}$$

where:

dX/dt = the rate of cliff erosion

F = the erosive force of waves.

F was defined as:

$$F \propto \ln\left(\frac{F_W}{F_R}\right) \qquad \textbf{3.7}$$

$$\frac{dx}{dt} = \kappa \ln\left(\frac{F_W}{F_R}\right) \qquad \textbf{3.8}$$

where:

κ is a constant with units LT^{-1}

Sunamura assumed that F_W could be expressed as the wave height at the base of the cliff and F_R could be expressed as the compressive strength of the cliff material so that:

$$F_W = A\rho g H_b \qquad \textbf{3.9}$$

and

$$F_R = BS_c \qquad \textbf{3.10}$$

where:

A = a constant representing abrasion by sediments

B = a constant representing discontinuities in the cliff

H_b = wave height at the cliff base

S_c = compressive strength of cliff material

g = gravitational acceleration

ρ = density of sea water

if A and B can be quantified then:

$$\frac{dX}{dt} = \kappa\left[\Gamma + \ln\left(\frac{\rho g H}{Sc}\right)\right] \qquad \textbf{3.11}$$

where:

$\Gamma = \ln(A/B)$ a nondimensional constant

Note that $dX/dt = 0$ when $F_W \leq F_R$. Equation 3.11 remains to be operationalised in the field since F_W and F_R have not been fully quantified. This model is important to the present study because it has been used in the construction of a model of platform development.

Sunamura (1978b) designed a model to explain the development of Type A platforms. The model assumed that the cliff was made of uniform, unweathered rock, with no beach developed at the base of the cliff, and that a surf zone existed at the cliff base because of a shallow sloping bottom. From equation 3.11 the distance the cliff retreats was given by (Fig 3.6):

$$x = (K_*/\beta_*)\left(1 - e^{-\beta_* \kappa t}\right) \qquad \textbf{3.12}$$

where:

$$K_* = \Gamma - \beta_* W_o + \ln(\rho g H_b / S_c) \qquad \textbf{3.13}$$

$$\beta_* = \alpha_* \sqrt{h_b} \,/\, (\sqrt{g}) h_a L_b^2 \qquad \textbf{3.14}$$

t = time

κ = a constant

H_b = breaker height

h_b = breaking depth

L_b = wave length at break point

h_a = wave base

α_* = a wave height attenuation coefficient

Wo = initial platform width defined in Fig 3.8

and the rate at which retreat occurred was given by:

$$dx / dt = K_* \kappa e^{-\beta_* \kappa t} \qquad \textbf{3.15}$$

Equation 3.15 indicates that the recession rate tends to zero as time approaches infinity, that is: dx/dt = 0 as $t \rightarrow \infty$. Since this model requires that x has a finite value, Sunamura (1978b) was able to predict platform width W_e and gradient I_e:

$$W_e = \lim_{t \to \infty} \qquad W = \frac{(\sqrt{g}) h_a L_b^2 \left[\Gamma + \ln(\rho g H_b / S_c)\right]}{\alpha_* \sqrt{h_b}} \qquad \textbf{3.16}$$

and

$$I_e = \lim_{t \to \infty} \qquad I = \frac{\alpha_* \sqrt{h_b}}{(\sqrt{g}) L_b^2 \left[\Gamma + \ln(\rho g H_b / S_c)\right]} \qquad \textbf{3.17}$$

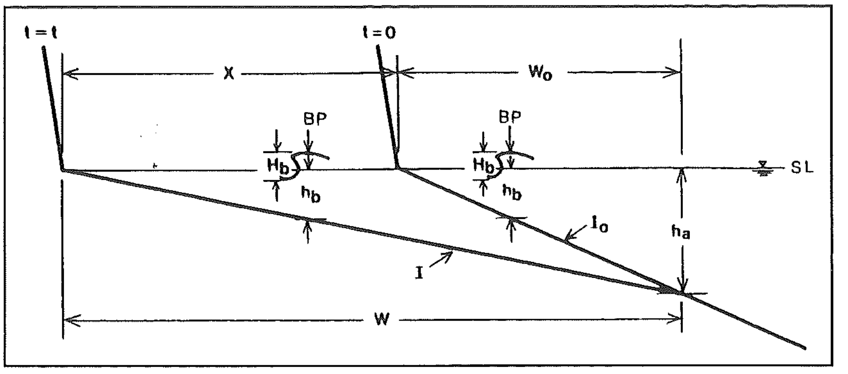

Figure 3.6 Definition sketch of Type A platform development (Sunamura 1992 Fig 7.8).

Equations 3.16 and 3.17 indicated that the final form of the platform is not influenced by the initial topography and the ultimate platform becomes wider and flatter when the rock is weaker, if other factors remain constant (Sunamura 1978b). The limitations of the model were noted as being the lack of quantification of α, κ and Γ. Sunamura (1992) noted another two limitations, 1) S_c changes through time as weathering weakens the rock and 2) the role of debris in front of the cliff supplied from erosion and longshore transport is not considered. Sediment at the cliff foot can either aid or hinder erosion.

Consideration of Type B platforms is somewhat more limited. Sunamura (1992) presented a model to describe the width of this type of platform. Figure 3.7 shows how waves break at the seaward edge of a platform and travel across it as a bore. Energy is lost through turbulence and friction. The height of the bore decreases as it travels further towards the backshore cliff. Sunamura (1992) used:

$$\frac{H}{H_b} = \exp\left(-\frac{35 \cdot 2l \tan\beta}{T\sqrt{(gh_b)}}\right) \qquad \textbf{3.18}$$

where:

H = wave height in the surf zone

H_b = breaker height

l = distance from breaking point

T = wave period

$\tan\beta$ = bottom gradient

to express the exponential decrease in height of the bore. The force of the bore also decreased exponentially and was expressed:

$$F_W(x) = F_W e^{-\alpha'_* x} \qquad \textbf{3.19}$$

where:

F_W = the assailing force of waves

α'_* = is an attenuation coefficient for bore height.

So that:

$$Fw = A\rho g H_b e^{-\alpha'_* x} \qquad \textbf{3.20}$$

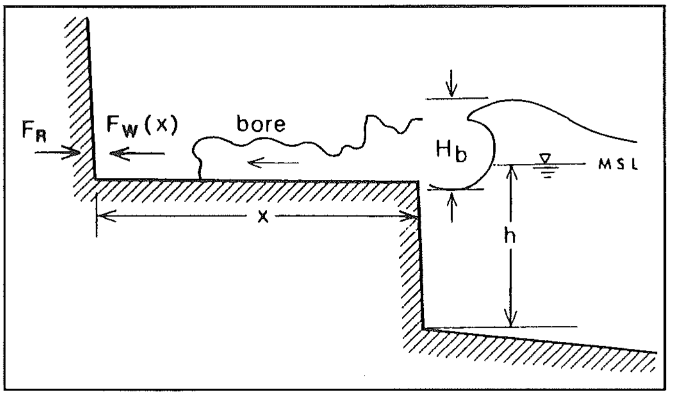

Figure 3.7 Definition sketch (Sunamura 1992 Fig 7.22).

By substituting equations 3.10 and 3.20 into equation 3.8 and integrating with the initial conditions of $x = 0$ at $t = 0$, platform width was expressed by:

$$x = \frac{1}{\alpha'_*}\left[\Gamma + \ln\left(\frac{\rho g H_b}{S_c}\right)\right]\left(1 - e^{-\alpha'_* \kappa t}\right) \qquad 3.21$$

Equation 3.21 showed that platform width x increased rapidly at the initial stage and reached equilibrium through time. From equation 3.21 Sunamura (1992) proposed that the width of a Type B platform after a given period of time $x_t = t_1$ can be expressed by:

$$x_{t=t_1} = G\left[\Gamma + \ln\left(\frac{\rho g H_b}{S_c}\right)\right] \qquad 3.22$$

where:

$$G = \left(1 - e^{-\alpha'_* \kappa t}\right) / \alpha'_* = \text{constant} \qquad 3.23$$

Equation 3.22 indicates that platforms cut in harder rock are narrower, and platforms exposed to larger waves are wider (Sunamura 1992). Since H_b is controlled by h, equation 3.22 indicates that the width of Type B platforms (as with Type A) is controlled by the depth of water in front of the seaward cliff. This was supported with data from Izu Peninsula, Japan where a positive correlation existed between front depth and platform width. However, where front depth exceeded 12m a negative correlation occurred (Sunamura 1992). This was explained as being a result of waves breaking only very rarely in such deep water. Equations 3.16, 3.17 and 3.22 have important implications for the kind of equilibrium that shore platforms may attain. Both equations 3.16 and 3.17 suggest (as did Davis (1896) and Johnson (1919)), that shore platforms develop towards a static state of equilibrium rather than a state of dynamic equilibrium as proposed by Challinor (1949), Edwards (1941, 1951) and Trenhaile (1974a, 1983a).

Sunamura (1992) presented a model describing the evolution of a rocky coast during a prolonged stable sea level (Fig 3.8). The model had a number of limiting assumptions:

1) the coast was made of uniform, insoluble rock with no structural influences,
2) it was in a micro-tidal environment,
3) with no sediment accumulated in the nearshore, and
4) the model identified five kinds of coast (I to V) with different profiles which were assumed to be exposed to waves with a very narrow spectrum of occurrence frequency and the same offshore conditions.

Sunamura acknowledged that these conditions are unrealistic, but he argued this allows exploration of the evolution of rocky coasts.

Sunamura (1992) described the five types of coasts and input wave conditions. Coast **I** is uniformly sloping with a low gradient so that broken waves act on it. Coast **II** is cliffed, and in front of the cliff, water depth, $h = 0$. Waves that act on this coast were broken. On Coast **III** h is less than H_b and broken waves act on this coast but with more energy than on coasts **I** and **II**. On Coast **IV** waves break directly against the cliff because $h = H_b$. In front of coast **V** h is greater than H_b, and waves are always reflected. If the slope of Coast **I** is greater than 45° then it becomes one of the other four coasts depending on the relationship between h and H_b. Although the model does not allow for variations in geology or lithology it does incorporate the role of rock strength. Sunamura (1992) categorised relative strength qualitatively into three groups:

a, very strong and resistant to weathering;
b, moderately strong and slightly resistant to weathering; and
c, very weak and strongly vulnerable to weathering.

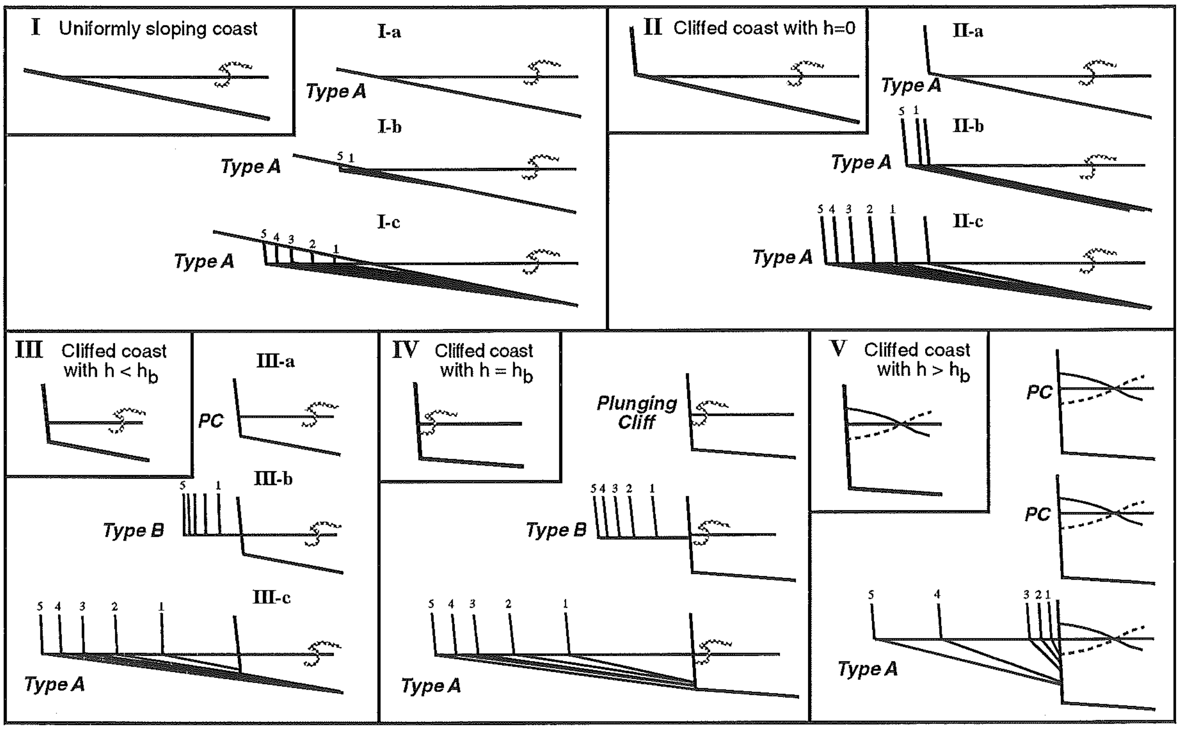

Figure 3.8 Model of rocky coast evolution beginning with five kinds of initial landforms (**I** through **V**) with different degrees of rock hardness (**a**, **b**, and **c**) (Sunamura 1992 Fig 7.25).

Sunamura summarised the development of different platform types as follows.

1) Type A shore platforms develop commonly in type **I** and **II** coasts where Type B and plunging cliffs never occur.
2) Plunging cliffs develop only on coasts **III** and **IV** when rocks are very hard.
3) Type B platforms develop only in rock of intermediate hardness on coasts **III** and **IV**, and Type A on **IIIc** and **IVc**.

4) Plunging cliffs (PC) are formed on **Va** and **Vb** coasts but on **Vc** coasts Type A platforms develop.
5) The rate of development of these profiles decreases through time.

An attempt was then made to quantify rock strength for the three classes. Using existing data on compressive strength values (Ohshima 1974; Takahashi 1976; Aramaki 1978; Kobayashi 1983; Tsujimoto 1987; Sunamura 1987; and Carter and Guy 1988) from Figure 3.9, Sunamura (1992) determined a range of values for both platform types and plunging cliffs. Figure 3.5 gives $1.7 \times 10^{-3} \leq \rho g H_1/S_c \leq 1.3 \times 10^{-2}$, which is equivalent to $77 \leq S_c/\rho g H_1 \leq 590$ for Type B shore platforms. The parameter for rock strength was expressed in terms of $S_c/\rho g H_1$ so that:

$$590 \leq \frac{S_c}{\rho g H_1} \qquad \text{for a}$$

$$77 \leq \frac{S_c}{\rho g H_1} \leq 590 \quad \text{for b} \qquad \textbf{3.24}$$

$$\frac{S_c}{\rho g H_1} \leq 77 \qquad \text{for c}$$

Equation 3.24 was based on a small data set and more data are required to further test this relationship (Sunamura 1992). While it has not been possible in the present study to test the global application of the relationships described in this model, it has been possible to test whether or not platforms on the Kaikoura Peninsula fit the range of values predicted by the model for Type A and B platforms.

This model was not intended to address questions of platform equilibrium but a number of points can be made from it. Figure 3.8 clearly illustrates that as platforms widen gradient decreases because the original low tide position of the platform is preserved, and there is no low tide cliff erosion. Sunamura (1992) noted that as time elapses the rate of platform extension decreases, which is the same as was proposed by Johnson (1919). Clearly this model was designed with the view that shore platforms tend towards a state of static equilibrium.

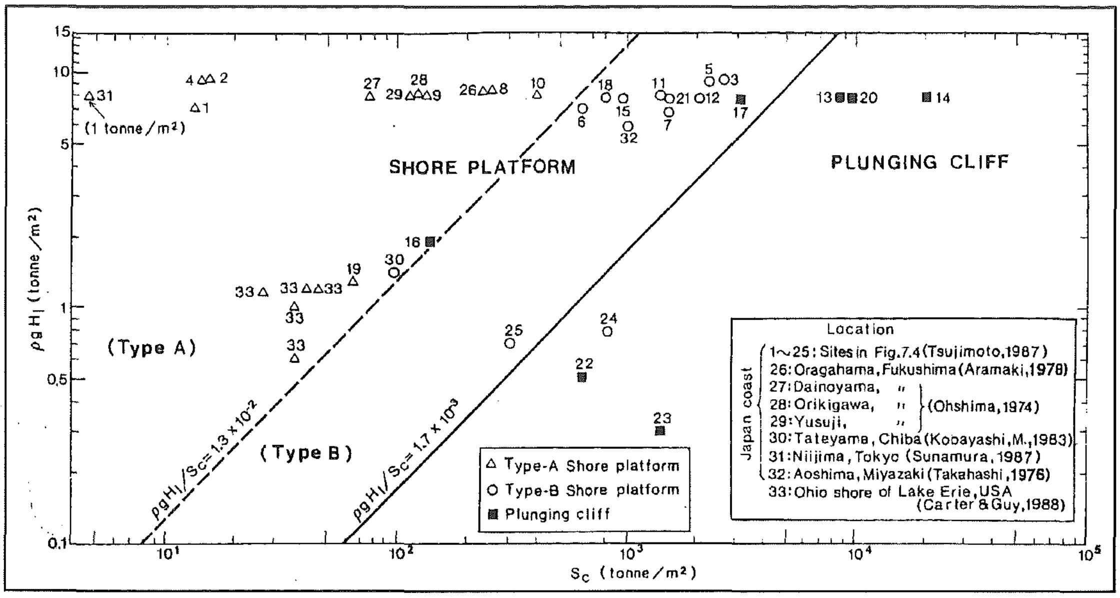

Figure 3.9 Demarcation between shore platforms and plunging cliffs (Sunamura 1992 Fig 7.6)

3.5 CONCLUSIONS

Modelling of shore platform development has been restricted largely by the lack of quantification of variables, such as weathering, discontinuities in rock, abrasion by sediments and wave energy. A more fundamental problem exists with testing the underlying assumptions the models are based on. The principal one is that wave erosion is solely responsible for the development of shore platforms. Chapter Two showed that the exact roles of waves and weathering processes are still not fully understood. It is difficult to have confidence in the models when the exact role of waves in platform development is still unclear. Conclusions to the effect that the models support the propositions that wave erosion is responsible for shore platform development are flawed since they are designed on that very assumption. Such arguments thus become circular, a situation not dissimilar to interpreting process from morphology as described by Mii (1962). A goal for this thesis is to identify the role different processes have in shore platform development. This would help address the issue of models predetermining the predicted outcome.

Modelling has so far failed to clearly identify the type of equilibrium shore platforms attain, or indeed, whether or not they do tend to an equilibrium state. Models developed by Trenhaile (1974a, 1983b) predicted a state of dynamic equilibrium whereas models presented by Sunamura (1990, 1991, 1992) have predicted a state of static equilibrium. The type of equilibrium that platforms may tend towards may depend largely on the whether or not the low tide cliff of shore platforms retreats or is stable. As discussed in Chapter Two it is unclear if the low tide cliff retreats or not. All the models presented in this chapter assume one of these preconditions, so that the outcomes of them are predetermined. A goal of this thesis is to answer the questions: 1) Do platforms have an equilibrium form? and 2) do shore platforms tend to a static or dynamic state of equilibrium?

4. SHORE PLATFORMS OF THE KAIKOURA PENINSULA

4.1 INTRODUCTION

As the chosen study area the Kaikoura Peninsula and its shore platforms are described in this chapter. This is achieved by reviewing previous investigations of the geology, geomorphology, climate, and the wave and tidal environment of the peninsula. This review is extended by including results from field investigations of platform morphology undertaken during this study. Such an examination is necessary in order to understand the environmental conditions that have and do influence shore platform development on the Kaikoura Peninsula. A question asked in Chapter Two was: does the Type A and Type B designation offered by Sunamura (1992) have universal application? It is not possible to answer this with the present study. The intention is to determine whether Type A and B platforms occur at Kaikoura. Answering this question will go some way towards answering the question of a universal morphology for shore platforms.

4.2 KAIKOURA PENINSULA

Figure 4.1 shows the coast of Kaikoura Peninsula. The map also shows place names on the shore that will be referred to throughout this thesis. Kaikoura Peninsula is located on the northeast coast of the South Island of New Zealand (42°25' S : 173°42' E). The peninsula juts out southeastwards from the general northeast-southwest strike of the coast, approximately 4.5km, and has a maximum elevation of 108m (Fig 4.2). The width of the peninsula varies from 3.2km, to 1.1km at its isthmus. Kaikoura Peninsula covers an area of 5.2km^2. Of this, 0.77km^2 is inter-tidal (Kirk 1977).

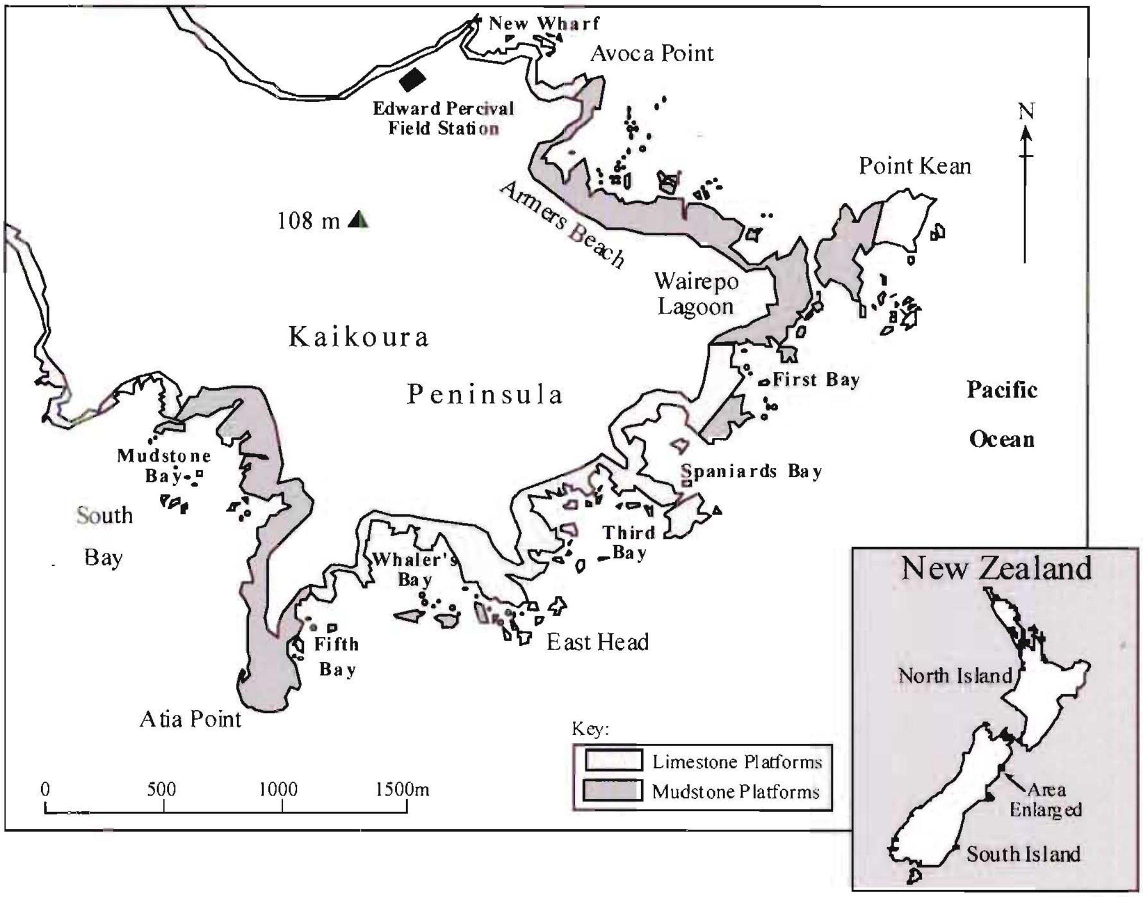

Figure 4.1 Kaikoura Peninsula and shore platforms (after Stephenson and Kirk 1996 Fig 1).

Figure 4.2 Oblique aerial view of Kaikoura Peninsula and hinterland.

4.2.1 GEOLOGY AND STRUCTURE

The sedimentary rocks that make up the Kaikoura Peninsula are Upper Cretaceous and Tertiary in age. In series from lower to upper the peninsula consists of Upper Cretaceous Mata Series sandstone, Palaeocene Dannevirke Series limestone, Eocene Arnold Series calcareous sandstone, Oligocene Landon Series limestone and Miocene Pareora-Southland mudstone (Duckmanton 1974). At two sites atop of the peninsula Quaternary alluvial and marine gravels and sands of the Parikawa Formation can be found (Fig 4.3) (Duckmanton 1974).

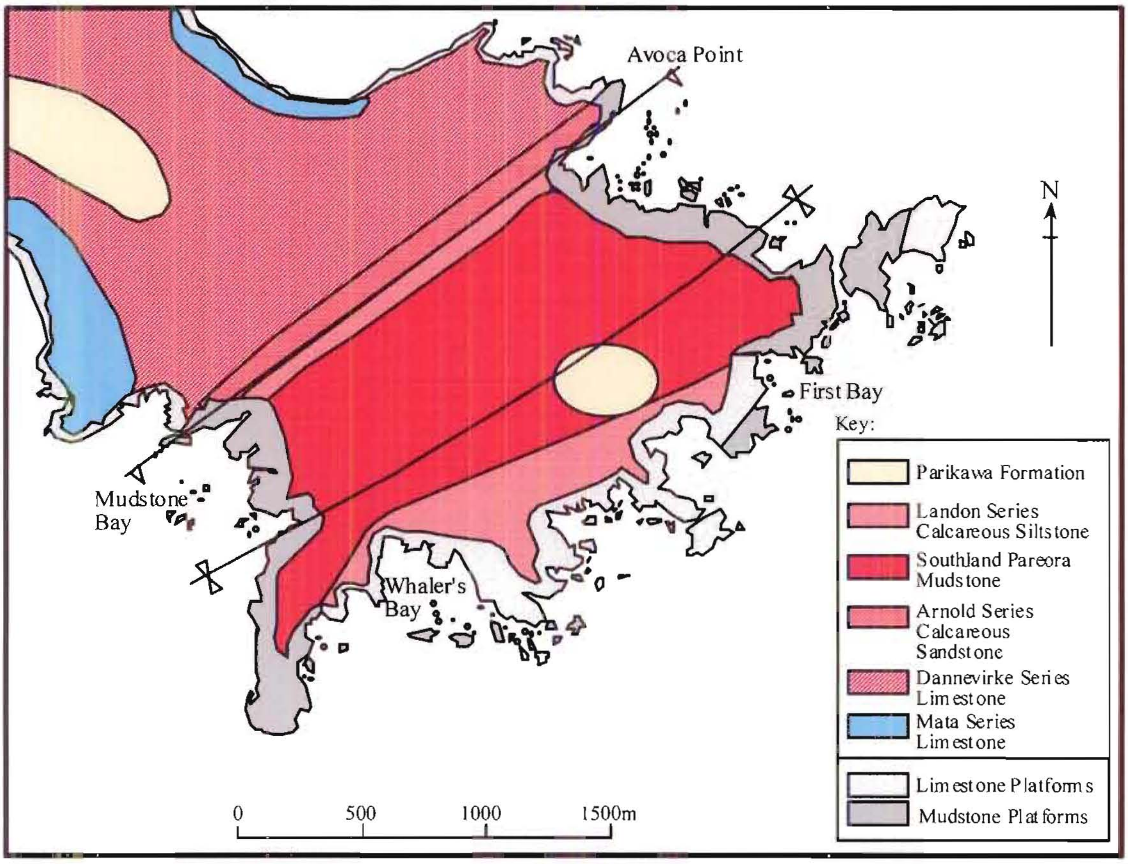

Figure 4.3 Geological Map of the Kaikoura Peninsula (after Duckmanton 1974).

On the eastern edge of the peninsula Landon Series calcareous siltstone occurs in a strip from First Bay south to Whaler's Bay. Bordering and overlying this is the Pareora-Southland mudstone which runs parallel to the Landon Series and extends west almost as far as Avoca Point in the north and Mudstone Bay in the south. Against the western margin of the Pareora-Southland mudstone the Landon Series re-appears as a narrow band. To the west and next to the Landon Series is a narrow strip of the Arnold Series calcareous sandstone. To the west again, Dannevirke Series limestone overlies Mata Series limestone. The Dannevirke Series is the largest unit making up the Kaikoura Peninsula. Structurally the Kaikoura Peninsula consists of a slightly asymmetrical anticline separated by two synclines, the axial planes of which run northeast-southwest. The limestone is disturbed by numerous minor strike-slip and dip-slip faults, and localised small scale folding (Fig. 4.4) (Duckmanton 1974). As a result, shore platforms are cut in a variety of rock types and have varying degrees of exposure to wave and weathering energies. Geology exerts a strong control over platform morphology. Limestone platforms are harder and display greater variations in morphology than those in mudstone (Kirk 1977).

Figure 4.4 Tightly folded limestone at First Bay December 1995.

4.2.2 GEOMORPHOLOGY

The most complete investigation of the geomorphology of the Kaikoura Peninsula and surrounding district was undertaken by Chandra (1968). Earlier investigations were undertaken by McKay (1887), Cotton (1914, 1916, 1950), Jobberns (1928), and Suggate (1965). Chandra (1968) identified three major physiographic units in the Kaikoura district: the peninsula block; beach ridges and raised beach ridges; and hard rock areas and alluvial fans. On the peninsula block, four erosional surfaces resulting from still stands during tectonic uplift were identified.

Cotton (1914, 1916, 1950), Jobberns (1928), Suggate (1965) and Chandra (1968) proposed that these surfaces are raised shore platforms. The elevation of these erosional surfaces were surveyed by Duckmanton (1974) at 108 to 94m, 80 to 76m, 68 to 58m and 40 to 50m. Suggate (1965) proposed tentatively that the surface at 40 to 50m correlated with the Otiran interglacial and the surface at 58 to 68m surface correlated with the penultimate interglacial, the Terangian. Chandra (1968) also proposed that the surface between 40 and 50m correlated with the Otiran interglacial.

Ota et al. (1996) identified five instead of four surfaces on the Kaikoura Peninsula (Fig. 4.5). The elevations of these surfaces were reported:

Terrace I at 95-108m,
Terrace II at 75-83m,
Terrace III at c. 64m to the west and 35-55 to the east,
Terrace IV between 46 and 58m and
Terrace V at c. 38m.

The variation in elevations for individual surfaces and between surfaces was attributed to tilting down of the peninsula in a westward direction.

The ages of these surfaces were established using amino acid racemisation and thermoluminescence dating. Ages were found to be:

Terrace I 100±5 ka,
Terrace II 96 ±5 ka,
Terrace III 81±5 ka,
Terrace IV 72 ±3 ka and
Terrace V 59±3ka.

Ota et al. (1996) were able to link the dates for these terraces to world wide sea level changes reported by Chappell and Shakleton (1986). Ota et al. (1996) proposed that Terrace I correlated to either oxygen isotope substage 5c or 5e of Chappell and Shakleton (1986). Based on the dominance of cold water species in the faunal assemblage Ota et al. (1996) preferred substage 5e. This result makes the surfaces younger than the correlation proposed by Suggate (1965).

Interestingly Ota et al. (1996) did not apparently find a very extensive raised mixed sand and gravel beach deposit known to occur on Terrace V on the south side of the peninsula (Kirk Department of Geography, Unversity of Canterbury 1997 *pers. comm.*) Based on terrace ages, elevations and correlation with past sea levels Ota et al. (1996) calculated tectonic uplift rates for each of the five surfaces. Uplift on Terraces I and II was 1.1±0.1m/ka, on Terrace III it was 0.9±02m/ka and on Terraces IV and V1.2±0.1m/ka. Suggate (1965) and Chandra (1968) both proposed that there has been no tectonic uplift of the Kaikoura Peninsula since the Otiran glaciation.

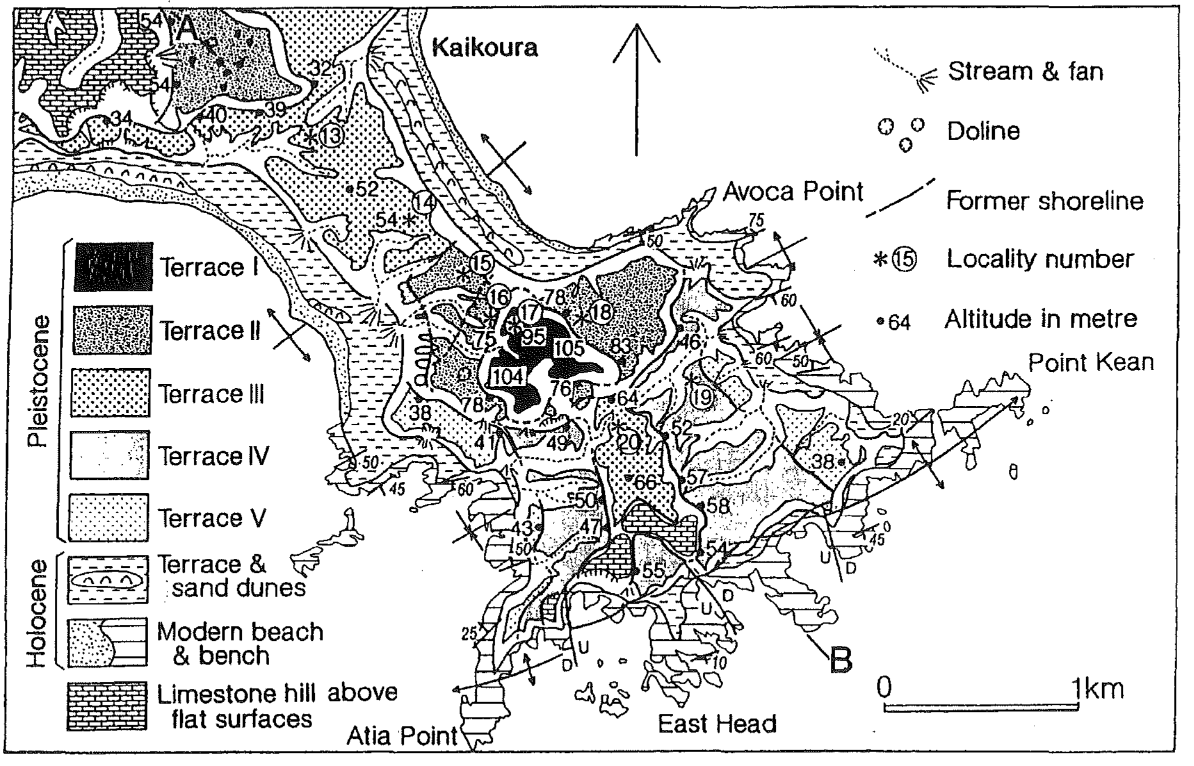

Figure 4.5 Marine terraces of the Kaikoura Peninsula (Ota et al. 1996 Fig 9).

Ota et al. (1996) did not investigate landforms on the Kaikoura Peninsula younger than 39ka. There are numerous raised beaches (Fig 4.6 and 4.7), sea caves, stacks (Fig 4.7) and lagoon deposits (Fig 4.8) backing modern platforms. Suggate (1965) and Chandra (1968) proposed that raised beaches and sea caves around the peninsula were evidence of a higher stand of sea level during the Holocene. Clearly neither author was aware of a sea cave behind the Edward Percival Field Station run by the University of Canterbury that is +4 to 5m above mean sea level. Beach gravels can be found in the floor of this cave. Duckmanton (1974) surveyed modern and raised beaches and found that absolute elevations varied according to the exposure to wave energy. The important point was that the difference in elevation between the modern beach and the raised one behind was always in the range of 2 to 2.5m regardless of the absolute elevations. Based on this evidence Duckmanton (1974) argued that these raised beaches were the result of an episode of tectonic uplift in the order of 2m. According to Duckmanton (1974) this tectonic episode initiated deposition on raised platforms that led to the development of barrier beaches and behind these, lagoons in Wairepo and Mudstone Bays. Dating of peat deposits behind barrier beaches that resulted from the tectonic episode put a minimum age on the tectonic event of 390±60 years B.P. From the degree of weathering on limestone cobbles in the raised barrier beaches Duckmanton (1974) cautiously proposed a maximum age in the order of 1000 years. The occurrence of the sea cave at +4 to 5m behind the Edward Percival Field Station suggests that there has been more than one tectonic episode since between 39ka and the one identified by Duckmanton (1974).

Figure 4.6 A raised beach in First Bay (foreground of photograph). Note that the modern platform is lower than the elevation of the beach ridge from where the photograph was taken.

Figure 4.7 Stacks and raised beaches in Third and Spaniards Bays. Photograph was taken from above East Head looking north. One stack is bottom centre and two are top right. Raised beaches are evident from the discoloured limestone above with the active beach. This discolourisation is the result of weathering.

Figure 4.8 Eroding lagoon deposits in Mudstone Bay. These overlie the active platform which is continually being exposed as the erosion removes the deposits which is 390±60 years old (backpack is 0.5m long).

4.2.3 CLIMATE

The climate of the Kaikoura area is a temperate one. Winds from the south dominate but there is also a strong northeasterly component. Southerly winds result from the passage of depressions and associated cold fronts over the South Island. Northeasterly winds are often a sea breeze, the result of lee trough conditions over the South Island, or due to cyclonic depressions off the northeast of New Zealand that travel south down the coast. Both northeast and southerly winds are important in the generation of waves and swells acting on the Kaikoura coast.

Temperature and rainfall data have been recorded on the Kaikoura Peninsula at an elevation of 108m since 1963 and 1949 respectively. In 1991 an automated weather station was installed at an elevation of 105m. An examination of summary climate data published by the New Zealand Meteorological Service reveals that between 1949 and 1980 average annual rainfall recorded at Kaikoura was 888mm/yr. Between 1963 and 1980 average monthly temperatures ranged from 7.7°C in July to 16.2°C in January. Frosts occurred on average 40 days per year. Sea surface temperatures recorded at the Edward Percival Field Station between 1989 and 1992 show a mean monthly average of 9.1°C in July and 17.3°C in February.

4.2.4 WAVE ENVIRONMENT

There is a general lack of wave data for the Kaikoura Peninsula area. Summary sea state data were presented by McLean (1968) and by Kirk (1972, 1973, 1974, 1975a) for the years 1967, 1971, 1972, 1973, and 1974. These data were collected by the New Zealand Meteorological Service using a descriptive 10 figure scale. Table 4.1 presents this scale with a description and a wave height range. Table 4.2 presents a summary of data from McLean (1968) and Kirk (1972, 1973, 1974, 1975a). For the majority of the year (48 per cent) the sea was classified as smooth with wave heights below 0.5m. Waves between 0.5 and 1.25m occurred 17 per cent of the time. Wave heights in excess of 1.25m had an occurrence of 4 per cent . Kirk (1975b) reported that waves on beaches adjacent to the Kaikoura Peninsula had significant heights between 0.3m and 2.44m with periods between 7.5 and 10 seconds. The occurrence of waves in excess of 1.5m was 15 per cent of the observation period on the southern side and only three per cent on the northern side of Kaikoura Peninsula.

Table 4.1 Sea state code, description and associated wave height (from Kirk 1975a).

Code Figure	State of the Sea Descriptive Terms	Height in Metres
0	Calm (glassy)	0.0
1	Calm (rippled)	0.0 - 0.1
2	Smooth (wavelets)	0.1 - 0.5
3	Slight	0.5 - 1.25
4	Moderate	1.25 - 2.5
5	Rough	2.5 - 4.0
6	Very Rough	4.0 - 6.0
7	High	6.0 - 9.0
8	Very High	9.0 - 14.0
9	Phenomenal	Over 14.0

Table 4.2 Summary sea state data recorded at Kaikoura for years 1967 and 1971 to 1974 (Kirk 1975a).

	Sea State and Percentage of Each Sea State Observed					
Year	1	2	3	4	5	Total
1967	20	52	24	4	0	100
1971	33	46	15	3	4	101
1972	34	48	13	4	0	99
1973	38	45	13	3	0.2	100
1974	31	48	17	4	0.5	100
Average	31	48	17	4	2	101

Directional wave data relevant to the Kaikoura Peninsula were presented by McLean (1972). Data were collected by ships passing the Kaikoura Peninsula approximately 32km offshore. Observations were made between January 1 1966 and June 1 1967. The directional wave and swell data are summarised in Table 4.3 for eight compass points. The prime points (north, south, east and west) cover arcs of 50°, while the minor points (northeast, southeast, southwest and northwest) cover arcs of 40°. There is a clear difference in the dominant direction for swells and waves. Waves emanated most often from the north (23 per cent) and northeast (19 per cent) while swells were most commonly observed from the south (43 per cent). Secondary modes occurred for swells from the north-west (17 per cent) and for waves from the northwest (32 per cent). However waves observed offshore from the northwest are not likely to be significant on the Kaikoura coast given its location in the mountain lee during westerly winds. Therefore the most significant secondary source of waves was from the south (17 per cent) and southwest (12 per cent).

Table 4.3 Summary data of wave direction observed off the Kaikoura coast from January 1 1966 and June 1 1967 (McLean 1972).

		Waves		Swells	
Wave Direction	Degrees (True)	No. of Reports	% of Reports	No. of Reports	% of Reports
North	335-024	47	23	14	14
Northeast	025-064	38	19	17	17
East	065-144	12	6	10	10
Southeast	115-154	9	4	6	6
South	155-204	35	17	43	43
Southwest	205-244	24	12	5	5
West	245-294	6	3	2	2
Northwest	295-334	32	16	6	6
Total		203	100	103	103
Calm		18			

The Kaikoura Peninsula is exposed to unlimited fetch, and the wave climate can be characterised as a high energy oceanic swell environment, where long periods of relatively calm seas are interrupted by high energy storms. The occurrence of these is related to the passage of cyclonic systems as discussed above. Storms can occur at any time of the year and affect any part of the peninsula.

4.2.5 TIDES

Kirk (1976) presented tidal data recorded at Kaikoura between October 1967 and October 1972. Tides at Kaikoura were described as dominantly semi-diurnal, but containing up to 20 per cent diurnal inequality in the magnitude of high water, the day time high being larger (Kirk 1976). Mean range for the observation period was 1.36m and the maximum range was 2.57m.

4.3 SHORE PLATFORMS

4.3.1 GENERAL DESCRIPTION

The shore platforms on the Kaikoura Peninsula have been described in most detail by Duckmanton (1974). From 28 profiles surveyed across platforms the general morphology was described in terms of width, mean elevation, lithology, the presence or absence of a seaward rampart, the type of backshore deposit and average slope.

Widths ranged from 40m to 500m with average elevations between -0·66m and 0·96m. Lithology was either limestone or mudstone, but those platforms cut in limestone displayed a wider variability in morphology (Fig 4.9). Of the 28 profiles nine did not have a seaward rampart present. Back shore deposits included actively eroding cliffs, eroding lagoon deposits, gravel beaches and hill slope deposits. Slope angles varied from 1°42′ to 0°05′. On mudstone platforms the range was between 0°26′ and 0°56′. In nine cases, slope could not be determined due to the high degree of irregularity of the surfaces. Elevation data showed that 90 per cent of surveyed platforms were within ±1.0m of mean sea level and 57 per cent were within ±0.5m of mean sea level. Platform elevations of +1.0m above mean sea level represented seven per cent of platform morphology.

Kirk (1977) used tidal data to determine the length of time platforms were submerged. Results showed that platform elevations of +1.0m above mean sea level were covered by water 2.5 per cent of the time. Elevations up to +0.5m represented 21 per cent of platform morphology and were submerged 48 per cent of the time. Over half of shore platform morphology occurred above mean sea level. 21 per cent of platforms occurred between mean sea level and -0.5m which was covered 63 per cent of the time. Platform morphology below -0.5m accounted for the remaining 22 per cent; this was covered 12 per cent of the remaining time.

Figure 4.9 Limestone shore platform in the foreground and mudstone shore platform in the upper middle of photograph showing contrasting morphology. The photograph was taken in First Bay looking northeast across Point Kean in December 1994 at low tide.

4.3.2 RATES OF DEVELOPMENT

Age and rates of development of shore platforms have been addressed by Duckmanton (1974), Kirk (1975c, 19977), and Stephenson and Kirk (1996). Kirk (1975c) determined rates of cliff and backshore erosion from aerial photographs. These ranged from 0.10m/yr in mudstone cliffs to 1.49m/yr in lagoon deposits in Mudstone Bay. Recall from Chapter Two, that Kirk (1977) reported the average rate of platform lowering was 1.53mm/yr and Stephenson and Kirk (1996) reported rates of surface lowering of 1.43mm/yr. Based on both rates of cliff retreat and surface lowering Kirk (1977) concluded that shore platforms at Kaikoura are contemporary features developed at the present sea level. However, the inner margins of shore platforms were adjusting to the 2m uplift event identified by Duckmanton (1974).

4.3.3 DESCRIPTION OF STUDY SITES

In 1973 Kirk (1977) established six profiles across shore platforms around the Kaikoura Peninsula. On these profiles he measured surface lowering rates at 31 sites using the micro-erosion meter. The results from this study were reviewed in Chapter Two. During initial field work in December 1993, 15 of the 31 micro-erosion meter bolt sites were found 20 years after they were installed. For this reason it was decide to continue to use these profiles and establish new micro-erosion meter sites. The micro-erosion meter technique is described in detail in the next Chapter. Kirk (1977) designated these profiles KM1 to 6. A seventh profile (KM7) was established for the present study in December 1993 to increase representation of limestone platforms. The locations of all seven profiles are shown in Figure 4.10. Each profile runs perpendicular to the shore and was surveyed using a Sokia Set 4B Total Station Theodolite and single prism. Profiles were related to an existing network of benchmarks around the Kaikoura Peninsula to establish elevations relative to mean sea level. Offshore profiles were inspected by the author using Scuba to gain an initial impression of the offshore topography, to identify lithology and to observe sediment characteristics where these occurred. Profiling was extended offshore by using a Raytheon Surveying Fathometer, Model DE719C operating at 208khz and sampling at a rate of 534 soundings per minute. This instrument was carried on a 4.5m Zodiac inflatable. The echo sounder can be calibrated for water density at the time of sounding which can vary, depending on water temperature, salinity and suspended sediment load. This procedure involves lowering a metal plate a known depth below the sounder head and setting the instrument according to that depth. Kirk and Allan (1995) report the accuracy of this technique to be within ±2.5cm.

Soundings began at the seaward most subaerial point surveyed on the platform. This meant that the person holding the prism staff would enter the water and proceed as far offshore as was practical. At this point the boat was held in position so that the sounder head was over the last surveyed point and sounding began. During sounding runs it is necessary to fix the horizontal position of the boat and keep the boat on the profile line. This was achieved using the total station and a triple prism which was attached to the boat. Using hand held radios the total station operator directed the boat operator to steer to port or starboard as necessary. Fixing the horizontal position of the boat was achieved by taking readings with the total station and the operator calling "mark" and at which point the operator of the echo sounder would "fix mark" the position of the boat on the echo sounder chart. Fixed marks on the echo sounder chart paper were used later to determine the horizontal scale. To construct profiles, sounding charts were digitised using a Summasketch II Professional digitising tablet and TOSCA software. From this, co-ordinate data could be entered into a spreadsheet, in this case Microsoft EXCEL and reduced to known levels relative to a datum.

Figures 4.11 to 4.32 illustrate surveyed platforms and offshore profiles. At KM6 and KM7 it was not possible to conduct offshore echo soundings because rugged nearshore topography prevented boat access. Table 4.4 summarises the location and morphological characteristics of the seven profiles. Platform gradient reported in Table 4.4 was calculated by taking the slope between the inner most micro-erosion meter bolt site and the most seaward bolt site. While many researchers report the gradient of shore platforms, none report how this slope was calculated. The use of bolt sites was adopted for the sake of consistency and because of the lack of reported methods in the literature.

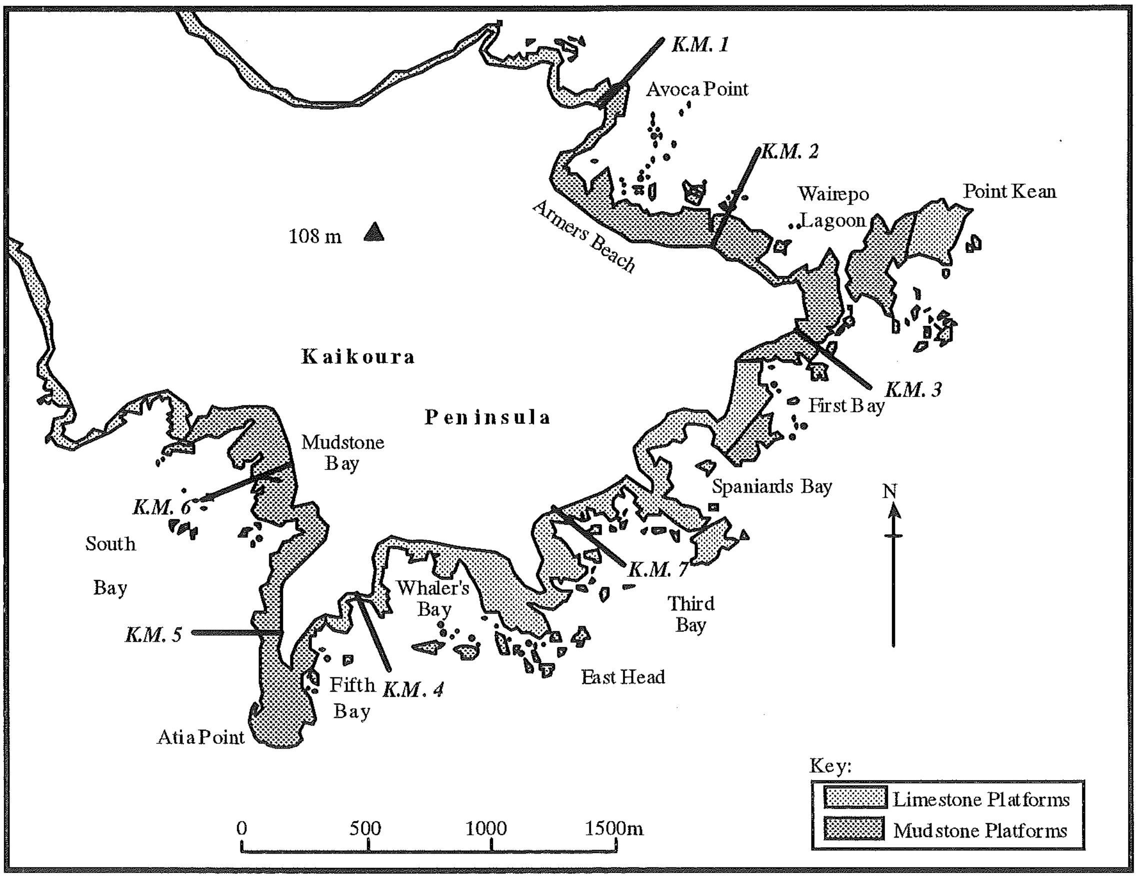

Figure 4.10 Locations of surveyed profiles on the Kaikoura Peninsula.

Location	Profile	Mean Elevation (m)	Length (m)	Slope	Orientation (mag)	Strike (mag)	Dip	Platform Type	Lithology	Backshore
Avoca Point	KM1	0.384	91	0°53′37.47″	031	130	-33	B	Mudstone	Pebble & cobble beach & road
Wairepo Lagoon	KM2	0.214	88	0°30′15.15″	330	240	+40	A	Mudstone	Pebble beach & road
Point Kean	KM3	0.406	85	1°16′10.08″	102	013	-9	B	Mudstone	Eroding cliff
Whaler's Bay	KM4	-0.226	52	0°13′34.74″	140	290	+10	A	Limestone	Pebble & cobble beach
Atia Point	KM5	0.340	65	0°10′8.48″	240	160	+30	B	Mudstone	Eroding hill
Mudstone Bay	KM6	-.074	137	0°26′28.21″	206	300	-30	A	Mudstone	Eroding lagoon deposit
Third Bay	KM7	-0.241	78	0°55′20.58″	108	24	+30	A	Limestone	Eroding cliff

Table 4.4 Characteristics of shore platform profiles used for this study

PROFILE KM1

KM1 (Figs 4.11, 4.12 and 4.13) is located on Avoca Point, a headland on the northern margin of the Kaikoura Peninsula (Fig 4.7). This platform is formed in mudstone and backed by a pebble and cobble limestone beach, behind which is a public road. The seaward end of this platform terminates in an abrupt low tide cliff indicating that it can be designated as a Type B platform. The slope between the landward and seaward bolt sites is 0°53′37.47″, in a seaward direction. The depth of water immediately in front of the low tide cliff is 1.42m below Mean Sea Level. The offshore survey shows that this platform drops rapidly to a depth of -9.5m at which point a gently sloping sandy bottom begins. The gradient of the submarine rock section is 1:12, the gradient of the sandy bottom is 1:38 while the gradient of the entire surveyed profile is 1:30. At the time this profile was inspected using Scuba, shore normal sand ripples were observed on the section of sandy bottom.

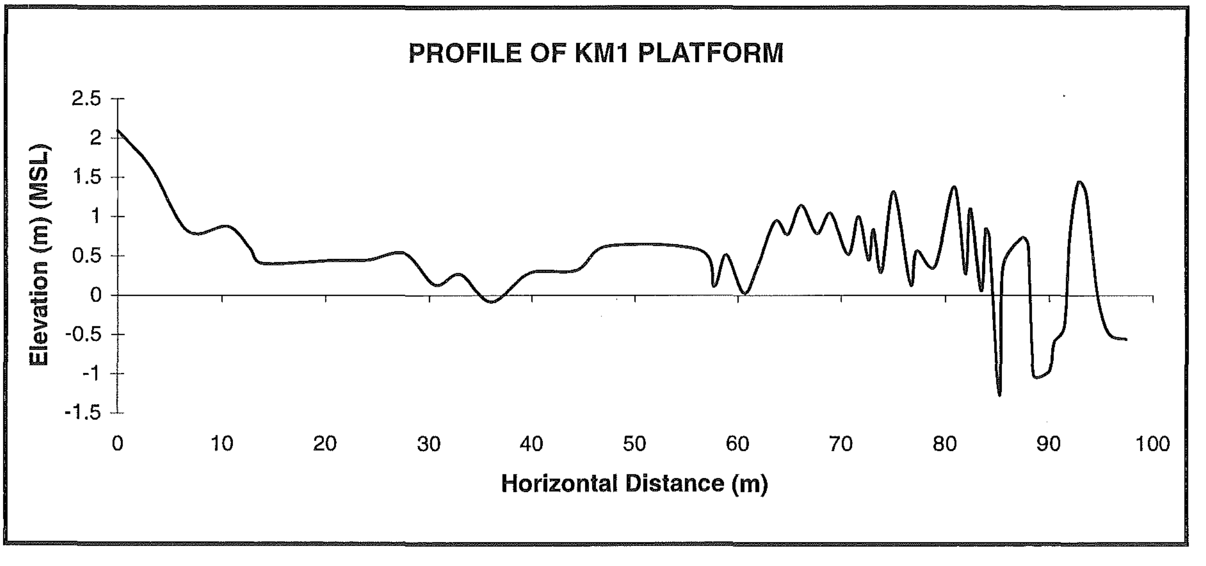

Figure 4.11 Surveyed profile of KM1.

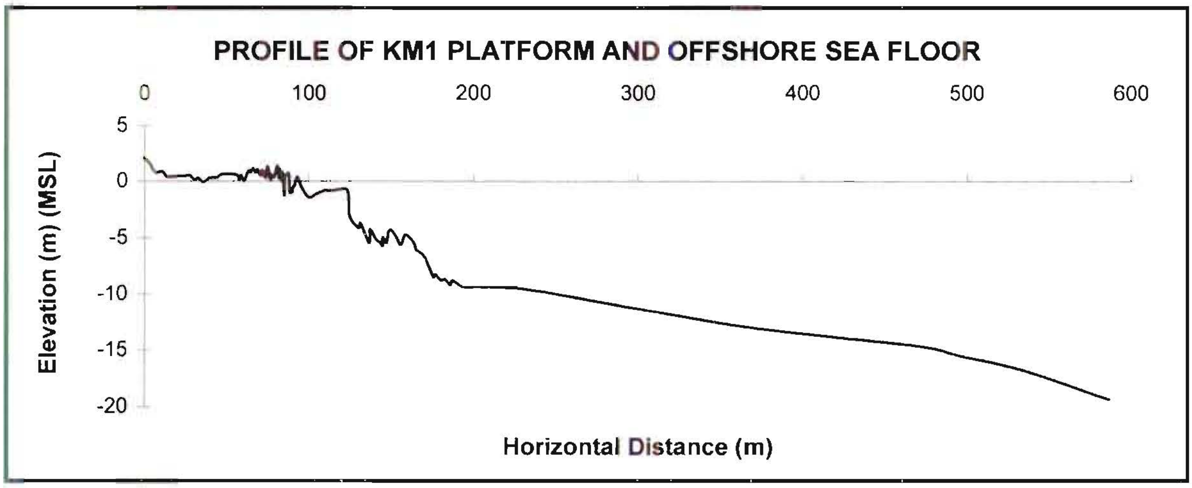

Figure 4.12 Profile KM1 and offshore topography.

Figure 4.13 Aerial view of KM1 (3 March 1996 at low tide).

PROFILE KM2

KM2 (Figs 4.14, 4.15 and 4.16) is situated between Armers Beach and the remnants of Wairepo Lagoon. KM2 is in mudstone and backed by a limestone cobble beach. This platform has a sloping profile with a gradient of 0°30′15.15″. It is therefore designated as a Type A platform. The offshore topography is rocky and irregular, with steeply rising pinnacles, suggesting a lithological control over topography. Scuba diving revealed thin layers of sediment between pinnacles of rock. The gradient of the offshore profile is 1:46 while the gradient of the entire profile is 1:52.

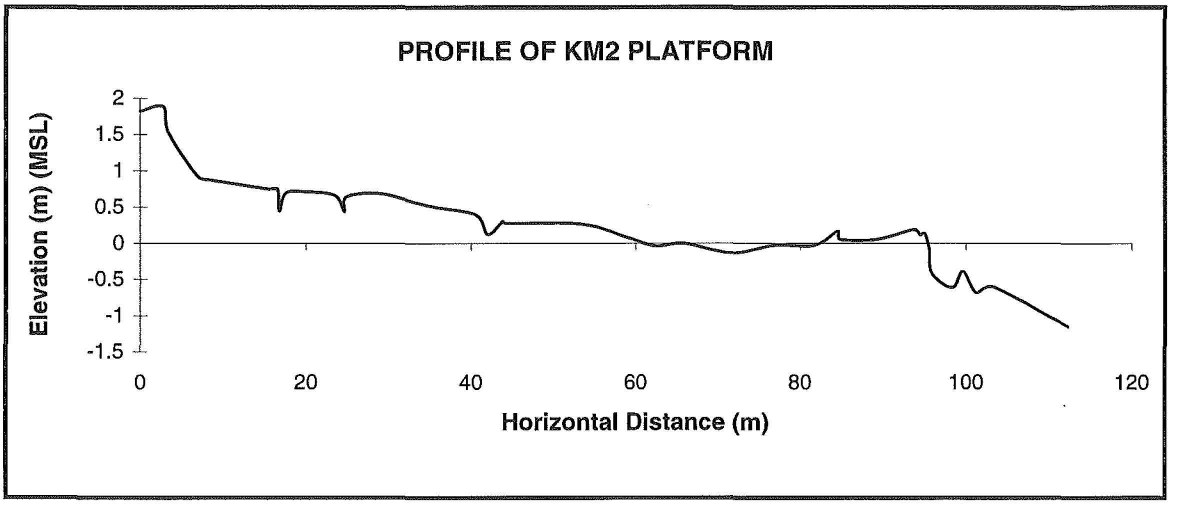

Figure 4.14 Surveyed profile of KM2.

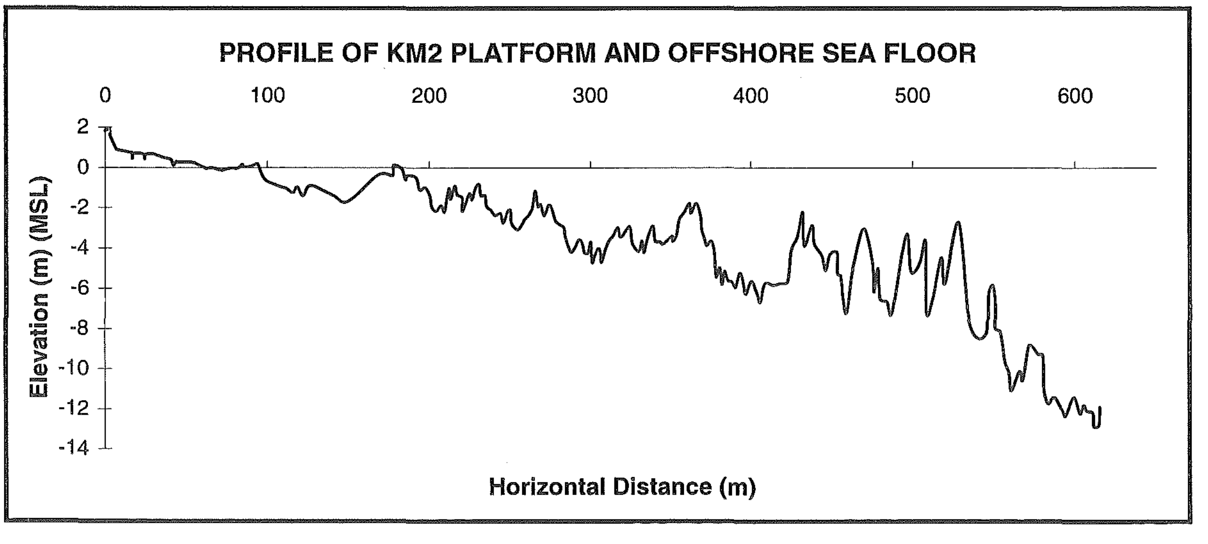

Figure 4.15 Profile KM2 and offshore topography.

Figure 4.16 Aerial view of KM2 (3 March 1996 at low tide).

PROFILE KM3

KM3 (Figs 4.17, 4.18 and 4.19) is located to the south of Point Kean. This platform is cut in mudstone and backed by an actively eroding cliff with a distinct low tide cliff. This suggests that it can be designated as a Type B shore platform. On this platform there is a clearly developed bench formed at the base of the landward cliff (Fig 4.20). This bench extends several hundred metres laterally along the cliff base and is approximately 0·5m high. Since a bolt site was installed on this ramp the overall gradient of 1°16′10.08″ is steeper than might be expected for a Type B platform. The offshore profile of KM3 was not inspected by Scuba diving because of rough seas at the time. The echo sounding revealed a rocky and irregular topography with an offshore gradient of 1:21. In front of the low tide cliff the depth of water is 1.82m below mean sea level, although a small pinnacle rises again to 0.32m below mean sea level before the profile begins to drop away.

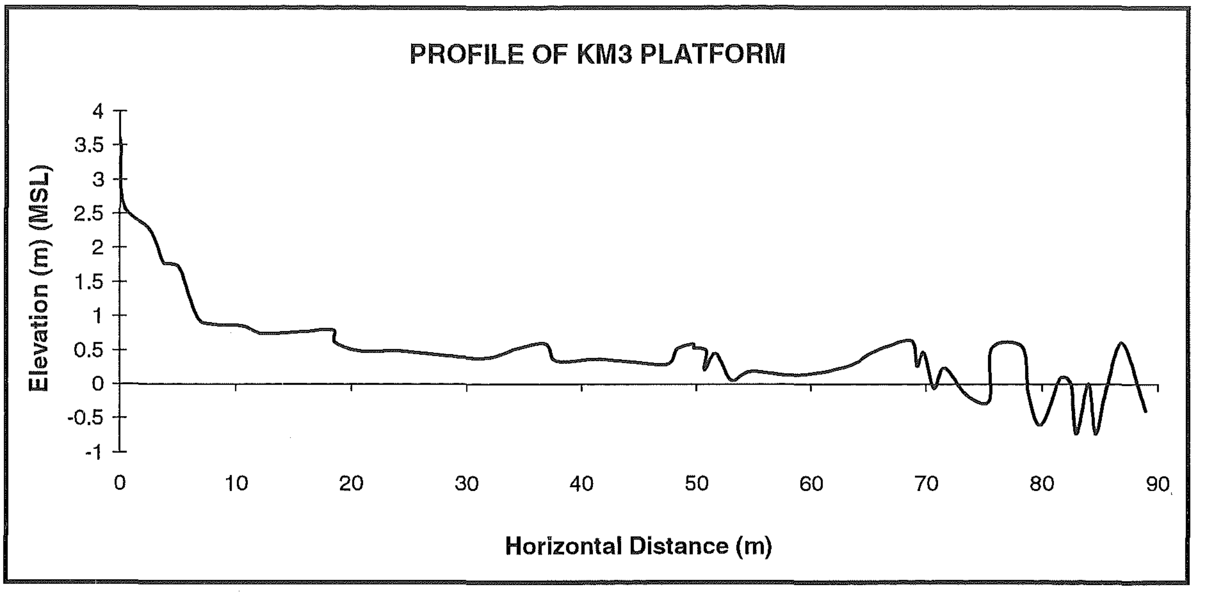

Figure 4.17 Surveyed profile of KM3.

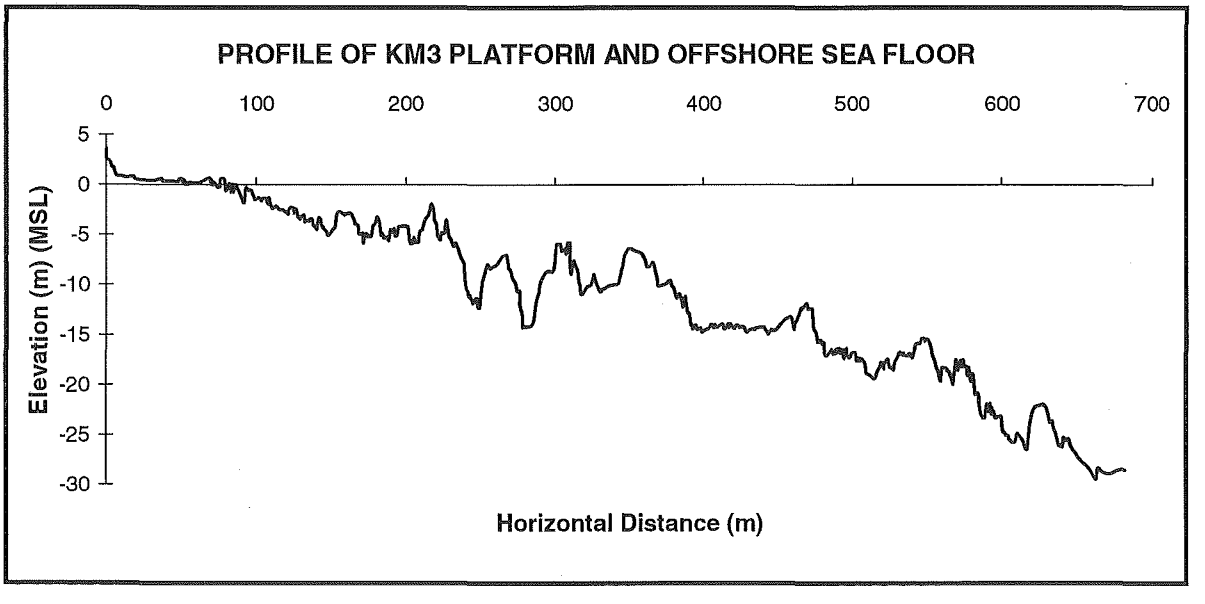

Figure 4.18 Profile KM3 and offshore topography.

Figure 4.19 Aerial view of KM3 (3 March 1996 at low tide).

Figure 4.20 Bench at base of cliff of KM3 (January 1994).

PROFILE KM4

KM4 (Figs 4.21, 4.22 and 4.23) is located in a small embayment within Fifth Bay (Fig 4.10). This is a narrow platform cut in limestone and backed by a limestone pebble and cobble beach. Behind the beach is a well vegetated talus slope rising to 14m above MSL, at which point an inactive marine cliff is evident. The offshore gradient of this profile is 1:28; if the platform is included then the gradient is 1:34. In comparison to KM2, and KM3 this profile shows less variability in offshore topography and is less steep. A thin covering of sediment was observed between rock pinnacles. The morphology of this platform makes it difficult to designate it either Type A or Type B. The slope of the platform is 0°13′34.74″, in a landward direction. At this point KM4 is tentatively classified as a Type A platform because of a lack of a distinct low tide cliff.

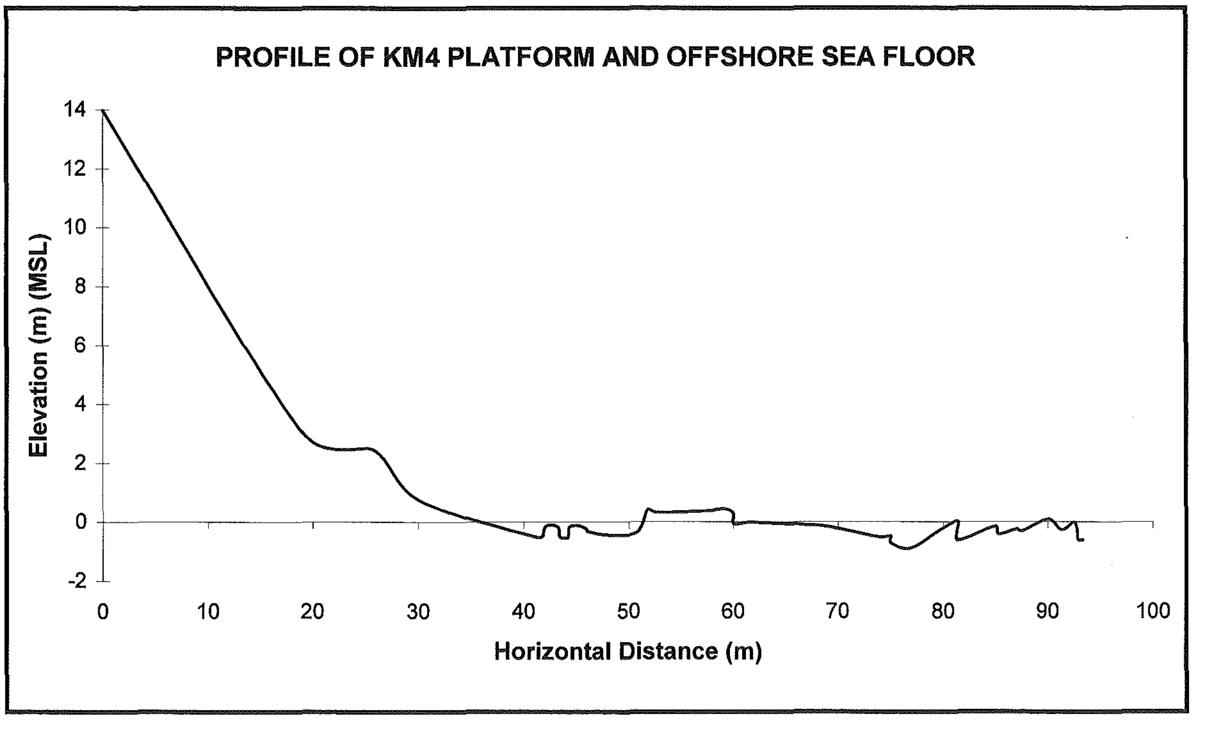

Figure 4.21 Surveyed profile of KM4.

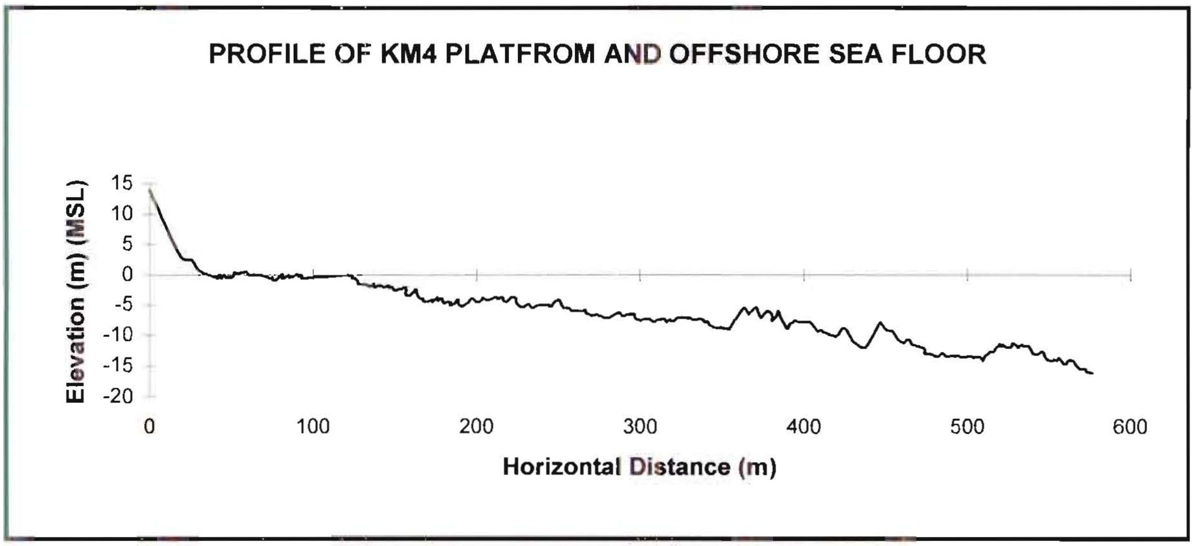

Figure 4.22 KM4 and offshore profile.

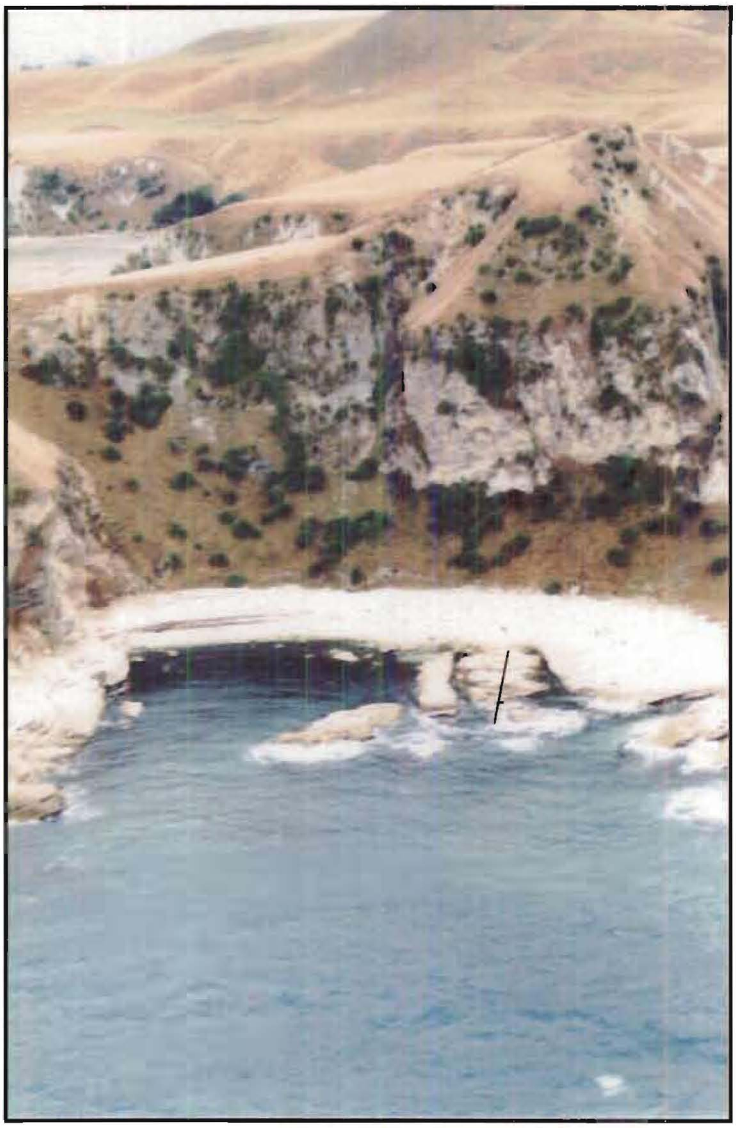

Figure 4.23 Aerial view of KM4 (3 March 1996 at low tide).

PROFILE KM5

KM5 (Figs 4.24, 4.25 and 4.26) is a mudstone platform located on the south side of Atia Point (Fig 4.10). This platform is backed by an eroding hillslope, and at the base of the hill is a ramp (Fig 4.27). The seaward edge of the platform is marked by a distinct low tide cliff. The depth of water in front of this low tide cliff is 3.86 below mean sea level, although this is the bottom of a narrow channel which rises again to 1.281 below mean sea level. KM5 is designated a Type B platform. The gradient of this platform is 0°10′8.48″. The offshore topography is again rocky and irregular, with thin veneers of sediment in crevasses. A distinct break in slope can be seen at 340m from the profile origin; here water depth drops to 15m below mean sea level. The gradient of the profile from the seaward drop of the platform to this break in slope is 1:37 and from 370m to the end of the profile the gradient is 1:26. The gradient of the entire offshore profile is 1:37.

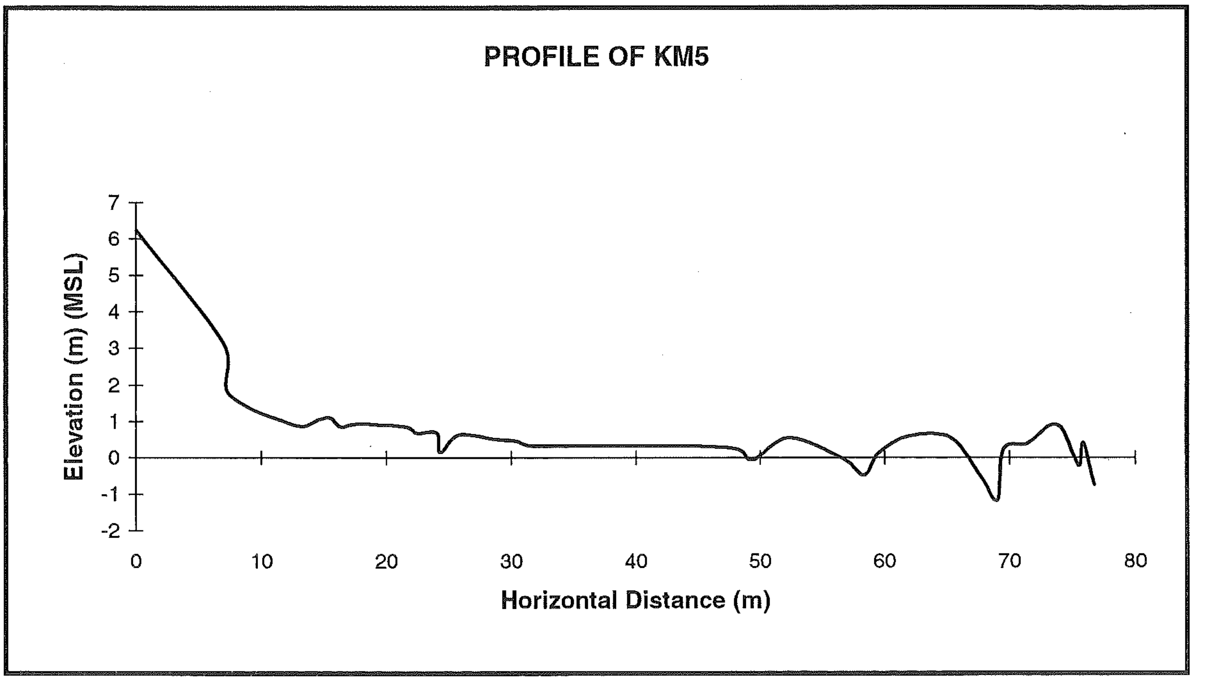

Figure 4.24 Surveyed profile of KM5.

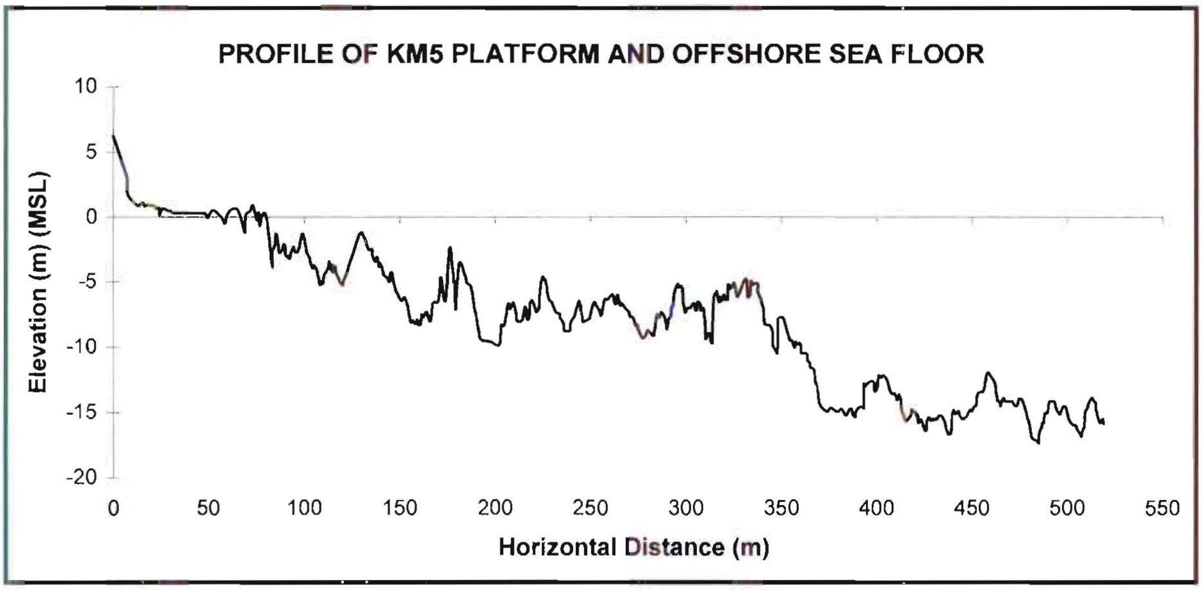

Figure 4.25 KM5 and offshore profile

Figure 4.26 Aerial view of KM5 (3 March 1996 at low tide).

Figure 4.27 Ramp at base of hill on KM5 at low tide (seal is approximately 0.5m high).

PROFILE KM6

KM6 (Fig 4.28 and 4.29) is a mudstone shore platform located in Mudstone Bay on the south side of Kaikoura Peninsula. This is a Type A platform with a slope of 0°26′28.21″, and is backed by eroding lagoon deposits (Fig 4.8). Difficulty with boat access prevented echo sounding the offshore profile but visual inspection while Scuba diving revealed that the sea floor is rocky with an irregular topography similar to other profiles.

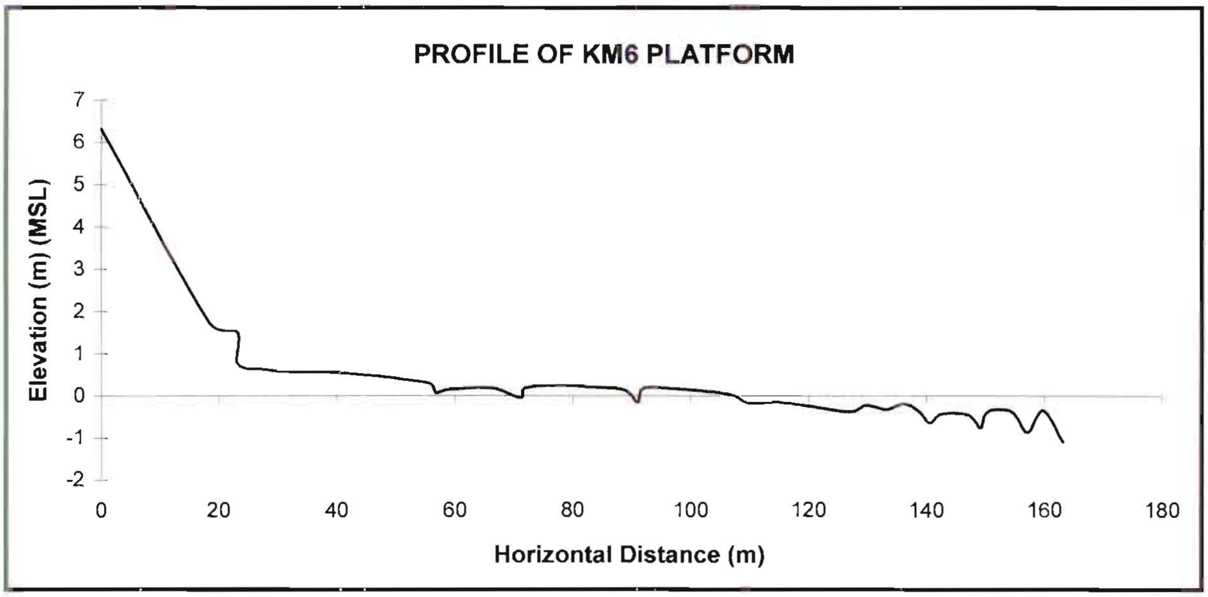

Figure 4.28 Surveyed profile of KM6.

Figure 4.29 Aerial view of KM6 (3 March 1996 at low tide).

PROFILE KM7

KM7 (Fig 4.30 and 4.31) is an embayed limestone platform located in Third Bay. This platform is backed by an actively eroding cliff also of limestone. As with KM3 this platform has a distinct bench located at the base of the cliff. There is no low tide cliff at the seaward edge of this platform so that the platform can be assigned the designation Type A. The slope of KM7 is 0°55′20.58″. No echo sounding of the offshore profile was carried because of difficulty with boat access, but inspection using Scuba showed a profile very similar in topography and slope to KM4.

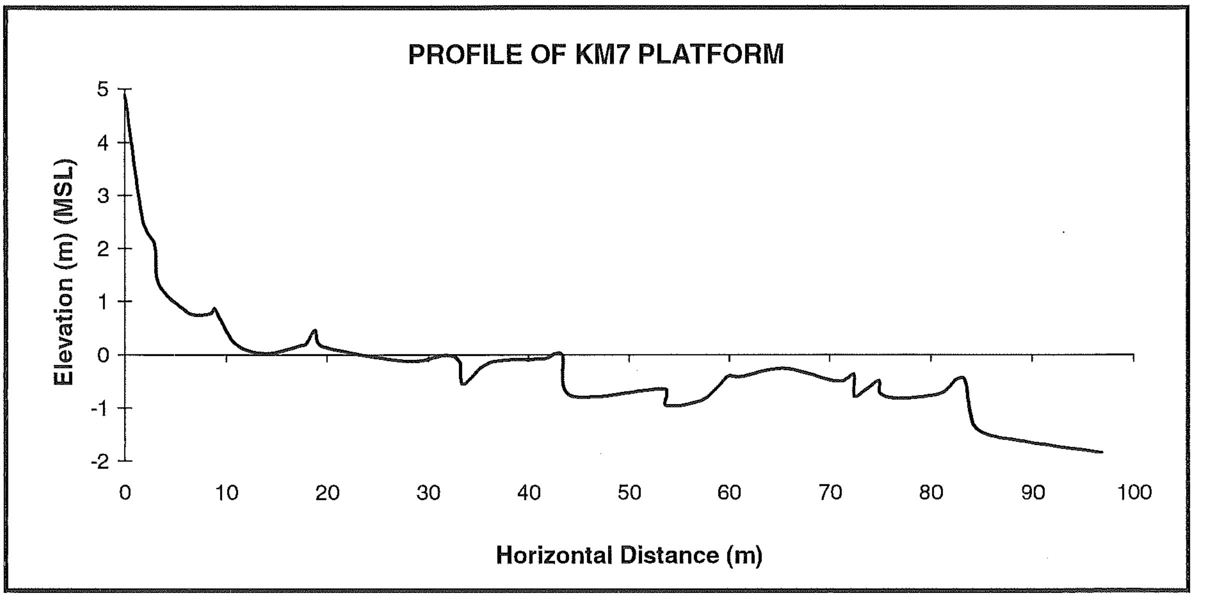

Figure 4.30 Surveyed profile of KM7.

Figure 4.31 Aerial view of KM7 (3 March 1996 at low tide).

4.3.4 COMPRESSIVE STRENGTH TESTING

The compressive strength of rock in which shore platforms of the Kaikoura Peninsula are formed was required to investigate the relationship between the erosive force of waves and the resisting force of rock as reviewed in Chapter Two. Data on compressive strength were also required to investigate the demarcation between Type A and B platforms which was provided by Tsujimoto (1987). Rock cores were taken from five locations around the Kaikoura Peninsula; these were at profile locations, KM1, KM2, KM3, KM7 and KM6. These were chosen to reflect lithology, exposure to wave energy and type of platform. Samples were not taken at KM4 or KM5 because of the difficulty of getting drilling equipment to these sites. On profiles where cores were taken, three cores were drilled from platform surfaces using a 56mm diameter diamond tip corer. These were taken at the seaward edge of the platform, the middle of the platform and on the landward margin. In all, 15 samples were collected from the five profiles. Drilling required water for cooling and lubrication, which meant cores were retrieved wet. Once recovered each core was wrapped in plastic Glad® Wrap to prevent drying during transportation to the laboratory, where they were submerged in sea water until testing.

Cores were prepared in accordance with the American Society for Testing of Materials standards D4543-85 and D2938-86. This involved cutting each core to a length between 2 and 2.5 times the diameter and sectioning the ends to ensure they were square. Tsujimoto (1987) tested cores soaked so that they are tested under conditions that replicate the conditions under which waves erode platforms. The American Society for Testing of Materials standard D2938-86 also recommends that moisture content should reflect field conditions. Each core was tested using the unconfined compressive strength test for intact rock. Tsujimoto (1985, 1987) used a discontinuity index calculated by dividing the longitudinal wave velocity measured in rock in-situ by the longitudinal wave velocity measured in a fresh specimen of the same rock type without visible cracks. Unfortunately the equipment necessary to measure longitudinal wave velocity was not available for this study. This means that S_c was calculated for shore platforms at Kaikoura, not S_c^*.

Of the 15 core samples taken from around the Kaikoura Peninsula only ten survived preparation for final compressive strength testing. The results of this testing are shown in Figure 4.32. The problem encountered was, that samples cracked during sectioning square ends. Despite this problem the ten results did provide useful data on the nature of the compressive strength values for shore platforms at Kaikoura. Figure 4.32 shows a clear separation of Type A and B mudstone platforms. Type A platform compressive strength values ranged from 8932 to 23432 KN/m^2, while Type B values ranged from 36894 to 57856 KN/m^2. Two limestone cores from KM7 had values of 57215 and 21750 KN/m^2.

In order to compare the above data with other published compressive strength data, values in Table 2.3 were converted to SI units, KN/m^2. These are presented in Table 4.4 with results from Kaikoura. Recall that the values for compressive strength for Kaikoura shore platforms have not been calculated using longitudinal wave velocity, nor were the data from Edwards (1941). An important difference between the Kaikoura platform values and the other data sets is that the samples from Kaikoura represent only one type of lithology. Values from Edwards (1941) included limestone, sandstone and basalt and granite. Sunamura (1994) does not report the lithologies in Tsujimoto's (1985) study. Tsujimoto's (1987) values were taken from a range of lithologies that included compacted gravel and sands, mudstones, shales, basalt and andesitic lava.

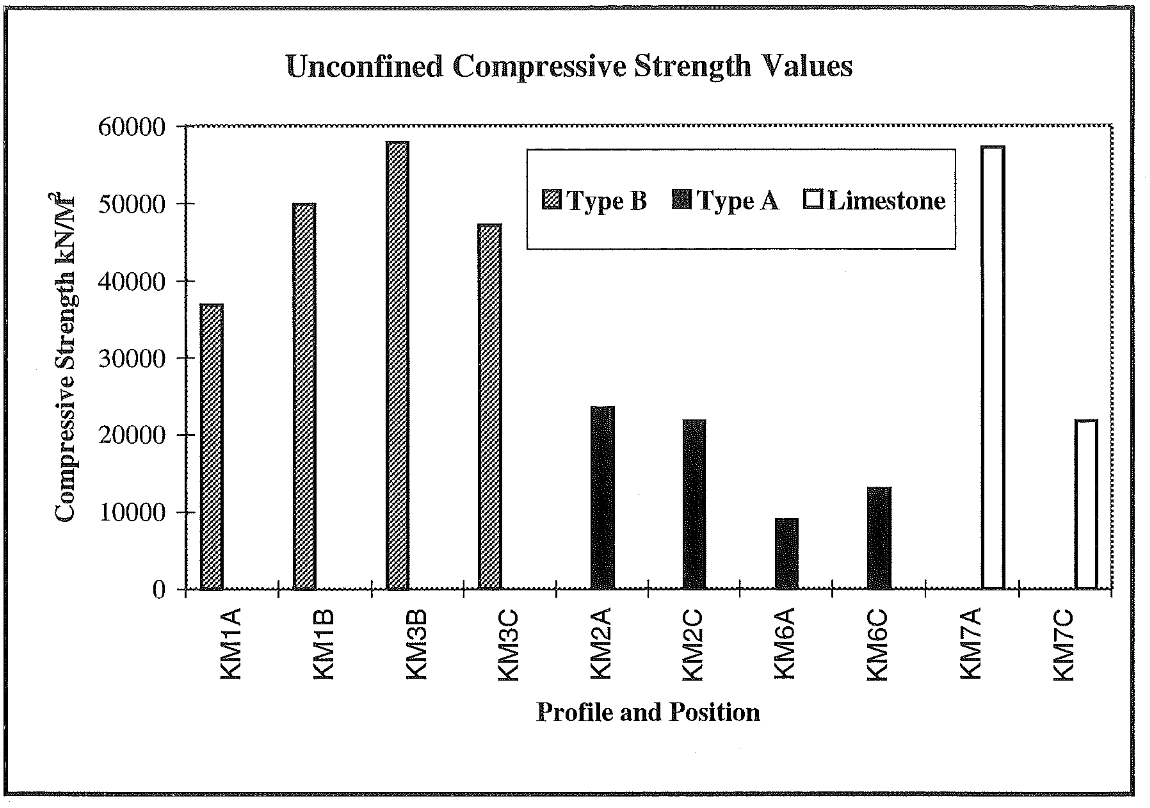

Figure 4.32 Results of unconfined compressive strength testing.

Table 4.4 Compressive strength values for Type A and Type B platforms and plunging cliffs.

Study	Type A	Type B	Plunging Cliff
Edwards (1941)	10290-20594 KN/m^2	20594-109838 KN/m^2	186038 KN/m^2
Tsujimoto (1985)	<2941KN/m^2	2941-14706 KN/m^2	>14706 KN/m^2
Tsujimoto (1987)	127-3824KN/m^2	1471-25498 KN/m^2	5982-196140 KN/m^2
This Study*	8932-23432KN/m^2	36893-57856 KN/m^2	>57856 KN/m^2

* Mudstone shore platforms only.

Despite differences, the pattern of platform type demarcation in previous studies is repeated in the Kaikoura data. Unlike Edwards and Tsujimoto however, there is no overlap. Rather, there is a difference of 13461KN/m^2 between the maximum value for a Type A platform and the minimum value of a Type B platform. This quantified difference supports empirical evidence from Bartrum (1926) who observed Type B platforms in "more resistant rock". Table 4.4 shows that at Kaikoura compressive strength values in excess of 57856KN/m^2 would according to Sunamura (1992) result in plunging cliffs. This must be seen as a minimum value, since no plunging cliffs are actually present at Kaikoura. These compressive strength data are important with regard to Tsujimoto's (1987) demarcation of Type A and B platforms. He showed a demarcation based on the differences between the shear force of breaking waves τ and the shear strength of rock S^*_s. At Kaikoura a demarcation exists between Type A and B platforms based solely on compressive strength. Type A platforms occur in "softer" rock than Type B. This result is the same as that of Edwards (1941).

Data in Table 4.32 do not include values from the two limestone cores. The relationship above is not supported by the limestone results These values do not support the designation of this profile as a Type A platform. One compressive strength value is within the range for Type A platforms and the other is within the range for Type B platforms. A larger number of samples may be required to gain more conclusive results. It is also possible that the lithology of the limestone has influenced these results. The core with the lower compressive strength is thought to have failed during testing along a bedding plain. The higher compressive strength value is probably accurate and lower values are a result of the structure of limestone at Kaikoura.

The above results offer an explanation for the morphology of shore platforms observed at Kaikoura. Type A platforms develop in softer material, that is more easily eroded than Type B platforms which develop in harder rock. This result can be used to address issues of platform elevation and occurrences on headlands and in embayments. At Kaikoura all Type A platforms are found in embayments and Type B platforms form headlands. The softer mudstones that Type A platform are formed in probably erode faster than the harder rock in which Type B platforms occur. If it is assumed that cliff recession is similarly different during early stages of development, then it would be expected that the embayments of the Kaikoura Peninsula occur where the softer mudstones are found. The result of this is that the slower to erode material is left behind and subsequently forms headlands. Type B platforms are found on headlands, not because of a direct relationship with wave energy as suggested by Duckmanton (1974) and Sunamura (1978a), but because they do not erode as quickly as Type A platforms. This point is illustrated by the location of Type A and Type B platforms around the Kaikoura Peninsula. Type

A platforms form two major bays on the north and south sides of the peninsula. The two major headlands of the peninsula, Atia Point and Point Kean are Type B platforms.

4.4 CONCLUSIONS

Since sea level has not been much higher during the Holocene than at present and given that the maximum elevation of a marine erosional surface is 108m, it is clear that tectonism has played a significant role in shaping the geomorphology of the Kaikoura Peninsula. The Kaikoura environment has been shown to be highly energetic with regard to both marine and weathering processes. Shore platforms are exposed to the dominant wave directions and are in the inter-tidal zone. This means that both marine erosive forces and weathering processes can cause erosion. While two investigations have occurred into the processes responsible for shore platform development at Kaikoura and the rates at which the processes operate more detailed examination is warranted. The next chapter is concerned with investigating and measuring erosion on the seven profiles described above. The seven profiles show that there is a wide variety in the morphology of shore platforms at Kaikoura, both within and below the tidal range. Offshore echo sounding has shown extremely irregular offshore topography with varying gradients. Scuba diving revealed that sediments are commonly located in crevices. They comprise limestone sediments with shell hash mixed through them. All profiles surveyed on mudstone shore platforms were readily identifiable as either Type A or B platforms. It was less obvious whether or not profiles in limestone were Type A or B. This is most probably because of the strong influence the geology of the limestone has on the morphology of these platforms. Despite these difficulties, three profiles have been designated Type B platforms and four Type A. All Type A platforms are in embayments while all Type B platforms are located on headlands. Type B platforms are higher in mean elevation than Type A platforms. The steepest and shallowest slopes are KM3 and KM5 respectively; both are Type B platforms. The main distinction between Type A and B platforms made by Sunamura (1992) was that Type B have a low tide cliff while Type A do not. This difference has been observed at Kaikoura. Compressive strength testing confirmed the Type A and B designation based on profile data. It was argued that differences in elevation observed between embayed platforms and those on headland are a result of the geology of the rocks making up platforms. Type B platforms are found on headlands and have higher compressive strength values than Type A platforms found in bays. Based on this observation it has been argued that Type A platforms erode faster than Type B and this is why they are found in bays. Erosion data presented in the next chapter will be used to test this idea.

5. RATES AND PATTERNS OF EROSION ON SHORE PLATFORMS AT KAIKOURA

5.1 INTRODUCTION

This chapter presents measurements of micro-erosion rates on shore platforms at Kaikoura. The rates at which platforms lower and cliffs retreat are calculated. The contributions of other forms of erosion which are more difficult to measure, are assessed relative to those actually measured. An attempt to measure low tide cliff retreat is presented. Erosion data patterns are used to make interpretations about the processes causing erosion on shore platforms and to illustrate the characteristics of erosion.

5.2 MICRO-EROSION DATA

5.2.1 MEASURING MICRO-EROSION RATES

There is one main method that has been developed to accurately measure the rate of surface lowering on bed rock. The micro-erosion meter (MEM) (Fig 5.1) was first described by High and Hanna (1970) and used to measure relatively slow rates of erosion on rock surfaces but not on coastal rock surfaces. Subsequently Kirk (1977), Robinson (1977a 1977b 177c), Spencer (1981, 1985), Gill and Lang (1983), Viles and Trudgill (1984), Spate et al. (1985), Mottershead (1989) and Stephenson and Kirk (1996) all used the technique to investigate processes and rates of erosion on shore platforms.

The micro-erosion meter consists of an equilateral triangular base, with legs located at each corner, and an engineering dial gauge located on a central pillar. The spindle of the gauge extends through the base plate. Readings are taken by placing the base on three masonry bolts permanently fixed into a rock surface (Fig 5.2). Three readings can be taken on each bolt site by rotating the instrument 120°. Exact relocation is achieved through the Kelvin Clamp principle. The end of each leg has been machined differently: one has a cone shaped depression, one a v-notch depression and the third is flat (High and Hanna 1970). Each leg end opposes movement in three, two and one directions respectively; thus preventing movement of the plate when placed on a bolt site. The micro-erosion meter used by Kirk (1977) at Kaikoura was available for use during this study. It was constructed according to the specifications outlined by High and Hanna (1970). In addition, a calibration block constructed at the same time was also available. This enabled the meter to be checked periodically to ensure it was still operating accurately.

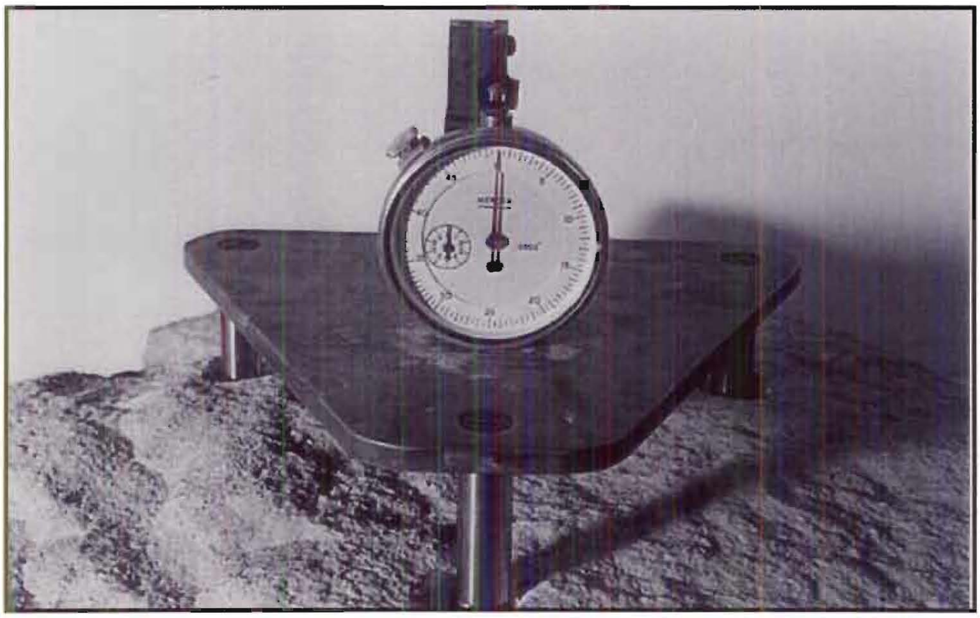

Figure 5.1 The micro-erosion meter showing brass plate and engineering dial gauge. The dial gauge has a diameter of 55mm. This instrument reads in half thousandths of an inch.

Figure 5.2 A micro-erosion meter bolt site at Kaikoura. Masonry expansion bolts forming the triangle are 150mm apart.

Trudgill et al. (1981) presented a modified version of the micro-erosion meter called the traversing micro-erosion meter (TMEM). The traversing micro-erosion meter differs in that the dial gauge is independent of the base and is mounted on a block with three arms separated at 120° intervals (Fig 5.3). The centre of the base plate is cut out to allow the dial gauge to be moved within the area defined by the permanent bolts. The dial gauge can be moved to a number of different positions by locating each horizontal arm between ball bearings fixed along the sides of the base. So long as each arm is at right angles to a side of the triangular base a precise location is obtained each time the instrument is placed on a bolt site. The number of locations depends on the size of the base, the number of ball bearings fixed along each edge and on the size and configuration of the dial gauge and arms. The TMEM utilises the same bolt sites as the MEM because it has the same leg spacings and configurations.

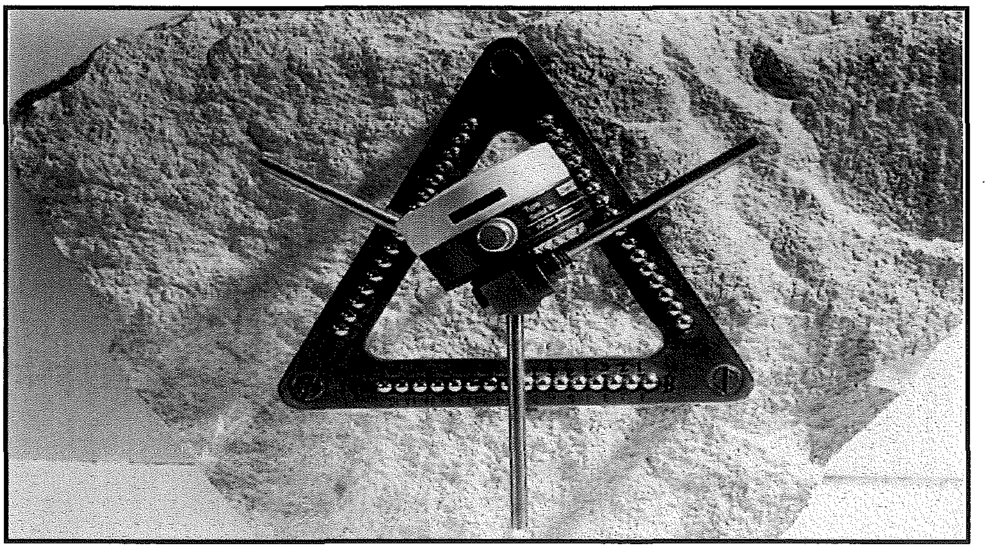

Figure 5.3 Top view of the traversing micro-erosion meter. The length of each side of the triangle base is 170mm.

For this study Stephenson (1997) (see Appendix Two) further modified the traversing micro-erosion meter by fitting it with a digital dial gauge (Fig 5.4). The gauge used was manufactured by SYLVAC, has a range of 25 - 0.001mm or 1 - 0.0005" and is accurate to 0.001mm. Previously published designs of the micro-erosion meter used an analogue dial gauge which required the operator to read and physically record results. This was considered to be too restrictive given the time constraints of working on shore platforms in the inter tidal zone where a large data set was being generated. The traversing micro-erosion meter used at Kaikoura allowed 120 individual measurements to be made at a bolt site. To further aid data collection the digital dial gauge was connected to a laptop computer via an optical RS 232 cable (Fig 5.4).

Each reading was logged directly to a spreadsheet using software supplied with the gauge. Stephenson (1997) also showed how data from the TMEM could be entered into a surface plotting programme called SURFER. This enabled 3-D visualisation of a site and this could be used to interpret of processes of erosion. Use of SURFER also allows the volume of material eroded from a site to be estimated.

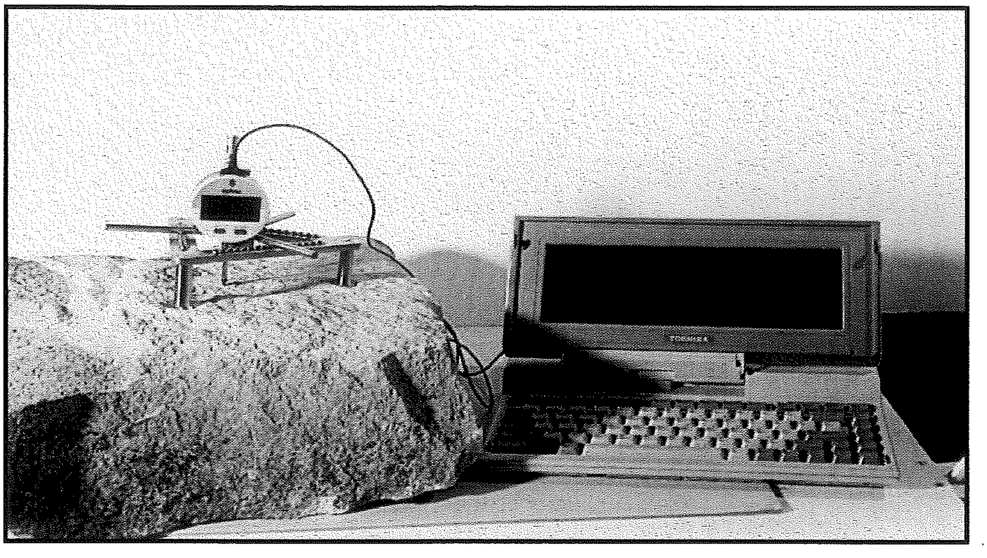

Figure 5.4 The traversing micro-erosion meter used at Kaikoura fitted with a digital dial gauge and connected to a lap top computer.

5.2.2 TRAVERSING MICRO-EROSION METER AND MICRO-EROSION METER PROFILES

As described in Chapter Four micro-erosion meter bolt sites installed in 1973 by Kirk (1977) were located on profiles across shore platforms. At least one micro-erosion meter site of the original 31 installed remains on each of the seven profiles. In the case of KM2 only one bolt site had been lost. It was necessary to re-survey the profiles established by Kirk in order to correctly identify bolt sites because missing sites made identification difficult. Since the present study is concerned with establishing whether or not processes operate zonally across a shore platform profile, new traversing micro-erosion meter sites were established in the same way as that of Kirk. To this end 42 new traversing micro-erosion meter sites were installed on the same profiles originally established by Kirk. The number of bolt sites on each profile depended on the width of the platform and the number of old micro-erosion meter sites still in place. The locations of each of the bolt sites on the seven profiles are shown in Figure 5.5 and the locations of each profile on the peninsula were given in Figure 4.10. The same bolt site designations used by Kirk were used for this study. Thus each profile was designated KM1 through to KM7 and each bolt site on a profile was labelled alphabetically in an offshore direction. Bolt sites with an A are on the landward margins of platforms as those with either G, H, or J are at the seaward edge of platforms. All bolt sites were surveyed and levelled relative to mean sea level on the Lyttelton datum. All bolt site positions were fixed using differential G.P.S. The type used was a Trimble Pro XL with a TDC1 data acquisition system. Data were differentially corrected using "Pathfinder" software and Terralink data from the Christchurch base station. G.P.S. location data are set out in Appendix Three.

Between December 1993 and March 1996 each bolt site was visited six or seven times. The maximum length of the erosion record was 800 days or 2.2 years. Not all visits to bolt sites resulted in measurements being taken, for reasons explained below, so that numbers of times measurements were taken varied from only two to a maximum of seven. In all a total of 24055 individual measurements were made using the traversing micro-erosion meter and 305 individual measurements using the micro-erosion meter. This was fewer than the total possible of 35280 from the TMEM and 315 from the MEM. This represents 68 per cent efficiency of data gathering for the TMEM and 97 per cent for the MEM. The reasons for less than the total number being collected are explained below.

A number of problems were experienced during the data collection period that prevented a "complete" set of data from being gathered. Gaps exist where bolt readings were not able to be taken when sites were visited. There are a number of reasons why this was the case. The most common reason was the growth of algae on platform surfaces particularly from April to September each year, although in some locations this would persist into November and December. This was especially the case on KM6. KM7E was only read twice throughout the entire study and on a number of visits to the profile could not be found. Species of algae included, *Scytosiphon lomentaria*, *Porphyra columbina* and *Enteromorpha ramulosa.* Because of the growth of algae during winter months, most readings occurred at the beginning and end of summer periods.

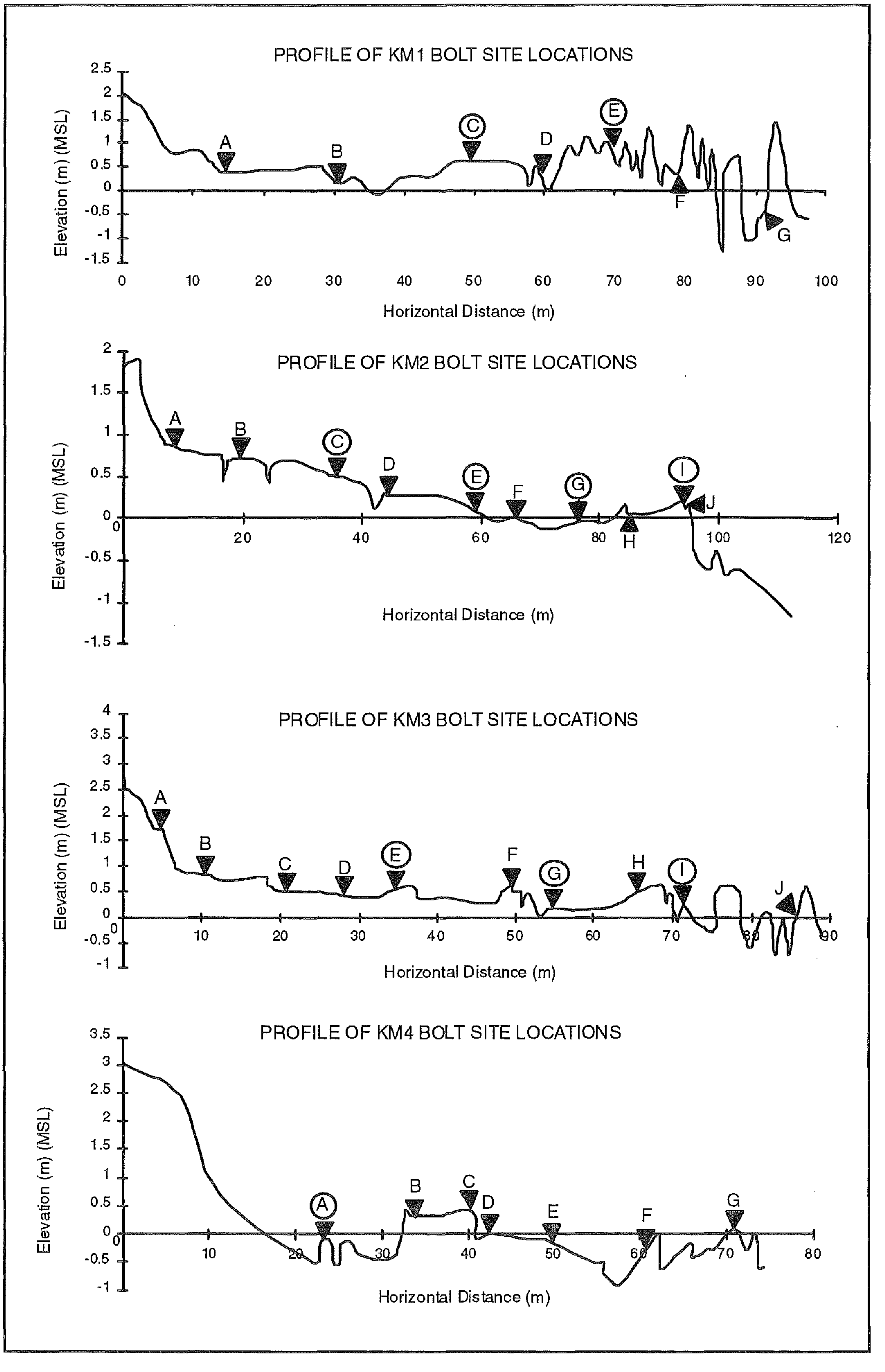

Figure 5.5 Location of bolt sites on profiles. Circled letters indicate old MEM sites from Kirk (1977).

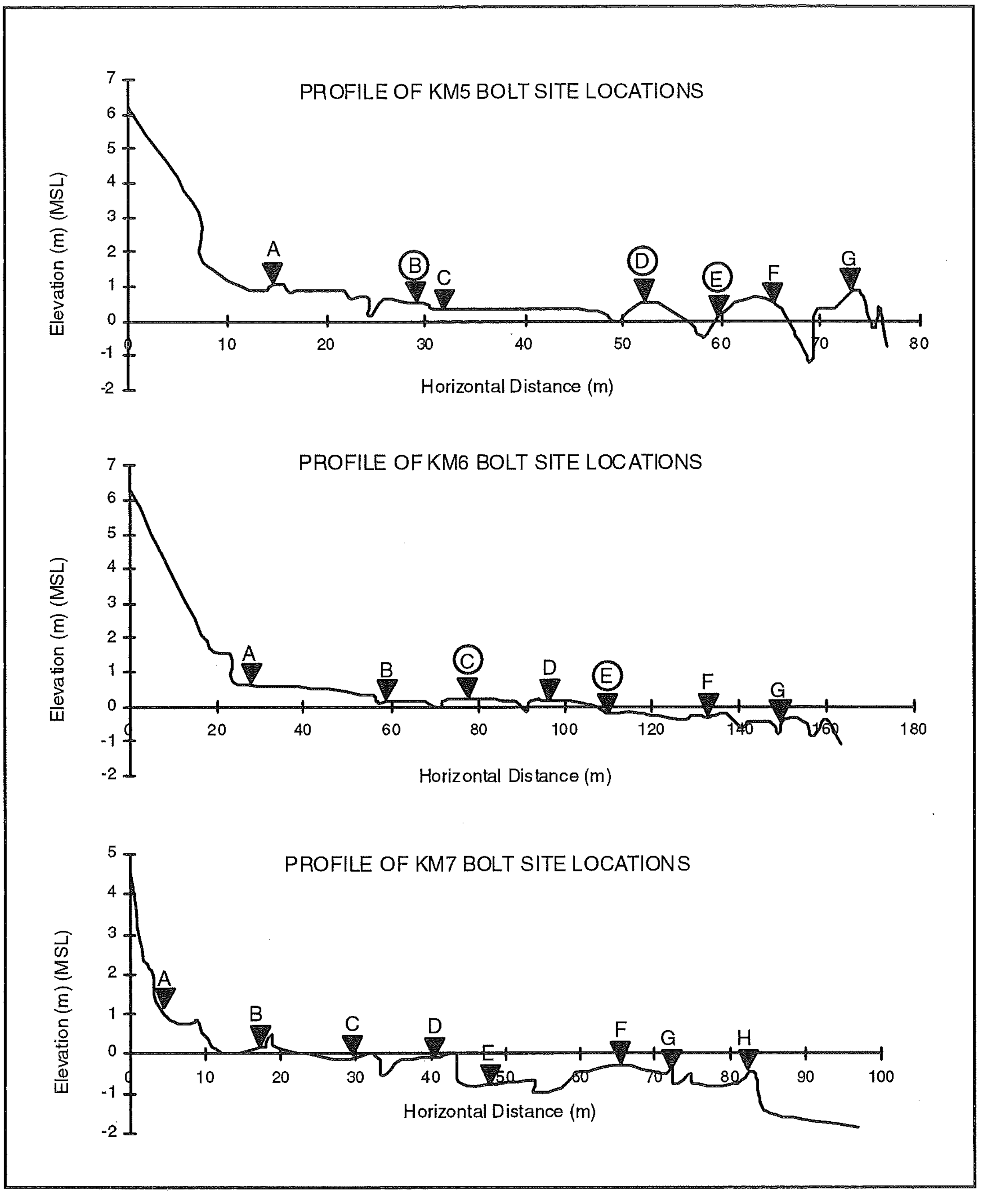

Figure 5.5 continued.

Another problem was that on occasions rough seas and high water levels prevented the more seaward bolts sites from being reached. This was a particular problem at KM4E. A further problem encountered was that, not all 120 readings could always be obtained from the traversing micro-erosion meter. In some instances the topography of the bolt site was such that the spindle of the gauge could not reach the surface or, the surface was too high, not allowing the spindle to travel at all. During the installation of some MEM sites, some bolts were set too deep into the rock surface and could not be read with the TMEM; to over come this another was constructed with longer legs. As a result, these sites were first measured in either March or April of 1994.

One problem that needed to be overcome before measurements on the old micro-erosion meter sites could continue was that the rates of surface lowering had been such in the interim that the original spindle of the dial gauge no longer reached the surface when the micro-erosion meter was placed on a bolt site. This problem was overcome by adding probe extensions to the original. These were purchased from an engineering tool supplier. It was necessary to add either a 25mm extension or one of two 12.5mm extensions or a combination of these. The length of whichever probe length was used was added to the recorded measurement.

An early result from measurements on micro-erosion bolt sites was that not all measurements indicated erosion at subsequent readings. It appeared as if the surface had "accreted". This phenomenon was attributed to swelling of the rock surface, as had been previously reported by Kirk (1977) and by Mottershead (1989). It became necessary to separate readings that indicated swelling from those that showed lowering, in order to calculate erosion rates and to examine the swelling phenomenon.

5.2.3 EROSION DATA

Tables 5.1 to 5.7 contain erosion data from shore platforms on the Kaikoura Peninsula. The values in these tables are average erosion, calculated from either the 120 readings taken on the TMEM or three readings in the case of the MEM at each bolt site. These average values were calculated after measurements showing swelling had been removed. The columns labelled "act" show the average erosion in millimetres since the previous measurement and the column labelled "total" contains the total erosion between the and the last measurements. The number of days between measurements is also given. Data are displayed in this form to illustrate the amount of erosion between measurement periods. It has been stated that the precision of the TMEM instrument was 0.001mm. The accuracy of the technique has not been assessed during this study but all results are reported to the same precision as the instrument. The largest total amount of erosion was on KM6A where 19.874mm was eroded. This was followed by KM2A where 13.036mm of erosion was measured during the study period. The smallest total amount of erosion was recorded on KM5C where 0.332mm of erosion was measured. Thus there is a wide range of values in erosion measured at Kaikoura. Figures 5.6 and 5.7 show frequency histograms of both actual and total erosion with distribution curves. Tables 5.8 and 5.9 contain summary statistics describing the data set.

Table 5.1 Average bolt site erosion between measurement periods and total erosion since first measurement (in millimetres) on KM1.

Date		KM1A		KM1B		KM1C		KM1D		KM1E		KM1F		KM1G	
	Days	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total
20/12/93 to 1/4/94	102	0.418	0.418	0.279	0.279	-	-	-	-	-	-	0.410	0.410	0.809	0.809
1/4/94 to 1/9/94	154	0.057	0.433	0.422	0.701	0.203	0.203	0.422	0.422	-	-	0.180	0.468	0.085	0.759
1/9/94 to 26/11/94	86	0.228	0.584	0.236	0.937	0.137	0.340	0.236	0.658	0.254	0.254	0.244	0.525	0.192	0.796
26/11/94 to 16/2/95	82	0.659	0.911	0.225	1.162	0.130	0.470	0.225	0.882	0.572	0.572	0.317	0.546	0.325	0.899
16/2/95 to 15/11/95	273	0.442	1.306	0.748	1.910	1.336	1.432	0.748	1.630	0.770	1.122	0.304	0.707	0.321	1.093
15/11/95 to 28/2/96	105	0.423	1.670	0.288	2.197	0.165	1.597	0.288	1.918	0.531	1.653	0.128	0.750	0.124	1.161

Table 5.2 Average bolt site erosion between measurement periods and total erosion since first measurement (in millimetres) on KM2.

Date		KM2 A		KM2 B		KM2 C		KM2 D		KM2 E		KM2 F		KM2 G		KM2 H		KM2I		KM2 J	
	Days	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total
22/12/93 to 1/4/94	102	-	-	0.715	0.715	-	-	0.609	0.609	-	-	-	-	-	-	-	-	-	-	0.290	
1/4/94 to 1/9/94	154	1.405	1.405	0.154	0.704	0.406	0.406	0.293	0.902	-	-	0.246	0.246	0.267	0.267	0.343	0.343	0.302	0.302	0.353	0.385
1/9/94 to 20/11/94	80	1.599	1.599	0.538	1.363	0.660	0.457	0.459	1.361	0.65	0.65	0.374	0.450	-	0.184	-	-	-	-	0.340	0.404
20/11/94 to 19/2/95	91	4.573	6.173	2.306	2.911	0.948	0.701	0.942	2.303	0.39	1.04	1.031	1.241	0.627	0.398	0.311	0.501	-	0.121	0.175	0.543
19/2/95 to 22/11/95	276	3.501	9.674	0.709	3.560	0.536	1.236	0.851	3.154	0.41	1.44	0.419	1.653	1.020	1.418	0.258	0.745	0.870	0.918	0.275	0.619
22/11/95 to 28/2/96	98	3.362	13.036	0.899	4.449	0.318	1.554	0.681	3.829	0.45	1.89	0.570	2.210	0.368	1.786	0.273	0.699	0.232	1.502	0.158	0.859

Table 5.3 Average bolt site erosion between measurement periods and total erosion since first measurement (in millimetres) on KM3.

		KM3 A		KM3 B		KM3 C		KM3 D		KM3 E		KM3 F		KM3 G		KM3 H		KM3I		KM3J	
Dates	Days	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total
21/12/93 to 31/3/94	96	0.835	0.835	0.573		0.464	0.464	0.542	0.542	-	-	0.612	-	-	-	-	-	-	-	0.146	-
31/3/94 to 30/8/94	152	0.302	1.010	0.581	0.540			-	-	0.681	0.681	0.194	0.678	0.584	0.584	0.213	0.213	1.503	1.503	0.105	0.179
30/8/94 to 21/11/94	83	0.498	1.466	0.667	0.835	0.313	0.684	0.369	0.777	-	-	0.502	0.921	0.460	0.416	0.385	0.511	-	-	0.176	0.211
21/11/94 to 20/2/95	92	1.220	2.652	0.876	0.835	0.352	0.622	0.285	0.880	0.226	0.741	-	-	1.287	1.240	0.153	0.605	*	0.578	0.232	0.321
20/2/95 to 23/11/95	277	0.747	3.385	0.728	1.936	0.265	0.742	0.296	1.011	0.352	0.974	0.382	1.214	0.438	1.679	0.382	0.987	0.633	0.988	0.346	0.567
23/11/95 to 27/2/96	99	0.637	3.981	0.656	2.371	0.234	0.840	0.236	1.186	0.099	0.978	0.162	1.357	0.155	1.833	0.106	1.049	0.445	1.433	0.082	0.622

Table 5.4 Average bolt site erosion between measurement periods and total erosion since first measurement (in millimetres) on KM4.

		KM4A		KM4B		KM4C		KM4D		KM4F		KM4G	
Dates	Days	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total
29/11/93 to 6/4/94	98	-	-	0.267	0.267	0.219	-	0.126	0.126	0.268	-	0.304	0.304
6/4/94 to 6/9/94	153	0.324	0.324	0.326	0.328	0.256	0.176	0.905	0.883	0.504	0.575	0.523	-
6/9/94 to 24/11/95	79	0.705	0.737	0.094	0.379	0.064	0.245	0.217	1.050	0.160	0.679	-	0.728
24/11/95 to 25/11/95	366	1.645	1.619	1.018	1.259	0.374	0.438	1.576	2.438	1.026	1.564	1.330	2.024

Table 5.5 Average bolt site erosion between measurement periods and total erosion since first measurement (in millimetres) on KM5.

		KM5A		KM5B		KM5C		KM5D		KM5E		KM5F		KM5G	
Dates	Days	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total
29/12/93 to 5/4/94	97	1.057	1.057	0.000	0.000	0.798	-	-	-	-	-	0.948	-	0.449	0.449
5/4/94 to 22/11/94	231	1.543	1.814	0.663	1.670	0.237	0.330	0.178	0.178	0.279	0.279	0.605	0.767	-	-
22/11/94 to 23/2/95	93	0.902	2.400	-	-	-	-	0.538	0.889	7.537	6.064	-	-	0.513	0.585
23/2/95 to 25/11/95	275	0.881	3.018	0.470	1.886	0.224	0.452	-	-	8.166	9.720	0.230	0.924	0.265	0.809
25/11/95 to 1/3/96	97	1.272	3.219	0.218	2.394	0.870	0.332	0.349	0.701	0.167	9.887	0.873	1.011	0.480	1.175

Table 5.6 Average bolt site erosion between measurement periods and total erosion since first measurement (in millimetres) on KM6.

		KM6A		KM6B		KM6C		KM6D		KM6E		KM6F		KM6G	
	Days	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total
28/12/93 to 4/4/94	97	3.598	-	-	-	-	-	-	-	-	-	-	-	-	-
4/4/94 to 25/11/94	234	3.039	6.637	-	-	-	-	0.536	0.536	0.444		0.609	-	-	-
4/4/94 to 25/2/95	326	-	-	0.887	-	-	-	-	-	-	-	-	-	-	-
25/11/94 to 25/2/95	92	4.987	11.624	-	-	0.923	0.923	0.796	1.088	0.716	0.070	-	-	-	-
25/11/94 to 26/2/96	458	-	-	-	-	-	-	-	-	-	-	1.373	1.538	-	-
25/2/95 to 26/2/96	366	8.250	19.874	1.056	1.832	1.869	2.792	1.079	2.125	1.204	1.682	-	-	0.380	0.380

Table 5.7 Average bolt site erosion between measurement periods and total erosion since first measurement (in millimetres) on KM7.

		KM7A		KM7B		KM7C		KM7D		KM7E		KM7F		KM7G		KM7H	
	DAYS	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total	Act	Total
22/12/93 to 4/4/94	154	-	-	0.559	0.559	0.338	0.338	-	-	0.282	0.282	-	-	-	-	-	-
4/4/94 to 5/9/94	79	0.507	0.507	0.207	0.651	-	-	-	-	-	-	0.118	0.118	0.276	0.276	0.144	0.144
4/4/94 to 23/11/94	233	-	-	-	-	0.364	0.416	0.396	0.396	-	-	-	-	-	-	-	-
5/9/94 to 23/11/94	92	0.806	1.275	0.609	1.025	-	-	-	-	-	-	0.197	0.296	0.319	0.428	0.145	0.218
23/11/94 to 26/11/95	368	2.555	3.368	1.362	2.182	0.348	0.359	0.716	0.880	-	-	0.826	1.099	0.743	1.070	0.570	0.747
26/11/95 to 2/3/96	97	-	-	1.046	2.970	0.871	0.400	1.423	0.955	-	-	0.752	1.082	0.979	1.606	0.804	0.844

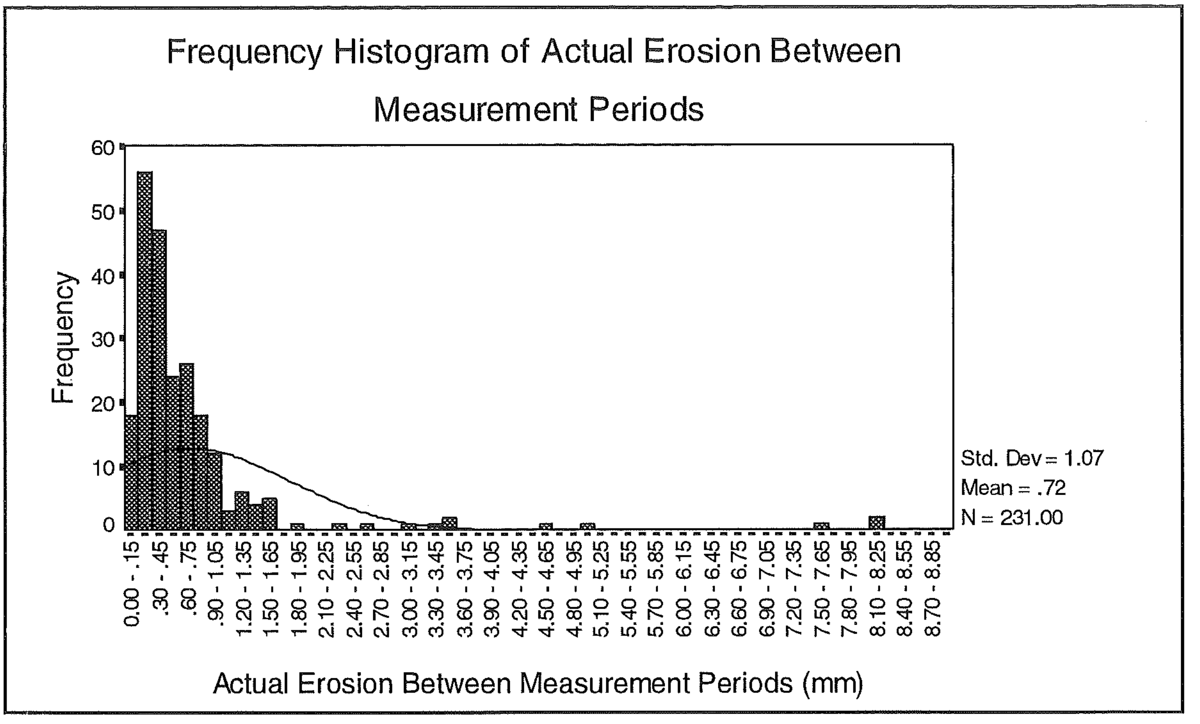

Figure 5.6 Frequency histogram of actual erosion between measurement periods for all bolt sites at Kaikoura.

Table 5.8 Summary statistics of actual erosion between measurement periods for all bolt sites at Kaikoura.

Summary Statistics					
Mean	0.726mm	Std err	0.071mm	Median	0.440mm
Mode	0.236mm	Std dev	1.071mm	Variance	1.148mm
Kurtosis	28.279	S E Kurt	0.320		
Skewness	4.899	S E Skew	0.160	Range	8.193mm
Maximum	8.250mm	Minimum	0.057mm	Sum	167.015

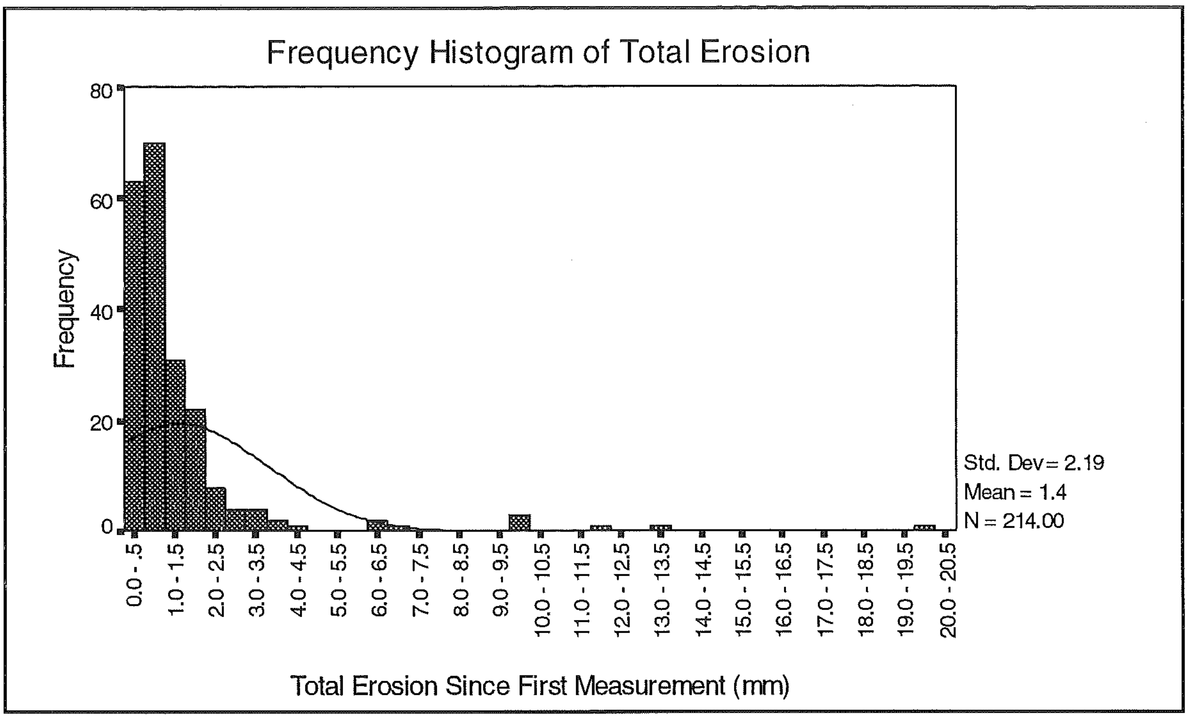

Figure 5.7 Frequency histogram of total erosion between the first and successive measurement periods for all bolt sites at Kaikoura.

Table 5.9 Summary statistics of total erosion between first and successive measurement periods for all bolt sites at Kaikoura.

Summary Statistics					
Mean	1.367mm	Std er	0.150mm	Median	0.787mm
Mode	0 .701mm	Std dev	2.190mm	Variance	4.798mm
Kurtosis	31.348	S E Kurt	0.331		
Skewness	5.029	S E Skew	0.166	Range	19.804mm
Maximum	19.874mm	Minimum	0.070mm	Sum	292.589

Tables 5.10 to 5.16 present inter-survey erosion rates as equivalent annual rates in mm/yr. Erosion data were converted to this form so that comparisons could be made between bolt sites, profiles, lithologies and measurement periods. These tables also contain the bolt site average, which is the equivalent mean annual erosion rate calculated from the total erosion over the total measurement period; not the average of all the inter-survey erosion rates.

Table 5.10 KM1 inter-survey erosion data (mm/yr).

Inter-survey Period	KM1 A	KM1 B	KM1 C*	KM1 D	KM1 E*	KM1 F	KM1 G
20/12/93 to 1/4/94	1.495	-	-	-	-	1.468	2.896
1/4/94 to 1/9/94	0.135	0.998	0.482	0.389	-	0.426	0.202
1/9/94 to 26/11/94	0.968	0.250	1.887	1.439	1.131	1.037	0.814
26/11/94 to 16/2/95	2.934	0.306	0.579	2.774	2.483	1.409	1.445
16/2/95 to 15/11/95	0.591	1.946	1.558	0.442	1.030	0.406	0.417
15/11/95 to 28/2/96	1.469	0.595	0.574	0.484	0.710	0.446	0.410
Bolt Site Average	0.760	0.246	0.833	0.484	1.109	0.341	0.525

* MEM bolt sites installed in 1973.

Table 5.11 KM2 inter-survey erosion data (mm/yr).

Inter-survey Period	KM2 A	KM2 B	KM2 C*	KM2 D	KM2 E*	KM2 F	KM2 G*	KM2 H	KM2 I*	KM2 J
22/11/93 to 1/4/94	-	2.558	-	2.973	-	-	-	-	-	1.037
1/4/94 to 1/9/94	1.405	0.487	0.962	1.384		1.122	0.948	0.814	0.715	0.837
1/9/94 to 20/11/94	7.297	2.453	3.013	2.573	1.893	-	-	-	-	1.549
20/11/94 to 19/2/95	18.344	9.392	3.803	3.930	2.819	-	6.011	-	3.489	0.703
19/2/95 to 22/11/95	4.630	1.019	0.706	1.122	0.449	2.659	1.344	0.414	0.920	1.102
22/11/95 to 28/2/96	12.523	3.316	1.171	2.577	1.444	8.150	1.358	1.008	0.855	0.581
Bolt Site Average	8.731	2.022	0.809	1.740	1.234	0.368	0.930	0.392	0.782	0.390

* MEM bolt sites installed in 1973.

Table 5.12 KM3 inter-survey erosion data (mm/yr).

Inter-survey Period	KM3 A	KM3 B	KM3 C	KM3 D	KM3 E	KM3 F	KM3 G*	KM3 H	KM3 I*	KM3 J
21/11/93 to 31/3/94	2.990	2.051	1.659	1.939	-	2.191	-	-	-	0.524
31/3/94 to 30/8/94	0.722	1.385	-	-	0.974	0.464	1.394	0.508	-	0.249
30/8/94 to 21/11/94	2.218	2.970	0.448	0.529	-	0.562	2.105	1.713	6.530	0.782
21/11/94 to 20/2/95	4.894	3.514	1.411	1.142	0.906	-	5.162	0.613	-	0.931
20/2/95 to 23/11/95	0.985	0.960	0.350	0.391	0.464	1.531	0.577	0.504	0.631	0.455
23/11/95 to 27/2/96	2.349	2.419	0.862	0.868	0.363	0.615	0.569	0.139	1.639	0.302
Bolt Site Average	1.810	1.078	0.372	0.538	0.645	0.522	0.956	0.533	0.829	0.283

* MEM bolt sites installed in 1973.

Table 5.13 KM4 inter-survey erosion data (mm/yr).

Inter-survey Period	KM4 A*	KM4 B	KM4 C	KM4 D	KM4 E	KM4 F	KM4 G
29-Dec-93 to 6-Apr-94	-	0.995	0.816	0.469	6.086	0.999	1.134
6-Apr-94 to 6-Sep-94	1.206	0.777	0.610	2.159	1.483	1.201	1.247
6-Sep-94 to 24-Nov-94	1.682	0.435	0.295	1.002	3.083	0.738	-
6-Sep-94 to 25-Nov-95	-	-	-	-	-	-	1.091
24-Nov-94 to 25-Nov-95	1.640	1.015	0.373	1.572	0.889	1.024	-
Bolt Site Average	1.274	0.660	0.230	1.278	1.050	0.820	1.062

* Three position MEM bolt sites.

Table 5.14 KM5 inter-survey erosion data (mm/yr).

Inter-survey Period	KM5 A	KM5 B*	KM5 C	KM5 D*	KM5 E*	KM5 F	KM5 G
29-Dec-93 to 5-Apr-94	3.979	-	3.004	-	-	0.682	1.688
5-Apr-94 to 22-Nov-94	2.438	-	0.374	0.281	0.415	0.682	-
22-Nov-94 to 23-Feb-95	3.539	2.600	-	-	11.240	-	-
23-Feb-95 to 25-Nov-95	1.169	0.624	-	0.533	5.419	-	0.267
25-Nov-95 to 1-Mar-96	4.786	0.820	3.274	1.314	0.629	3.283	1.807
Bolt Site Average	1.482	1.255	0.154	0.367	1.664	0.465	0.487

* MEM bolt sites installed in 1973.

Table 5.15 KM6 inter-survey erosion data (mm/yr).

Inter-survey Period	KM6 A	KM6 B	KM6 C*	KM6 D	KM6 E*	KM6 F	KM6 G
28-Dec-93 to 4-Apr-94	13.540	-	-	-	-	-	-
4-Apr-94 to 25-Nov-94	4.740	-	-	0.836	0.693	0.950	-
4-Apr-94 to 25- Feb-95	-	0.993	-	-	-	-	-
25-Nov-94 to 25-Feb-95	19.785	-	3.622	3.157	2.842	-	-
25-Nov-94 to 26-Feb-96	-	-		-	-	1.094	-
25-Feb-95 to 26-Feb-96	8.227	1.053	1.864	1.076	1.201	-	0.380
Bolt Site Average	9.194	0.660	2.7270	1.121	0.887	0.811	0.380

* MEM bolt sites installed in 1973.

Table 5.16 KM7 inter-survey erosion data (mm/yr).

Inter-survey Period	KM7 A	KM7 B	KM7 C	KM7 D	KM7 E	KM7 F	KM7 G	KM7 H
22/11/93 to 4/4/94	-	1.980	1.198	-	2.643	-	-	-
4/4/94 to 5/9/94	1.203	0.487	-	-	-	0.279	0.654	0.339
4/4/94 to 23/11/94	-	-	0.570	0.621	-	-	-	-
5/9/94 to 23/11/-94	3.724	2.416	-	-	-	0.783	1.267	0.576
23/11/94 to 26/11/95	2.535	1.351	0.345	0.712	-	0.822	0.739	0.567
26/11/95 to 2/3/96	-	3.938	3.277	5.356	-	2.830	3.686	3.025
Bolt Site Average	2.046	1.332	0.182	0.500	-	0.556	0.825	0.433

Tables 5.10 to 5.16 show a wide range of values for inter-survey mean annual erosion rates from 0.202mm/yr at KM1G (Table 5.10) to 19.785mm/yr at KM6A (Table 5.15). Average rates of erosion ranged from 0.154mm/yr at KM5C (Table 5.14) to 9.194mm/yr at KM6A (Table 5.15).

To better examine trends in erosion data from Tables 5.8 to 5.14, data for each profile have been plotted as bar graphs (Figures 5.8 to 5.15). The data are arranged according to measurement interval and bolt site. Intervals of data collection can be broadly separated into seasons, most often summer and winter, but spring is also covered for some profiles. The terms "winter" and "summer" are used generally to describe those months that the majority of the measurement interval covers. Summer and winter periods often included spring and autumn.

Figure 5.8 shows erosion results from KM1 plotted as equivalent annual erosion rates (mm/yr). There is a clear pattern of summer maximum in erosion rates, particularly for the period 26 November 1994 to 16 February 1995. The exception was KM1C where erosion was highest during spring and winter months. This pattern of maximum erosion was repeated for the first summer period, 20 December 1993 to 1 March 1994 when rates were higher than all winter months. Rates of erosion increased with the onset of spring. The spring period, 1 September 1994 to 26 November 1994, shown as brown bars in Figure 5.8, shows a marked increase in erosion on all bolt sites from the preceding winter period, 1 April 1994 to 1 September 1994. The over all winter-summer difference in erosion rates was not as well illustrated by the second winter-summer period in the record. Erosion rates during the winter period 16 February 1995 to 15 November 1995 exceeded rates during the summer period 15 November 1995 to 28 February 1996 on KM1C and KM1E and were very similar on sites KM1D, KM1F and KM1G. This may be because the measurement period also included spring and autumn months.

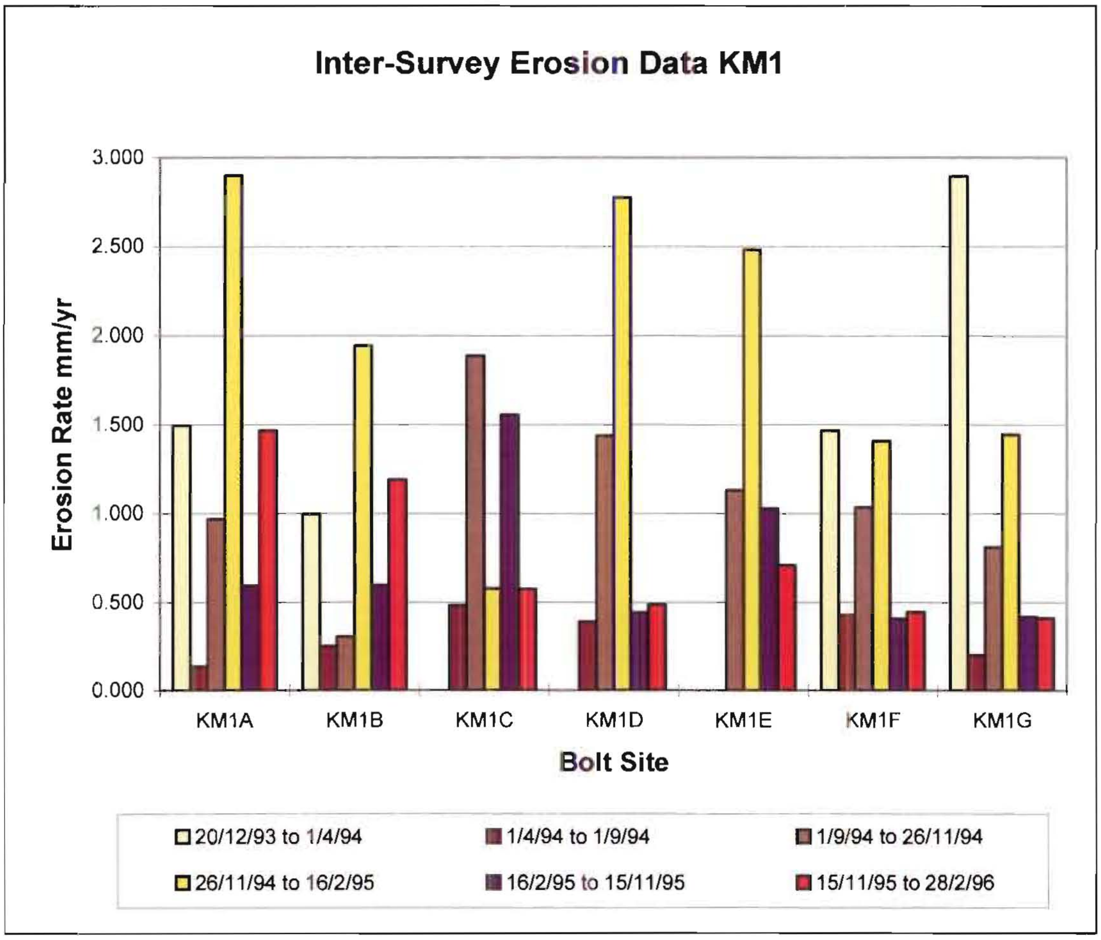

Figure 5.8 Mean annual erosion rates from inter-survey data for KM1.

Plotted inter-survey erosion data from KM2 are presented in Figure 5.9. As with KM1, seasonal variations are evident on KM2 with erosion rates higher during summer than winter. During the winter period 1 April 1994 to 1 September 1994, rates of erosion did not exceed 1.405mm/yr, but in the following summer period 20 November 1994 to 19 February 1995, rates were as high as 18.344mm/yr on KM2A and 9.392mm/yr on KM2B. One exception to this trend was on KM2J, where the winter erosion rate for the period 1 April 1994 to 1 September 1994 was 0.837mm/yr, and the summer period was 0.703mm/yr. The intervening spring period had the highest erosion rate on this bolt site of 1.549mm/yr. Seasonal differences continued into the next winter-summer period. During the winter months between 19 February 1995 and 22 November 1995 erosion rates were lower than for the preceding summer period, with the exception of KM2J. Erosion rates during this winter period were lower than the following summer period 22 November 1995 to 28 February 1996 on all bolt sites except KM2I and KM2J.

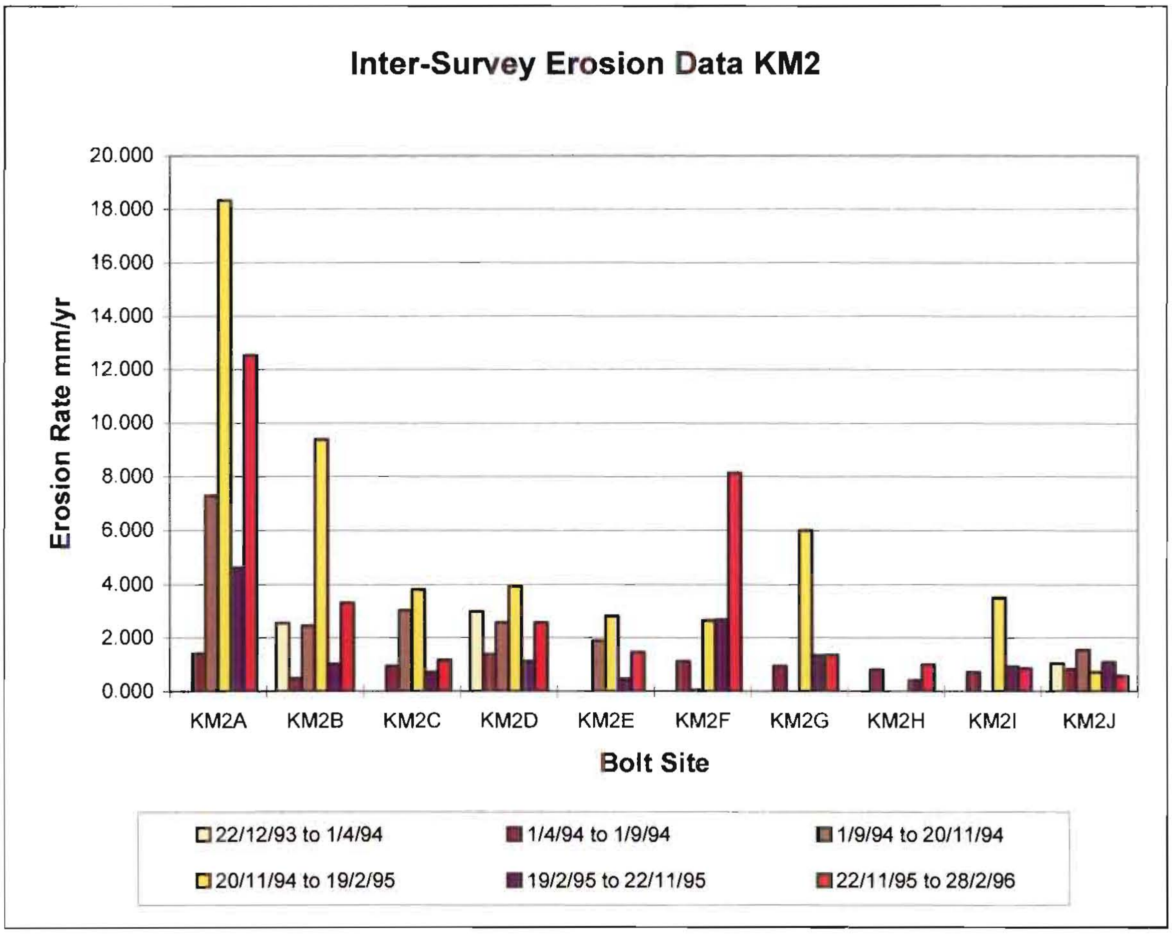

Figure 5.9 Mean annual erosion rates from inter-survey data for KM2.

Figure 5.10 illustrates inter-survey erosion data from profile KM3. While there were summer maxima in erosion rates on some bolt sites, this seasonal pattern was not consistent for all sites. On KM3A, KM3B, KM3C, and KM3D erosion rates were higher during the summer periods 21 December 1993 to 31 March 1994 and 21 November 1994 to 20 February 1995, than for the winter periods 31 March 1994 to 30 August 1994 and 20 February 1995 to 23 November 1995. Although on KM3C and KM3D data for the winter period 31 March 1994 to 30 August 1994 are missing, for the spring period 30 August 1994 to 21 November 1994 erosion rates were lower than for the following summer period. On KM3E erosion during the winter period 31 March 1994 to 30 August 1994 was 0.976mm/yr, while during the following summer it dropped slightly to 0.906mm/yr. However, this rate was higher than the 0.464mm/yr for the following winter period 20 February 1995 to 23 November 1995. On KM3F, KM3G, KM3H and KM3J erosion rates during the winter period 20 February 1995 to 23 November 1995 were higher than in the following summer period 23 November 1995 to 27 March 1996, but lower than in the preceding summer period 21 November 1994 to 20 February 1995.

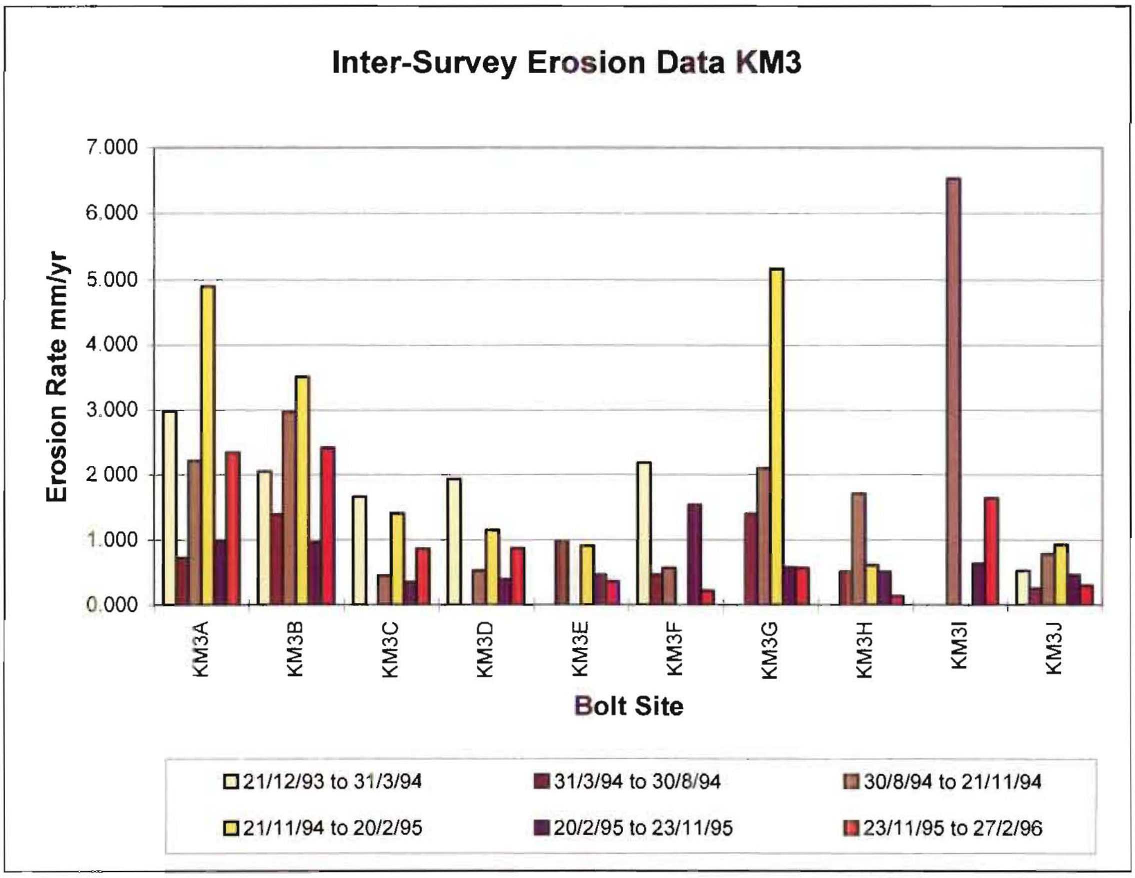

Figure 5.10 Mean annual erosion rates from inter-survey data from KM3

Inter-survey erosion data from KM4 are presented in Figure 5.11. The infrequency of measurements on this profile limits discussion of seasonal trends in erosion rates. There are enough data however to examine one summer, one winter and one spring period. On KM4B, KM4C and KM4E there was a summer (29 December 1993 to 6 April 1994) maximum in erosion rates, whereas on KM4D, KM4F and KM4G there was a winter (6 April 1994 to 6 September 1994) maximum in erosion rates. A clear seasonal pattern is less evident on this profile.

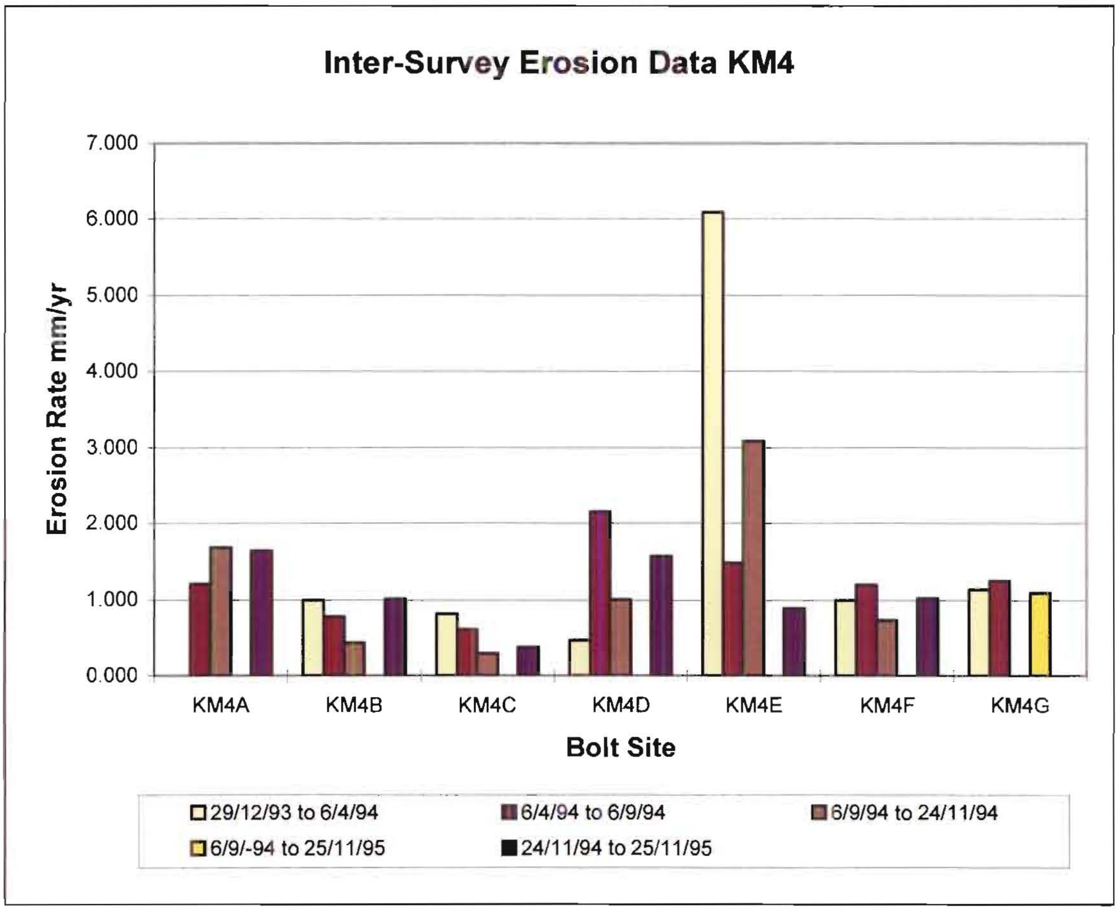

Figure 5.11 Mean annual erosion rates from inter-survey data for KM4.

As with KM4, erosion data for KM5 (Figure 5.12) are also lacking seasonal detail. However some seasonal pattern can be seen. On KM5A and KM5C higher erosion rates occurred during the summer period 29 December 1993 to 5 April 1994 compared with the following winter period 5 April 1994 to 22 November 1994. The same seasonal pattern can be seen again in the winter and summer periods 23 February 1995 to 25 November 1995, and 25 November 1995 to 1 March 1996, on bolt sites KM5A, KM5B, KM5D and KM5G.

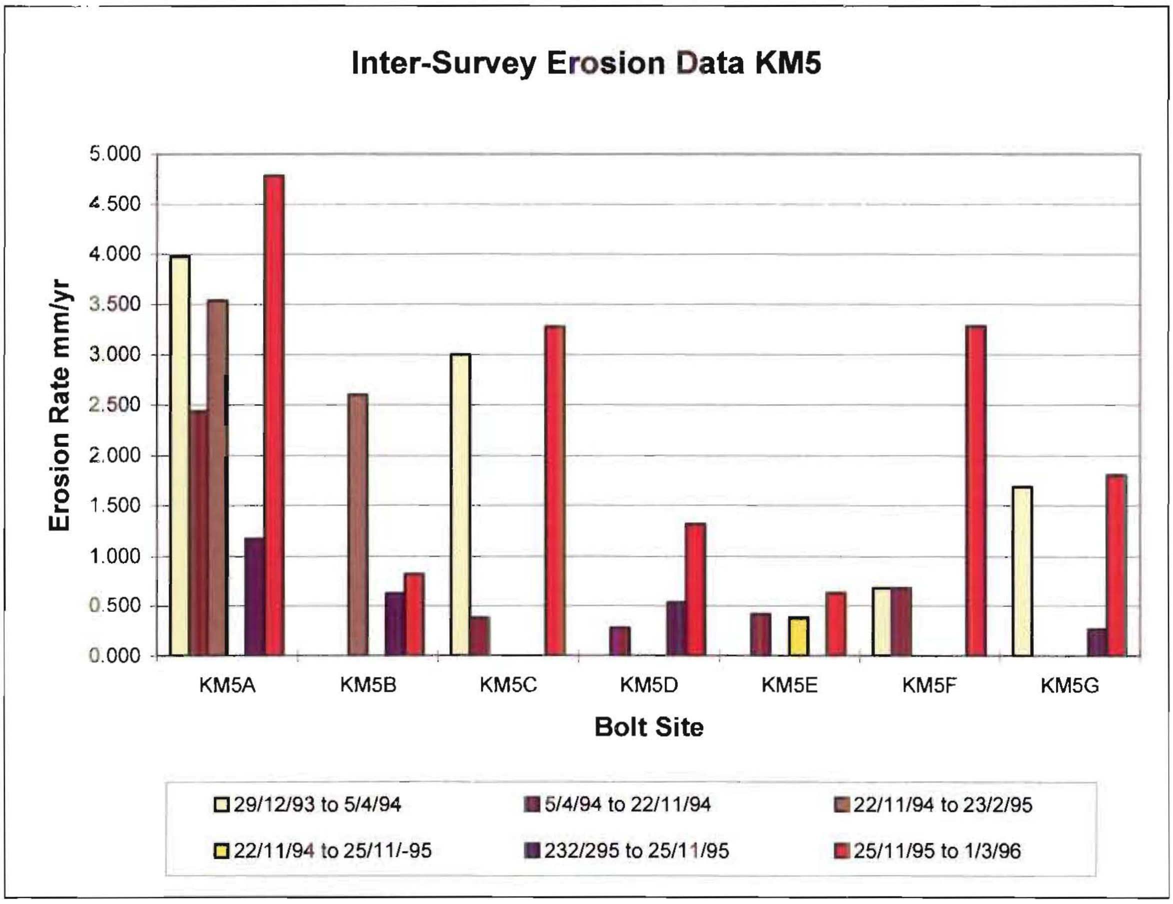

Figure 5.12 Mean annual erosion rates from inter-survey data for KM5.

The lack of data collected from KM6 (Figure 5.13) prevents consideration of seasonal variations in erosion rates. The exception was on KM6A the erosion rate was 13.540mm/yr during the summer period (28 December 1993 to 4 April 1994); significantly more than the 4.740mm/yr measured during the winter period (4 April 1994 to 25 November 1995).

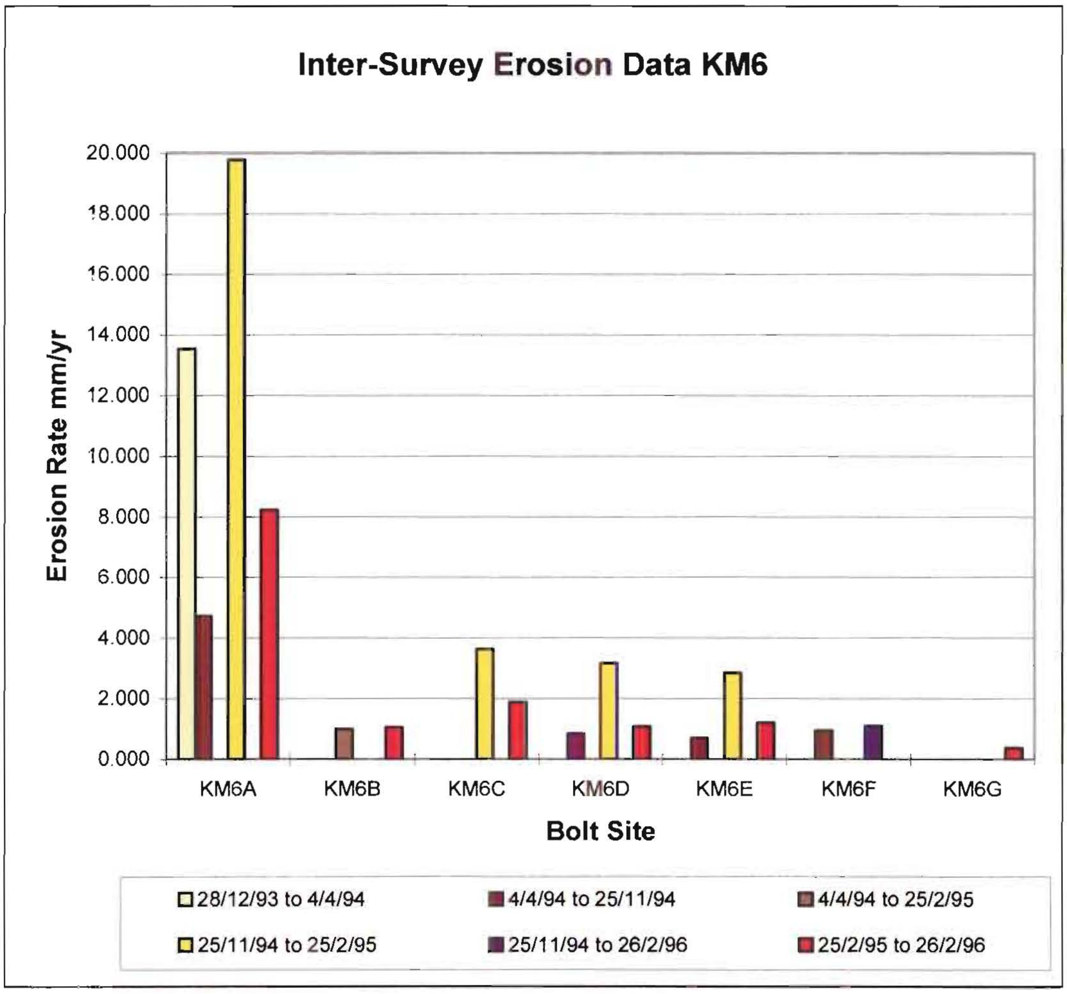

Figure 5.13 Mean annual erosion rates from inter-survey data for KM6.

Inter-survey erosion data from KM7 are presented in Figure 5.14. It is not possible to see detailed seasonal patterns because measurement periods were not frequent enough. The point can be made that high erosion rates did occur during the summer period (26 November 1995 to 2 March 1996) relative to the year between 23 November 1994 and 26 November 1995.

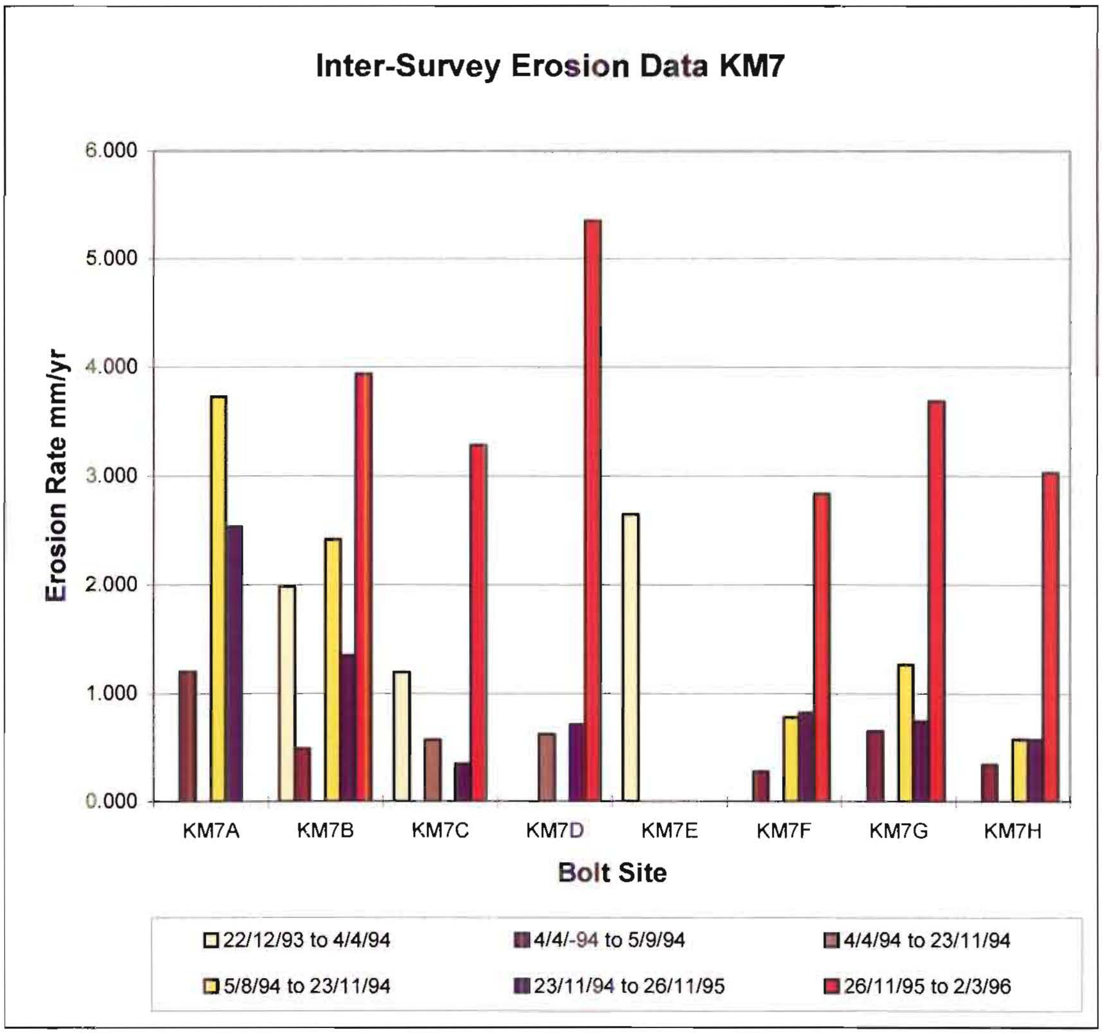

Figure 5.14 Mean annual erosion rates from inter-survey data for KM7.

The finding that erosion rates were higher during summer and spring months suggests that there is a seasonal control on erosion rates. Other studies have also suggested this. Robinson (1977b) found that erosion at the cliff foot was higher in winter. It was suggested that this was because storms were more frequent in winter, while weathering processes such as wetting and drying are more common in summer months. Mottershead (1989) found erosion rates were highest during summer months and were positively correlated with monthly average air temperature.

It might be expected that during summer, wetting and drying is more common at Kaikoura. If this is the case then the data indicate that subaerial weathering is an important erosion process on the shore platforms of the Kaikoura Peninsula. Further investigation of possible relationships between erosion rates and season is required for such a conclusion to be sustained. Such an analysis is presented later in this chapter after consideration of swelling data in Section 5.25.

SUMMARY DATA

Table 5.17 presents a summary of the micro-erosion data collected from Kaikoura. It is arranged so as to show an equivalent mean annual erosion rate (mm/yr) for each profile. Values have been arrived at by averaging the mean annual erosion rate from each bolt site on that profile. Data in Table 5.17 are also separated to show differences between platform type and lithology.

Table 5.17 Summary erosion data from the Kaikoura Peninsula.

Platform Type	Profile	Equivalent Mean Annual Erosion Rate mm/yr
Type B	KM1	0.614
Type A	KM2	1.740
Type B	KM3	0.747
Type A*	KM4	0.910
Type B	KM5	0.839
Type A	KM6	2.226
Type A*	KM7	0.839
Grand Mean		1.130
Mudstone		1.233
Limestone* (Type A)		0.875
Type A	Mudstone	1.983
Type A	Limestone and mudstone	1.428
Type B	Mudstone	0.733

Kirk (1977) reported a grand mean for surface lowering from the Kaikoura Peninsula of 1.53mm/yr and 1.43mm/yr was reported by Stephenson and Kirk (1996). The grand mean erosion rate for the Kaikoura Peninsula has been calculated to be 1.130mm/yr, from Table 5.17. One possible reason for this lower rate is the higher number of bolt sites on limestone platforms used for this study compared with Kirk (1977) and Stephenson and Kirk (1996). There appears to be a clear difference in erosion rates between lithologies, with mudstone platforms eroding at a rate of 1.233mm/yr, compared with limestone platforms eroding at 0.875mm/yr. A Students *t*-test was used to establish if the observed difference was significant. The *t*-statistic = 0.405 with 54 degrees of freedom and *t* critical = 1.673; therefore H_o cannot be rejected and differences in erosion rates may not be as a result of differences in lithology.

Table 5.17 indicates that there are differences between Type A and B shore platform erosion rates. Type A shore platforms in mudstone eroded at a rate of 1.983mm/yr, compared with 0.733mm/yr on Type B platforms. Even when limestone and mudstone Type A platforms are grouped together, the erosion rate of 1.428 is still higher than for Type B platforms. Again, a Student's *t*-test was used to discover if this difference was significant. The *t*-statistic = -2.703 with 114 degrees of freedom and the critical value of t = 1.684, therefore H_o cannot be rejected and differences in erosion rates between Type A and B platforms are not statistically significant. The result that there is not a significant difference may be as a result of the non-normal distribution of the erosion data. A normal distribution is a requirement of the student *t*-test, although the test is tolerant of some skewness (Shaw and Wheeler 1985). While no statistically significant difference between platform types and lithologies was found, it is argued that Type A platforms erode faster than Type B platforms.

Kirk's (1977) results showed that mudstone platform erosion rates were higher (1.21mm/yr) than limestone platforms (0.69mm/yr) based on erosion rates although no statistical test for significance was performed. Despite absolute differences in erosion rates, all results are within the same order of magnitude as those reported by Kirk (1977) and Stephenson and Kirk (1996) for the Kaikoura Peninsula, and by other studies from around the world. The difference in erosion rates between Type A and B platforms has an important implication for Tsujimoto's (1987) demarcation of Type A and B shore platforms. He assumed that on Type B platforms there was no surface lowering. Clearly from the above results there is. In support of Tsujimoto (1987), rates of surface lowering are an order of magnitude lower on Type B platforms compared with Type A. Differences in erosion rates between Type A and B platforms are likely to be as a result of differences in compressive strengths shown in Chapter Four. Softer Type A platforms clearly erode faster than Type B platforms. These data seem to support the proposition made in Chapter Four that compressive strength controls the outline shape of the Kaikoura Peninsula, because Type A platforms erode faster than Type B.

5.2.4 CROSS-SHORE VARIATIONS IN EROSION

It will be recalled from Chapter Two that Kirk (1977) found erosion rates were higher on the inner and outer margins of shore platforms at Kaikoura and from this proposed that weathering and marine processes operated zonally across the platform profile. To test this, the erosion rates contained in Tables 5.10 to 5.16 were normalised using the equation:

$$B_Z = \frac{(B_T - B_{\overline{X}})}{\overline{X}} \qquad \textbf{5.1}$$

where:

B_Z = normalised erosion rate (dimensionless)

B_T = the equivalent annual erosion rate of an individual bolt site

$B_{\overline{X}}$ = mean erosion rate for profile all bolt sites on a given profile

Note: $\overline{X}$ varies from profile to profile.

Normalised data allow comparison between bolt sites across a given profile. Each profile is treated individually and B_Z is calculated for each bolt site on a profile. Negative values denote erosion rates less than the mean for the profile while positive values indicate erosion rates greater than the mean. Kirk (1977) proposed the hypothesis that shore platforms develop as a result of marine processes eroding the seaward edge with a transition to subaerial weathering on the landward side. If this is correct then high erosion rates on the seaward and landward margins would be expected. In Figures 5.15 to 5.21 the expectation would be to see positive values on the inner bolt sites such as A and B and the outer sites G, H, and J depending on which profile is being considered. Clearly from Figures 5.15 to 5.21, this pattern does not exist. There is no clear pattern in cross shore variations of erosion rates. No two profiles show the same pattern. Given the range of exposures, orientations, and different lithologies, then a lack of clear pattern is not unexpected. However, some pattern can be discerned when regression trend lines are fitted to each graph. On profiles KM2, KM3, KM5, KM6, and KM7 the trend lines suggest that there is a general pattern of decreasing erosion rates in a seaward direction. Profiles KM1 and KM4 show the trend in the opposite direction, but the gradients of both lines are low compared with the other profiles, suggesting the relationship is weaker. These data then do not support the hypothesis proposed by Kirk (1977). The general pattern that is evident in Figures 5.15 to 5.21 is that erosion rates are higher on the inner landward bolt sites and decrease in a seaward direction. An explanation for this pattern is not yet available but since erosion is a response to processes operating on shore platforms then further explanation may be possible after the examination of erosional processes presented in Chapter Six.

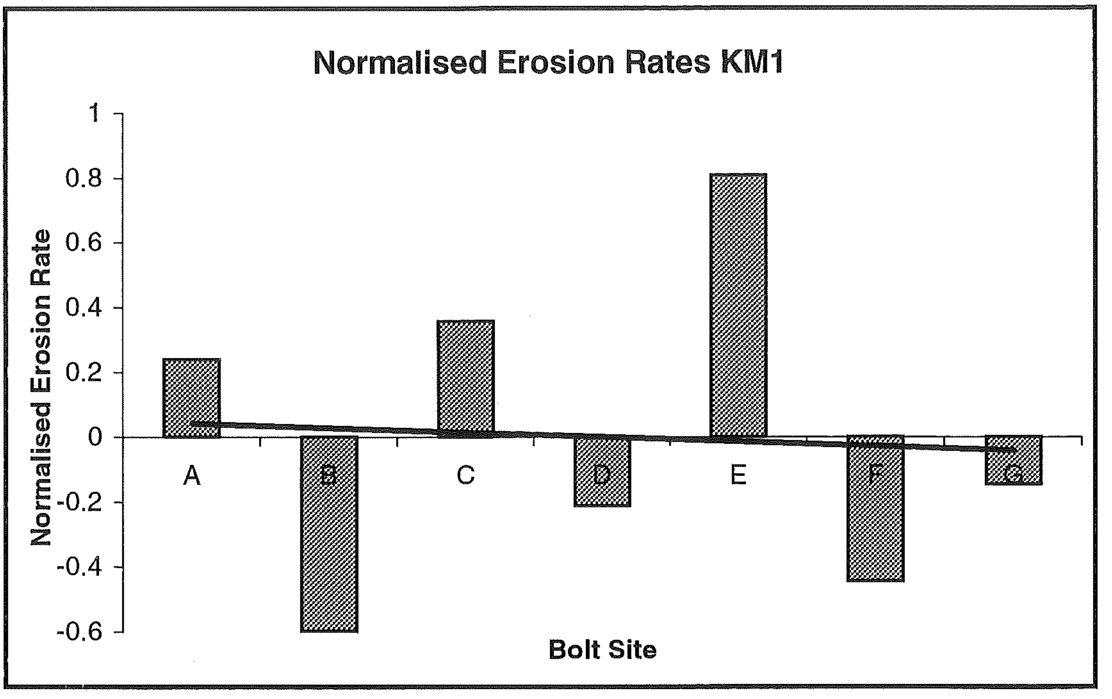

Figure 5.15 Normalised erosion rates for KM1 and trend line.

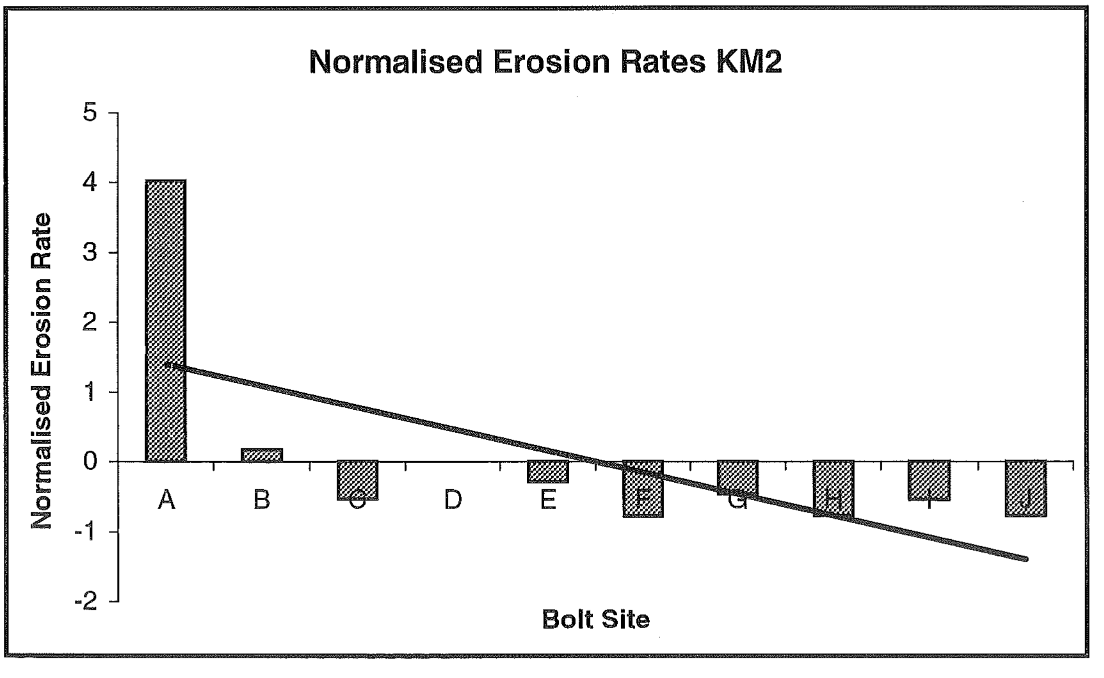

Figure 5.16 Normalised erosion rates for KM2 and trend line.

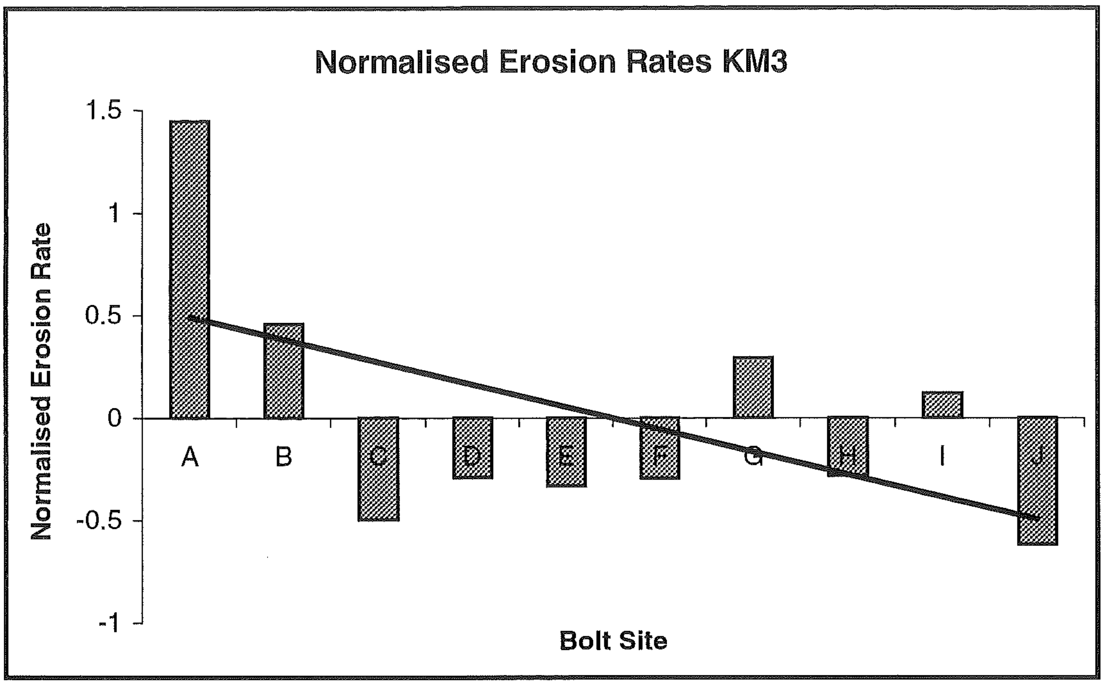

Figure 5.17 Normalised erosion rates for KM3 and trend line.

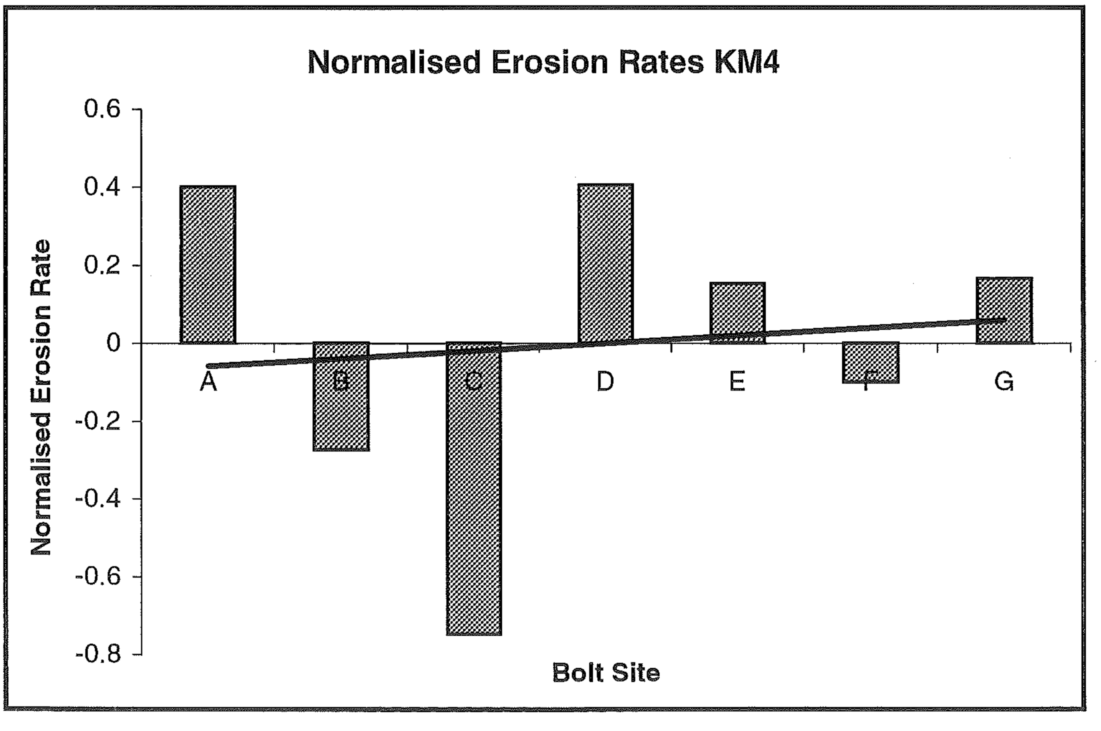

Figure 5.18 Normalised erosion rates for KM4 and trend line.

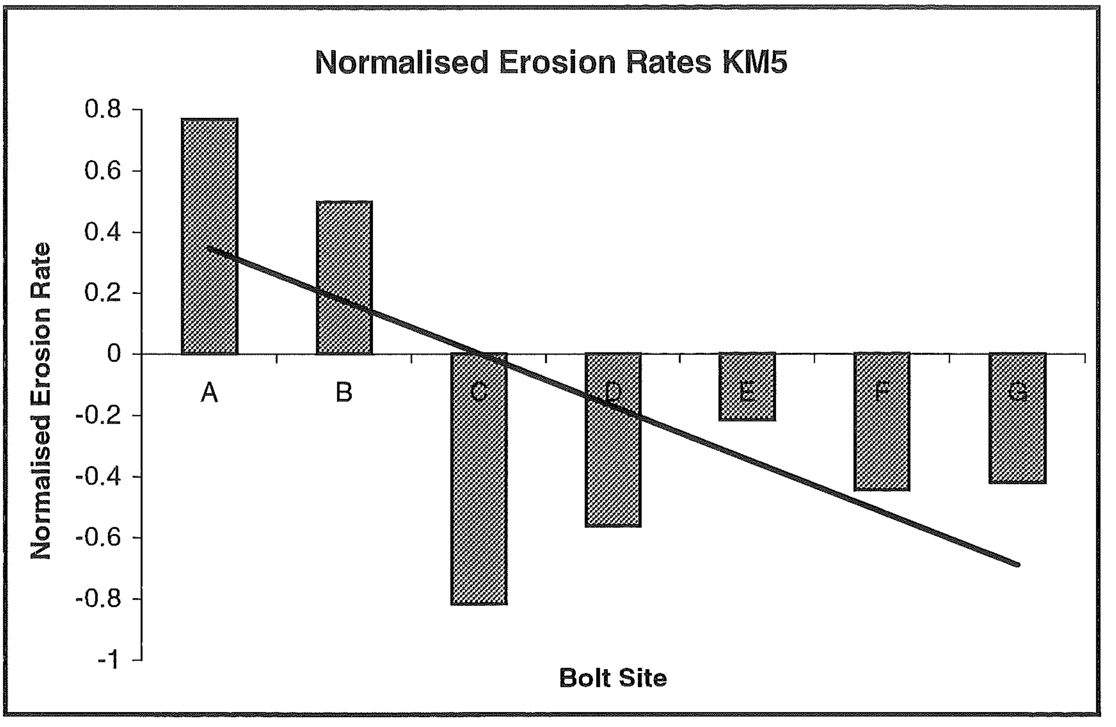

Figure 5.19 Normalised erosion rates for KM5 and trend line.

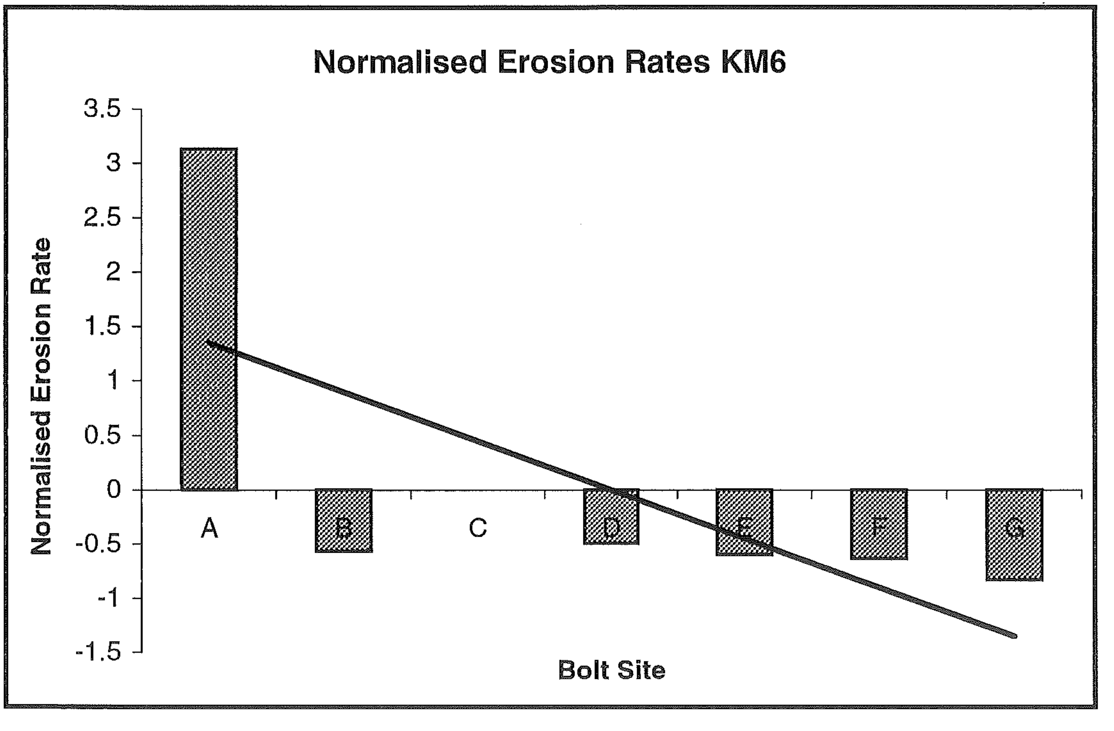

Figure 5.20 Normalised erosion rates for KM6 and trend line.

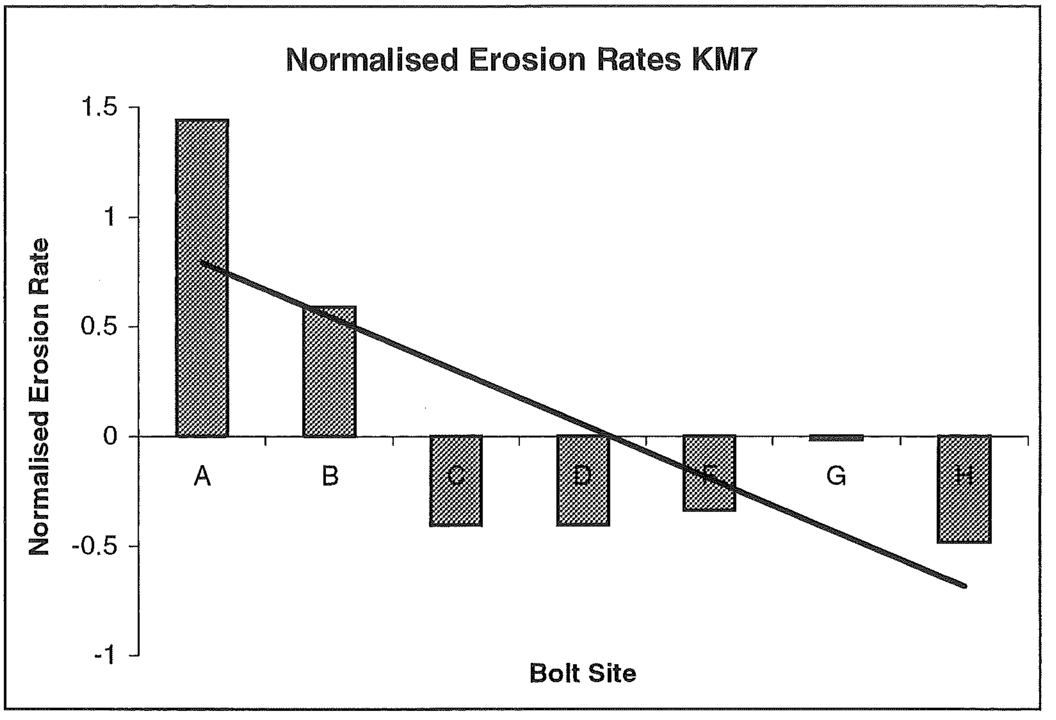

Figure 5.21 Normalised erosion rates for KM7 and trend line.

5.2.5 SURFACE SWELLING

Results from TMEM and MEM readings did not always show surface lowering; results often indicated that the surfaces had risen. Initially, operator error was suspected. However despite careful attention during measurements, instances of the surface swelling continued. This phenomenon was reported by Kirk (1977) and Mottershead (1989). The term "swelling" is used to describe measurements that show the elevation of a point on a bolt site surface has increased relative to the previous reading. The term has no genetic implication. Kirk (1977) observed surface swelling of up to 3.0mm. He attributed the cause of this to the growth of algae on some sites and the expansion of mudstone when wetted. Mottershead (1989) observed swelling on supra-tidal greenshists on the Start-Prawl Peninsula in south Devon, England. He summarised the main features of the phenomenon as follows (Mottershead 1989:393):

1. There was a peak frequency in the occurrence in spring (April and May), with 7 of 12 measurement points recording swelling. There was no clear seasonal pattern in respect of summer and winter.
2. There was no correspondence between frequency and moisture state of the surface.
3. Fifty five per cent of swelling measurements (n = 45) were greater than 0.01mm.

4. Of swelling cases above the initial base, the duration of 11 of the 25 swelling events was longer than two months and one was in excess of 12 months.
5. The magnitude of the swelling was commonly in the range of 0.03 to 0.05mm and occasionally greater than 0.1mm.
6. The values for duration and magnitude were minimum values since several occur in the first or last readings and may represent swellings that began prior to or terminated subsequent to the monthly readings. Seasonal data showed a maximum but incomplete duration of 48 months with a maximum elevation of 0.266m. The longest completed swelling identifiable lasted 16 months and had an elevation of 0.382mm.

Point six illustrates that the swelling phenomenon did not appear to have an identifiable end and sequence. This was because sampling was not frequent enough over a long enough time period to identify what could be called a swelling "event". Mottershead did not use the term "event" but it will be used here. The term "event" is used to describe when a surface point is above the previous measured elevation and is lower at the next reading. An "event" occurs when the point does not stay elevated.

Mottershead (1989) did not find any statistical correlation between the occurrence of swelling and a number of climatic variables which included daily mean temperature, daily maximum temperature, daily minimum temperature, monthly total of negative grass minimum temperature, monthly total precipitation and monthly total run of wind. He considered that swelling was consistent with rock bursting by salt weathering, but the most suitable climate for this is in summer and there was no seasonal pattern in swelling events. Since surface lowering was generally low in winter months Mottershead proposed that surface swelling stood out in the data, while in summer when surface lowering rates were high, swelling was not as easily detected. He concluded that the nature of the field observation underestimated summer surface swelling and that surface swelling was consistent with rock bursting by halocasty (Mottershead 1989).

Measured instances of surface swelling on traversing micro-erosion meter bolt sites at Kaikoura are presented in Tables 5.18 to 5.24. These tables include mean, maximum and minimum values for each bolt site between observation periods. Also included is the percentage of the total readings taken that recorded swelling. This provides a measure of the amount of swelling relative to erosion. A zero in Tables 5.18 to 5.24 indicates no swelling and a blank space indicates no reading. Table 5.18 presents swelling data for profile KM1. Mean values for surface swelling ranged from 0.028 to 2.219mm, maximum values ranged from 0.055 to 6.741mm and minimum values ranged from 0.005 to 0.933mm. The percentage of total readings that recorded surface swelling ranged from 0.8 to 57.5 per cent. In the period 26 November 1994 to 16 February 1995 there were no recorded swelling events at KM1A and similarly, from 16 February 1995 to 15 November 1995 at sites KM1B, KM1D and KM1G no swelling events were noted.

Swelling data from KM2 are presented in Table 5.19. Here there are some important differences from KM1 data. In particular those swelling events that were recorded from more than 50 per cent of bolt site surfaces occurred in the winter period (1 April 1994 to 1 September 1994) on sites KM2B, KM2F and KM2J. During this period swelling on KM2D was recorded in 43.3 per cent of readings. There appears to be a clear reduction in swelling events during summer on KM2. The mean values for swelling ranged from 0.071 to 2.600mm, while minimum vales ranged from 0.003 to 1.284mm, and maximum values ranged from 0.143 to 5.862mm. The percentage of readings that recorded surface swelling ranged from as low as 0.8 (1 position) to 73.3 per cent. No swelling was recorded at all on KM2A. This is probably because the erosion rate was so high (8.731mm/yr) and the inter-survey period too long to be able to detect swelling if it occurred at all.

Table 5.20 contains swelling data from KM3. Mean swelling values ranged from 0.019 to 1.183mm, minimum vales from 0.003 to 0.1574mm, and maximum values from 0.061 to 4.530mm. The percentage of surface swelling readings ranged from as low as 0.8 (1 position) to 86.3 per cent (107 positions). During the summer period 21 December 1993 to 31 March 1994 the percentage of readings where surface swelling was recorded was high relative to the rest of the data set for KM3. The occurrence of surface swelling during the following winter period 30 August 1994 to 21 November 1994 was significantly lower with no more than 12.5 per cent of any one site recording swelling. Contrary to this apparent summer-winter pattern, the percentage of surface swelling readings during the next summer period (21 November 1994 to 20 February 1995) was low, ranging from 0.8 to 5.8 per cent (7 readings). Very few instances of surface swelling were also noted during the winter period 20 February 1995 to 23 November 1995 when only two sites showed any swelling.

Swelling data from KM4 are presented in Table 5.21. The mean values ranged from 0.18 to 3.244mm, minimum values ranged from 0.005 to 0.111mm and maximum values from 0.28 to 8.882mm. The frequency of surface swelling ranged from 0.8 to 75 per cent. Again there was a significant seasonal difference in the occurrence of surface swelling. During the summer period (29 December 1993 to 6 April 1994) surface swelling was recorded on all bolt sites and ranged from 23.3 per cent of the surface on KM4G to 75 per cent on KM4B. These percentages dropped dramatically during the next winter season, (6 April 1994 to 6 September 1994).

Table 5.22 presents swelling data from KM5. The mean values for swelling ranged from 0.072 to 1.891mm, minimum vales ranged from 0.007 to 0.058mm, and maximum values ranged from 0.072 to 5.517mm. The frequency of recorded surface swelling ranged from 0.8 to 92.5 per cent which is the highest value in the entire data set. It represents a total of 111 recorded swelling measurements out of 120. Recorded swelling again was more prevalent in summer particularly in the period 29 December 1993 to 5 April 1994, compared with the winter period (23 February 1995 to 25 November 1995).

The lack of data from KM6 (Table 5.23) prevents seasonal comparisons though some points regarding recorded values can still be made. Mean values for swelling ranged from 0.044 to 1.036mm, minimum vales ranged from 0.009 to 0.305mm, maximum values ranged from 0.044 to 1.1678mm. The percentage of surface swelling ranged from 1.1 per cent to 87.5 per cent. As with KM2A, no swelling was recorded on KM6A. Given that the erosion rate on this site was 9.194mm/yr it seems unlikely that surface swelling occurred.

Table 5.24 contains swelling data from KM7. Mean values for swelling ranged from 0.034 to 3.108mm, minimum vales from 0.005 to 0.143mm, and maximum values from 0.055 to 6.152mm. The percentage of recorded surface swelling ranged from 0.8 to 74.2 per cent. There was a summer peak in the occurrence of surface swelling events especially during the summer period 26 November 1995 to 2 March 1996. During the winter period (4 April 1994 to 5 September 1994) swelling was much less evident.

Table 5.18 Surface swelling data from KM1 (mm).

Mean	KM1A	KM1B	KM1D	KM1F	KM1G
20-Dec-93 to 1-Apr-94	0.608	0.310	-	0.503	0.605
1-Apr-94 to 1-Sep-94	0.027	0.085	0.554	0.042	0.187
1-Sep-94 to 26-Nov-94	1.291	2.219	0.639	0.456	0.084
26-Nov-94 to 16-Feb-95	0.000	0.971	0.219	0.168	0.315
16-Feb-95 to 15-Nov-95	0.056	0.000	0.000	0.933	0.000
15-Nov-95 to 28-Feb-96	1.016	0.228	0.544	0.789	0.028
Maximum	KM1A	KM1B	KM1D	KM1F	KM1G
20-Dec-93 to 1-Apr-94	2.891	1.422	-	2.577	2.240
1-Apr-94 to 1-Sep-94	0.098	0.140	1.446	0.125	2.537
1-Sep-94 to 26-Nov-94	3.659	6.741	4.173	3.557	0.207
26-Nov-94 to 16-Feb-95	0.000	2.272	0.756	1.097	0.670
16-Feb-95 to 15-Nov-95	0.098	0.000	0.000	0.933	0.000
15-Nov-95 to 28-Feb-96	1.995	4.820	0.544	3.826	0.055
Minimum	KM1A	KM1B	KM1D	KM1F	KM1G
20-Dec-93 to 1-Apr-94	0.066	0.009	-	0.013	0.029
1-Apr-94 to 1-Sep-94	0.006	0.030	0.036	0.023	0.005
1-Sep-94 to 26-Nov-94	0.006	0.072	0.007	0.017	0.012
26-Nov-94 to 16-Feb-95	0.000	0.007	0.007	0.005	0.009
16-Feb-95 to 15-Nov-95	0.013	0.000	0.000	0.933	0.000
15-Nov-95 to 28-Feb-96	0.008	0.010	0.544	0.005	0.007
Percentage	KM1A	KM1B	KM1D	KM1F	KM1G
20-Dec-93 to 1-Apr-94	27.5	60.0	-	53.3	53.3
1-Apr-94 to 1-Sep-94	10.0	2.5	4.2	3.3	15.8
1-Sep-94 to 26-Nov-94	21.7	15.0	29.2	28.3	20.0
26-Nov-94 to 16-Feb-95	0.0	4.2	57.5	40.0	3.3
16-Feb-95 to 15-Nov-95	2.5	0.0	0.0	0.8	0.0
15-Nov-95 to 28-Feb-96	10.0	91.7	0.8	19.2	6.7

Table 5.19 Surface swelling data from KM2 (mm).

Mean	KM2A	KM2B	KM2D	KM2F	KM2H	KM2J
22-Dec-93 to 1-Apr-94	0.000	0.171	0.397	-	-	0.476
1-Apr-94 to1-Sep-94	0.000	0.091	0.087	0.090	0.469	0.070
1-Sep-94 to 20-Nov-94	0.000	0.676	2.600	1.452	0.178	1.106
20-Nov-94 to 19-Feb-95	0.000	0.000	1.291	1.396	0.071	0.142
19-Feb-95 to 22-Nov-95	0.000	0.111	0.000	0.000	0.000	0.000
22-Nov-95 to 28-Feb-96	0.000	0.000	0.358	1.209	0.319	0.000
Minimum	**KM2A**	**KM2B**	**KM2D**	**KM2F**	**KM2H**	**KM2J**
22-Dec-93 to1-Apr-94	0.000	0.021	0.035	-	-	0.004
1-Apr-94 to1-Sep-94	0.000	0.005	0.003	0.003	0.071	0.005
1-Sep-94 to 20-Nov-94	0.000	0.057	0.264	0.260	0.020	0.741
20-Nov-94 to 19-Feb-95	0.000	0.000	0.767	1.284	0.007	0.036
19-Feb-95 to 22-Nov-95	0.000	0.011	0.000	0.000	0.000	0.000
22-Nov-95 to 28-Feb-96	0.000	0.000	0.096	0.007	0.224	0.000
Maximum	**KM2A**	**KM2B**	**KM2D**	**KM2F**	**KM2H**	**KM2J**
22-Dec-93 to1-Apr-94	0.000	0.319	1.700	-	-	1.455
1-Apr-94 to1-Sep-94	0.000	0.203	0.220	0.522	0.830	0.162
1-Sep-94 to 20-Nov-94	0.000	1.243	5.862	4.379	0.534	1.820
20-Nov-94 to 19-Feb-95	0.000	0.000	1.815	1.508	0.143	0.588
19-Feb-95 to 22-Nov-95	0.000	0.242	0.000	0.000	0.000	0.000
22-Nov-95 to 28-Feb-96	0.000	0.000	0.621	3.582	0.504	0.000
Percentage	**KM2A**	**KM2B**	**KM2D**	**KM2F**	**KM2H**	**KM2J**
22-Dec-93 to1-Apr-94	0	5.0	17.5	-	-	2.5
1-Apr-94 to1-Sep-94	0	55.8	43.3	60.0	2.5	73.3
1-Sep-94 to 20-Nov-94	0	9.2	3.0	9.2	24.2	2.5
20-Nov-94 to 19-Feb-95	0	0	1.6	1.7	2.5	7.5
19-Feb-95 to 22-Nov-95	0	2.5	0	0.8	0	0.8
22-Nov-95 to 28-Feb-96	0	0	1.6	2.5	3.3	0

5.20 Surface swelling data from KM3 (mm).

Mean	KM3A	KM3B	KM3C	KM3D	KM3F	KM3H	KM3J
21-Dec-93 to 31-Mar-94	0.321	0.388	0.531	0.590	-	-	0.332
31-Mar-94 to 30-Aug-94	0.067	0.566	-	-	0.071	0.220	0.023
30-Aug-94 to 21-Nov-94	0.045	0.282	0.153	0.413		0.336	0.532
21-Nov-94 to 20-Feb-95	0.010	0.034	0.993	0.217	0.157	1.183	0.019
20-Feb-95 to 23-Nov-95	0.046	0.058	0.000	0.000	0.000	0.000	0.000
23-Nov-95 to 27-Feb-96	0.116	0.156	0.104	0.067	0.432	0.361	0.048
Minimum	KM3A	KM3B	KM3C	KM3D	KM3F	KM3H	KM3J
21-Dec-93 to 31-Mar-94	0.015	0.008	0.024	0.010	-	-	0.025
31-Mar-94 to 30-Aug-94	0.006	0.011	-	-	0.005	0.013	0.023
30-Aug-94 to 21-Nov-94	0.028	0.003	0.009	0.007		0.005	0.009
21-Nov-94 to 20-Feb-95	0.010	0.034	0.635	0.010	0.157	0.006	0.019
20-Feb-95 to 23-Nov-95	0.085	0.007	0.000	0.000	0.000	0.000	0.000
23-Nov-95 to 27-Feb-96	0.031	0.031	0.005	0.014	0.006	0.008	0.004
Maximum	KM3A	KM3B	KM3C	KM3D	KM3F	KM3H	KM3J
21-Dec-93 to 31-Mar-94	1.292	2.182	2.450	3.895	-	-	1.138
31-Mar-94 to 30-Aug-94	0.156	1.241	-	-	0.749	1.144	0.023
30-Aug-94 to 21-Nov-94	0.061	0.869	0.374	0.949	-	0.958	1.838
21-Nov-94 to 20-Feb-95	0.010	0.034	1.345	0.676	0.157	4.530	0.019
20-Feb-95 to 23-Nov-95	0.006	0.198	0.000	0.000	0.000	0.000	0.000
23-Nov-95 to 27-Feb-96	0.244	1.645	0.792	0.170	1.847	2.686	0.452
Percentage	KM3A	KM3B	KM3C	KM3D	KM3F	KM3H	KM3J
21-Dec-93 to 31-Mar-94	11.7	65.0	86.3	81.3	44.2	-	90.0
31-Mar-94 to 30-Aug-94	8.3	81.7	-	-	27.5	12.5	0.8
30-Aug-94 to 21-Nov-94	1.7	5.8	5.0	4.2		5.8	12.5
21-Nov-94 to 20-Feb-95	0.8	0.8	1.7	5.8	0.8	3.3	0.8
20-Feb-95 to 23-Nov-95	1.7	15.8	0.0	0.0	0.0	0.0	0.0
23-Nov-95 to 27-Feb-96	5.0	24.2	16.7	13.3	4.2	14.2	20.0

Table 5.21 Surface swelling data from KM4 (mm).

Mean	KM4B	KM4C	KM4D	KM4E	KM4F	KM4G
29-Dec-93 to 6-Apr-94	0.195	0.203	0.108	0.471	0.091	0.098
6-Apr-94 to 6-Sep-94	0.018	0.139	0	2.123	0	0.065
6-Sep-94 to 24-Nov-94	0.083	0.847	1.411	0.821	1.177	-
24-Nov-94 to 25-Nov-95	0.962	1.486	3.244	3.043	3.131	0.044
Minimum	**KM4B**	**KM4C**	**KM4D**	**KM4E**	**KM4F**	**KM4G**
29-Dec-93 to 6-Apr-94	0.014	0.019	0.006	0.011	0.005	0.008
6-Apr-94 to 6-Sep-94	0.009	0.013	0	0.015	0	0.065
6-Sep-94 to 24-Nov-94	0.009	0.013	0.021	0.064	0.01	-
24-Nov-94 to 25-Nov-95	0.009	0.111	0.077	0.109	0.127	0.028
Maximum	**KM4B**	**KM4C**	**KM4D**	**KM4E**	**KM4F**	**KM4G**
29-Dec-93 to 6-Apr-94	0.939	0.71	0.738	3.824	0.287	0.544
6-Apr-94 to 6-Sep-94	0.028	0.315	0	5.067	0	0.065
6-Sep-94 to 24-Nov-94	0.674	3.104	3.004	1.58	5.01	-
24-Nov-94 to 25-Nov-95	4.565	4.895	6.397	6.701	8.882	0.061
Percentage	**KM4B**	**KM4C**	**KM4D**	**KM4E**	**KM4F**	**KM4G**
29-Dec-93 to 6-Apr-94	75.0	74.2	65.8	54.2	55.0	23.3
6-Apr-94 to 6-Sep-94	1.7	4.2	0.0	23.3	0.0	0.8
6-Sep-94 to 24-Nov-94	30.0	17.5	11.7	8.3	18.3	-
24-Nov-94 to 25-Nov-95	18.3	17.5	16.7	14.2	24.2	1.7

Table 5.22 Surface swelling data from KM5 (mm).

Mean	KM5A	KM5C	KM5F	KM5G
29-Dec-93 to 5-Apr-94	0.797	0.239	0.153	0.145
5-Apr-94 to 22-Nov-94	0.476	-	-	-
5-Apr-94 to 23-Feb-95	0.188	0.517	0	0
23-Feb-95 to 25-Nov-95	1.891	0.767	1.690	0.937
25-Nov-95 to 1-Mar-96	0.119	0.083	0.085	0.072
Minimum	**KM5A**	**KM5C**	**KM5F**	**KM5G**
29-Dec-93 to 5-Apr-94	0.015	0.015	0.008	0.019
5-Apr-94 to 22-Nov-94	0.058	-	-	-
5-Apr-94 to 23-Feb-95	0.014	0.023	0	0
23-Feb-95 to 25-Nov-95	0.027	0.007	0.033	0.043
25-Nov-95 to 1-Mar-96	0.017	0.008	0.007	0.072
Maximum	**KM5A**	**KM5C**	**KM5F**	**KM5G**
29-Dec-93 to 5-Apr-94	3.971	0.475	0.819	0.76
5-Apr-94 to 22-Nov-94	0.853	-	-	-
5-Apr-94 to 23-Feb-95	1.048	3.038	0	0
23-Feb-95 to 25-Nov-95	5.133	5.517	4.44	4.56
25-Nov-95 to 1-Mar-96	0.348	5.133	0.442	0.072
Percentage	**KM5A**	**KM5C**	**KM5F**	**KM5G**
29-Dec-93 to 5-Apr-94	50.0	92.5	71.7	66.7
5-Apr-94 to 22-Nov-94	5.8	-	-	-
5-Apr-94 to 23-Feb-95	17.5	11.7	0.0	0.0
23-Feb-95 to 25-Nov-95	20.8	72.5	25.8	11.7
25-Nov-95 to 1-Mar-96	43.3	29.2	34.2	0.8

Table 5.23 Surface swelling data from KM6 (mm).

Mean	KM6A	KM6B	KM6D	KM6F	KM6G
28-Dec-93 to 4-Apr-94	0	-	-	-	-
4-Apr-94 to 25-Nov-94	0	-	-	0.452	-
4-Apr-94 to 25-Feb-95	-	0.044	1.036	-	-
25-Nov-94 to 25-Feb-95	0	-	0	-	-
25-Feb-95 to 26-Feb-96	0	0.542	0	0.078	0.081
Minimum	**KM6A**	**KM6B**	**KM6D**	**KM6F**	**KM6G**
28-Dec-93 to 4-Apr-94	0	-	-	-	-
4-Apr-94 to 25-Nov-94	0	-	-	0.288	-
4-Apr-94 to 25-Feb-95	-	0.044	0.305	-	-
25-Nov-94 to 25-Feb-95	0	-	0	-	-
25-Feb-95 to 26-Feb-96	0	0.014	0	0.01	0.009
Maximum	**KM6A**	**KM6B**	**KM6D**	**KM6F**	**KM6G**
28-Dec-93 to 4-Apr-94	0	-	-	-	-
4-Apr-94 to 25-Nov-94	0	-	-	0.549	-
4-Apr-94 to 25-Feb-95	-	0.044	1.678	-	-
25-Nov-94 to 25-Feb-95	0	-	0	-	-
25-Feb-95 to 26-Feb-96	0	1.033	0	0.276	0.207
Percentage	**KM6A**	**KM6B**	**KM6D**	**KM6F**	**KM6G**
28-Dec-93 to 4-Apr-94	0	-	-	-	-
4-Apr-94 to 25-Nov-94	0	-	-	6.7	-
4-Apr-94 to 25-Feb-95	-	1.1	12.7	-	-
25-Nov-94 to 25-Feb-95	0	-	0	-	-
25-Feb-95 to 26-Feb-96	0	4.5	0	17.0	87.5

Table 5.24 Surface swelling data from KM7 (mm).

Mean	KM7A	KM7B	KM7C	KM7D	KM7F	KM7G	KM7H
22-Dec-93 to 4-Apr-94	-	0.309	0.453	-	-	-	-
4-Apr-94 to 5-Sep-94	0.034	0.483	-	-	0.051	0.207	0.244
4-Apr-94 to 23-Nov--94	-	-	0.370	-	-	-	-
5-Sep-94 to 23-Nov-94	1.218	0.893	-	-	0.123	0.189	0.086
23-Nov-94 to 26-Nov-95	3.108	0.758	0.501	1.864	2.018	0.206	2.314
26-Nov-95 to 2-Mar-96	-	0.876	0.382	0.895	0.662	0.168	0.426
Minimum	**KM7A**	**KM7B**	**KM7C**	**KM7D**	**KM7F**	**KM7G**	**KM7H**
22-Dec-93 to 4-Apr-94	-	0.007	0.043	-	-	-	-
4-Apr-94 to 5-Sep-94	0.016	0.06	-	-	0.019	0.006	0.005
4-Apr-94 to 23-Nov--94	-	-	0.007	-	-	-	-
5-Sep-94 to 23-Nov-94	0.006	0.016	-	-	0.123	0.009	0.013
23-Nov-94 to 26-Nov-95	0.025	0.143	0.018	0.039	0.027	0.007	0.029
26-Nov-95 to 2-Mar-96	-	0.088	0.006	0.006	0.006	0.007	0.006
Maximum	**KM7A**	**KM7B**	**KM7C**	**KM7D**	**KM7F**	**KM7G**	**KM7H**
22-Dec-93 to 4-Apr-94	-	1.101	1.085	-	-	-	-
4-Apr-94 to 5-Sep-94	0.055	0.906	-	-	0.086	0.698	3.234
4-Apr-94 to 23-Nov--94	-	-	0.858	-	-	-	-
5-Sep-94 to 23-Nov-94	3.656	3.106	-	-	0.123	1.086	0.722
23-Nov-94 to 26-Nov-95	5.817	2.028	3.531	4.872	4.505	0.913	6.152
26-Nov-95 to 2-Mar-96	-	1.998	3.921	5.903	4.063	0.882	4.83
Percentage	**KM7A**	**KM7B**	**KM7C**	**KM7D**	**KM7F**	**KM7G**	**KM7H**
22-Dec-93 to 4-Apr-94	-	40.7	87.5	-	-	-	-
4-Apr-94 to 5-Sep-94	7.6	1.7	-	-	10.8	6.7	18.3
4-Apr-94 to 23-Nov--94	-	-	15.0	19.2	-	-	-
5-Sep-94 to 23-Nov-94	8.0	7.5	-	-	0.8	39.2	10.8
23-Nov-94 to 26-Nov-95	22.5	7.5	64.2	15.8	14.2	14.2	16.7
26-Nov-95 to 2-Mar-96	-	9.2	74.2	60.8	43.3	39.2	33.3

From an examination of TMEM data it was apparent that some episodes of swelling caused the surface to rise above the level of first reading and then subsequently erode (but not below the initial level) and then to undergo swelling again. The effect of this was that episodes of erosion and swelling were superimposed on larger scale episodes of erosion and swelling; that is, swelling and erosion occurred above the initial level of the first reading. On KM1A there was the impression of swelling and erosion occurring at two scales superimposed on each other. This is illustrated in Figure 5.22. Seven individual measurement positions from KM1A are plotted over time. Positions 1, 2 and 5 show swelling at reading two after the initial reading, and then a small amount of erosion at the third reading, followed by a large swelling event at the fourth reading. This swelling event was eroded away by the fifth reading, but the surface was still above the initial level. Erosion continued at readings 6 and 7, but by the seventh reading was still above the first reading. This one swelling event began between readings 1 and 2, and was not completed by the final reading, a duration in excess of 697 days. Superimposed on this was a swelling event that lasted between 86 and 168 days. Readings 6 and 7 in Figure 5.22 also show swelling events that became evident after the second reading. The elevation of the surface then remained above the level of first reading for the remainder of the observation period, a duration exceeding 697 days.

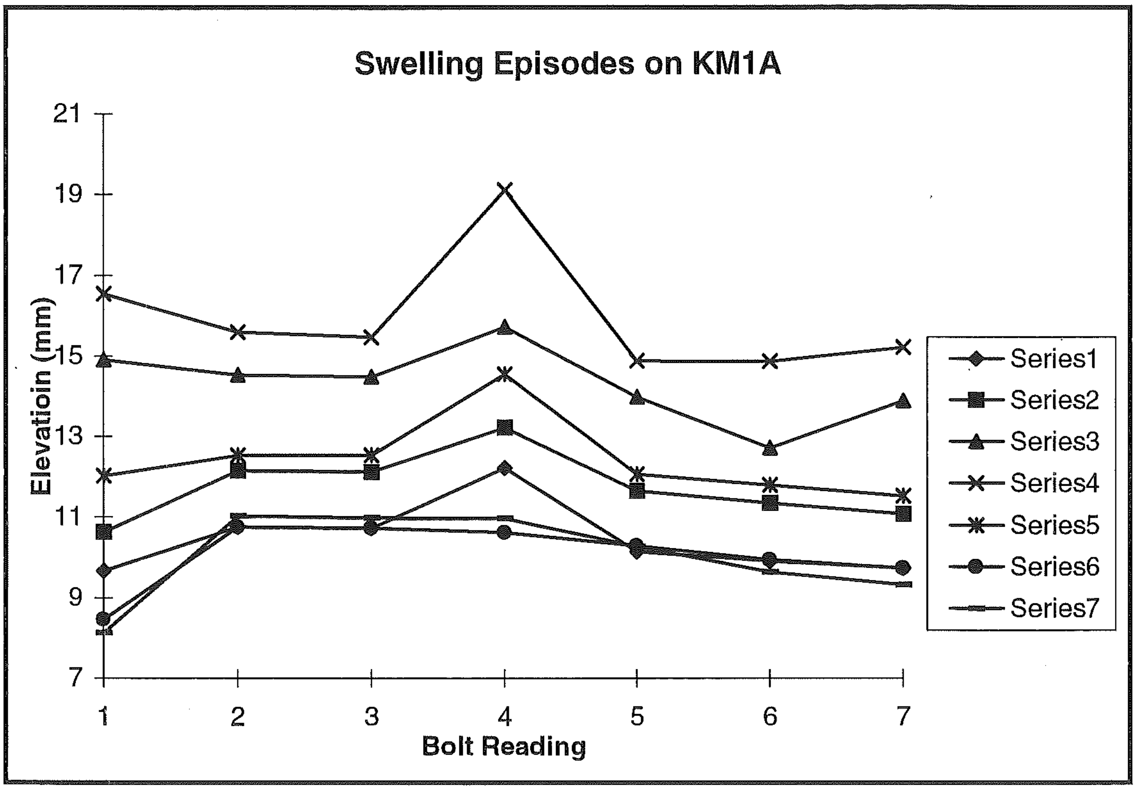

Figure 5.22 Examples of surface swelling from KM1A showing different forms of swelling.

DURATION OF SWELLING EVENTS

A main finding from investigating swelling is that some episodes caused the surface to rise above the level of first reading and there was then subsequent erosion, but not below the initial level. Then the surface under went swelling again. The effect of this was that episodes of erosion and swelling were superimposed on larger scale episodes of erosion and swelling. Given that 24055 individual measurements were taken, identifying and calculating the duration of swelling events in the TMEM data set is difficult. Another difficulty arises from the frequency of bolt readings. Since the time between readings is counted in months, an accurate calculation of duration is impossible. Duration can only be reported as more than or less than the interval between bolt readings. Mottershead (1989) reported the duration of swelling events as the amount of time a surface was above the level of the initial measurement. It is obvious from data from Kaikoura that this definition is not robust enough to accurately represent duration. Future investigations of swelling duration will need to take readings at much shorter periods, perhaps as frequently as daily or even at each low tide. For these reasons only some of the general characteristics of the duration of swelling have been reported.

5.2.6 SEASONAL VARIATIONS IN SWELLING AND EROSION

Both the erosion and the swelling data presented above indicate that there is a seasonal pattern to both swelling and erosion. A link between surface change and season would provide evidence that subaerial weathering is an important erosional agent on shore platforms at Kaikoura. This is because summer provides better conditions for wetting and drying and salt weathering than does winter. Marine processes can be excluded because storms do not have a seasonal pattern at Kaikoura. To test whether or not a relationship exists Chi Square tests were carried out. The form of Chi Square test used was a 2×2 contingency table of swelling and erosion against winter and summer (Shaw and Wheeler 1985). This was achieved by counting the number of recorded swelling and erosion measurements in either summer or winter measurement periods. Clearly some leniency was required as to what data were included as either winter or summer. Spring readings were included in summer and autumn readings were included in winter. The test was carried out for individual bolt sites and then on combined data to test each profile site.

The results of the Chi Square test for bolts sites on KM1 and for the KM1 profile are shown in Table 5.25. With the exception of KM1A, H_o was rejected when $\alpha = 0.001$; that is, both swelling and erosion on bolts sites KM1B, KM1C, KM1D, KM1F, and KM1G are linked with season. There is more change in summer than winter. When all data were combined to test the profile as a whole against season, the χ^2 statistic exceeded the critical value so that H_o was rejected. A statistically significant link between surface change and season supports the view that erosion results from subaerial weathering.

Chi Square test results for KM2 are presented in Table 5.26. On KM2A it was not possible to use a 2×2 contingency table since there were no recorded swelling events. Instead erosion was tested against season using a one sample test. The resulting χ^2 statistic was 0 so that H_o was accepted. This was not unexpected since at every measurement interval there were always 120 recorded erosion measurements. For KM2B, KM2D, KM2F, and KM2J, H_o was rejected and a seasonal link with swelling and erosion is confirmed. On KM2H the statistic did not exceed the critical value and H_o was accepted.

Table 5.25 KM1 χ^2 2×2 contingency table results.

Bolt Site	χ^2	Reject H_o $\alpha = 0.001$
A	8.6	No
B	83.8	Yes
D	33.7	Yes
F	123.0	Yes
G	35.7	Yes
PROFILE	242.5	Yes

Table 5.26 KM2 χ^2 2×2 contingency table results.

Bolt Site	χ^2	Reject H_o $\alpha = 0.001$
A	0	No
B	63.93	Yes
D	12.62	Yes
F	77.03	Yes
H	1.61	No
J	16.34	Yes
PROFILE	105.31	Yes

Table 5.27 contains the results of Chi Square test for bolt sites on KM3 and the profile as a whole. The Chi statistic for three bolt sites, KM3A, KM3F and KM3H did not exceed the critical value, so that H_o was accepted. For the remaining bolt sites, KM3B, KM3C, KM3D, and KM3J, H_o was rejected. Overall for the whole profile, H_o was rejected and a seasonal influence over swelling and erosion is accepted.

The results of the Chi Square test for KM4 and bolt site are shown in table 5.28. Without exception the Chi statistic for all bolt sites and the profile exceeded the associated critical values. Therefore H_o was rejected and the link of erosion and swelling with season is accepted.

Table 5.27 **KM3 χ^2 2×2 contingency table results.**

Bolt Site	χ^2	Reject H_o $\alpha = 0.001$
A	0.5	No
B	36.4	Yes
C	69.4	Yes
D	65.2	Yes
F	6.2	No
H	1.4	No
J	85.9	Yes
Profile	65.4	Yes

Table 5.28 KM4 χ^2 2×2 contingency table results.

Bolt Site	χ^2	Reject H_o $\alpha = 0.001$
B	144.2	Yes
C	144.4	Yes
D	121.8	Yes
E	24.8	Yes
F	96.6	Yes
G	31.1	Yes
Profile	478.5	Yes

Table 5.29 contains the results of Chi Square tests for KM5. Here, the Chi statistic exceeded the critical value on KM5A and KM5C but not on KM5F and KM5G. Despite this 50/50 split the profile Chi statistic was greater than the critical value and H_o could be rejected for the profile as a whole. For KM6 not enough data were available to conduct Chi Square tests, except on KM6A. As with KM2A, this bolt site did not record any swelling events so it was not possible to use a 2×2 contingency table. Again to test erosion against season, a one sample Chi

Square test was used. The resulting χ^2 statistic was 0 so that H_o is accepted. As with KM2A this was not unexpected since every measurement interval always recorded 120 measurements of erosion.

Table 5.29 KM5 χ^2 2×2 contingency table results.

Bolt Site	χ^2	Reject H_o $\alpha = 0.001$
A	15.565	Yes
C	162.434	Yes
F	2.768	No
G	9.944	No
Profile	74.097	Yes

Chi Square test results for KM7 are shown in Table 5.30. With the exception of KM7H, all other bolt sites had Chi statistic values that exceeded the critical value in each case, thus rejecting H_o. The Chi statistic for the profile also exceeded the appropriate critical value. These χ^2 tests showed that on 74 per cent of all bolt sites erosion and swelling were linked with season. A seasonal link suggests that subaerial weathering is occurring. This is because summer provides optimum conditions for subaerial weathering. Caution is needed as this point because it has been discussed how morphology and morphological change can be an ambiguous indicator of process. Before accepting the view that erosion on shore platforms at Kaikoura can be attributed to subaerial weathering, there is a need to investigate the processes thought to cause erosion. This will occur in Chapter Six. So far surface change evidence provides some support for the view that subaerial weathering causes erosion on shore platforms at Kaikoura.

Table 5.30 KM7 χ^2 2×2 contingency table results.

Bolt Site	χ^2	Reject H_o $\alpha = 0.001$
B	56.7	Yes
C	194.9	Yes
D	53.5	Yes
F	32.6	Yes
G	38.7	Yes
H	6.2	No
Profile	194.9	Yes

5.2.7 THREE DIMENSIONAL VOLUME ANALYSIS OF TRAVERSING MICRO-EROSION METER DATA

Of the 42 traversing micro-erosion meter sites at Kaikoura data from only 35 were suitable for three dimensional analysis and volume calculations. This was because on some bolt sites it was not possible to gain all 120 readings. It was decided arbitrarily that only sites where 100 or more readings were taken should be used, since the accuracy of the surface plot and volume calculation are reduced with fewer measurement points. The software used for this was SURFER, from Golden Software, Colorado, USA. The input variables for this program are x, y, and z co-ordinates. Co-ordinates x and y represent positions of the dial gauge in the horizontal plane. The z axis is the vertical reading given by the gauge which is in reference to the position of the probe when it is at zero, or at rest. Recorded results can be plotted directly into SURFER giving a graphical representation of bolt site surface. At the beginning of Section 5.2 it was stated that in order to calculate an erosion rate data had to be screened to removed results showing surface swelling. This was not the case for analysis performed in SURFER, and all measurements of surface change were included. With SURFER the volume of a surface plot can be calculated, as can the difference in volumes between successive plots. SURFER utilises three methods for calculating volumes, each of which generates slightly different results. These methods are discussed in the accompanying manual. It is therefore possible to calculate the volume of material eroded from each bolt site, which may provide an insight into the contribution of shore platforms to local sediment budgets around the Kaikoura Peninsula. Figures 5.23 to 5.32 illustrate plotted surfaces for selected examples from each profile. The elevations reported are relative to the level of the TMEM spindle when it is at zero, referred to below as Gauge Level (G.L.).

Tables 5.31 to 5.37 display the volumetric changes on each profile calculated in SURFER for the study period. Positive values in Tables 5.31 to 5.37 indicate the amount of material eroded from each site. Negative values indicate a volumetric gain, because of surface swelling. However, not all surface swelling results in a volume increase; episodes of swelling did occur when there was a net loss of material from the bolt site. This is apparent when there are differences between gross and net volume changes. The volumetric data contained in Tables 5.31 to 5.37 include gross erosion rate in cm^3, net erosion in cm^3 and the mean annual rate of erosion in cm^3/yr. Gross erosion is the addition of all erosion episodes during the study period for a bolt site and net erosion is the difference between the first and last bolt readings. The remaining part of this section contains descriptions of selected bolt sites; these have been chosen to illustrate key characteristics of bolt site erosion and swelling episodes. Not all 35 bolt sites are presented.

Table 5.31 shows volume changes for KM1A, KM1B, KM1D, KM1F from December 1993 to February 1996. Figure 5.23 shows the plotted surface of KM1A. This clearly shows significant surface swelling from December 1993 to April 1994, evident from the presence of pink and dark blue colours at elevations of 1.6+ and 1.7+cm above G.L. However there was a net loss of material during this period of 0.718cm^3. By September 1994 there was little change (net loss of 0.223cm^3 between April and September), but by November 1994 a new area at the lower right apex of the triangle emerged (dark blue) with a net gain of 0.798cm^3. This area had almost disappeared by February 1995 when 3.457cm^3 was removed and the area was completely removed by November 1995 when a further 1.809cm^3 was lost. By February 1996 there was significant lowering over a large part of the whole site. The appearance of the lower level yellow coloured area on the plot (1.3+cm above gauge level) and the green area (1.2+cm above G.L.) is clearly evident. During this period 1.184cm^3 was eroded. Overall the total volume of sediment yielded by the site was 7.392cm^3 at an annual rate of 3.364cm^3/yr.

Table 5.31 Volumetric erosion rates from KM1 (cm^3/yr).

Inter-survey Period	KM1A	KM1B	KM1D	KM1F	KM1G
20-Dec-93 to 1-Apr-94	0.718	-0.325	-	-0.203	0.055
1-Apr-94 to 1-Sep-94	0.223	0.475	0.634	0.789	0.179
1-Sep-94 to 26-Nov-94	-0.798	-1.235	-0.054	0.195	0.742
26-Nov-94 to 16-Feb-95	3.457	1.736	0.872	0.555	1.319
16-Feb-95 to 15-Nov-95	1.809	2.148	1.592	1.337	24.268
15-Nov-95 to 28-Feb-96	1.184	-0.901	-1.274	-0.271	2.592
Gross Total Erosion cm^3	7.392	4.359	3.098	2.877	29.155
Net Erosion cm^3	6.594	1.898	1.771	2.402	29.155
Annual Rate cm^3/yr	3.364	1.982	1.615	1.309	13.269

Bolt site KM1B is shown in Figure 5.24. This bolt site also displayed significant swelling. From December 1993 to April 1994 a large portion of the surface in the 1.3cm to 1.5cm elevation range disappeared. A large part of the surface was in the 1.5 to 1.7cm range by April. This caused a net gain in volume of 0.325cm^3. Also noteworthy is that the "hole" shown at the lower left apex of the triangle became smaller. Visually there was little change by September 1994, but there was a net loss of material of 0.475cm^3. From September 1994 to November 1994 a significant piece of the surface "stood up"; this is clearly shown by the dark blue peaks in the November plot, representing an elevation 1.9cm above gauge level. As a result there was a net gain in volume of 1.235cm^3. By February 1995 these "peaks" had been completely removed with a net loss of material of 1.736cm^3. There was a further loss of 1.809cm^3 between February 1995 and November 1995. Between November 1995 and February 1996 there was a net loss of 1.184cm^3, but a new "peak" emerged at the upper right hand apex. The gross volume of material removed from this bolt site was 4.359cm^3 at an annual rate of 1.982cm^3/yr. The net loss was only 1.898cm^3.

Table 5.32 contains volume data for profile KM2. Figure 5.25 shows the surface of KM2A. This bolt site was the second fastest eroding site at Kaikoura, only KM6A having a higher erosion rate and volume yield. Over the measurement period from September 1994 to February 1996 there was a total sediment yield of 60.252cm^3 at an annual rate of 39.697cm^3/yr. Erosion on this site occurred as a continual downward process with no swelling evident.

Table 5.32 Volumetric erosion rates from KM2 (cm^3/yr).

Inter-survey Period	KM2A	KM2D	KM2F	KM2J
22-Dec-93 to 1-Apr-94	-	3.004	-	-0.471
1-Apr-94 to1-Sep-94	-	1.240	0.187	0.267
1-Sep-94 to 20-Nov-94	7.357	2.029	5.740	1.263
20-Nov-94 to 19-Feb-95	21.360	4.541	1.955#	0.751
19-Feb-95 to 22-Nov-95	16.118	3.698	-	2.083*
22-Nov-95 to 28-Feb-96	15.415	3.193	2.128	-
Gross Total Erosion cm^3	60.252	17.705	10.011	4.365
Net Erosion cm^3	60.252	17.705	10.011	3.893
Annual Rate cm^3/yr	39.697	8.048	5.613	1.984

#20/11/94 to 20/11/95 *19/2/95 to 28/2/96

Figure 5.26 shows the surface plots of KM2D. This site also illustrates erosion occurring as a continual downward process. The surface was lowered without any significant swelling occurring. A small swelling episode is evident in the November 1994 plot in the top apex compared with the preceding September 1994 surface. From KM2D, 17.706cm^3 was removed at an annual rate of 8.048cm^3/yr. From KM2F a total of 10.011cm^3 eroded at an annual rate 5.613cm^3/yr. KM2J was the only bolt site on KM2 that showed a gain in volume (0.471cm^3) during the summer observation period, December 1993 to April 1994. This caused a small difference in the net and gross erosion volumes for KM2J. For the other three sites there were no differences in net and gross volumes.

KM3 volume data are set out in Table 5.33. Gross erosion on KM3A was 18.201cm^3 at an annual rate of 8.325cm^3/yr. The net erosion on this site was 16.833cm^3, indicating that surface swelling did occur despite the high volume yield. Figure 5.27 displays the surface plot of KM3B. Between December 1993 and April 1994 there was a loss of material form the site of 1.303cm^3 but a gain of 1.979cm^3 between April 1994 and August 1994. This can be seen on the August 1994 plot, with the red areas on the plot and the reappearance of dark blue indicating an elevation of 2.45cm+ above G.L. Unlike swelling episodes on KM1 and KM2 which occurred in summer and spring, swelling on KM3B occurred over the winter of 1994.

Table 5.33 Volumetric erosion rates from KM3 (cm^3/yr).

Inter-survey Period	KM3A	KM3B	KM3D	KM3E	KM3F	KM3H	KM3J
21-Dec-93 to 31-Mar-94	2.427	1.303	-0.208	-	0.736	-	-0.521#
31-Mar-94 to 30-Aug-94	1.153	-1.979	1.476*	0.484*	0.496	0.707	-
30-Aug-94 to 21-Nov-94	2.355	3.128	-	-	2.383	1.362	0.439
21-Nov-94 to 20-Feb-95	6.003	3.754	1.311	1.025	-	0.435	1.052
20-Feb-95 to 23-Nov-95	3.516	2.782	1.353	1.656	1.783	1.794	1.644
23-Nov-95 to 27-Feb-96	2.747	2.075	0.934	0.163	0.623	0.077	0.258
Gross Total Erosion cm^3	18.201	13.043	5.075	3.327	6.021	4.375	3.393
Net Erosion cm^3	16.833	11.064	4.867	3.327	6.021	4.375	2.872
Annual Rate cm^3/yr	8.325	5.966	2.321	1.682	2.754	2.288	1.552

*31/3/94 to 21/11/94 # 21/12/93 to 30/8/94

Calculated volume changes for KM4 are presented in Table 5.34. As with other bolt sites already presented, a noticeable period of surface swelling occurred on sites at KM4. There is also a marked seasonal trend in this, with swelling episodes occurring in the spring and summer periods. Surface plots of KM4C are presented in Figure 5.28 Surface swelling occurred between December 1993 and April 1994 with a net volume gain of 0.356cm^3. This can clearly be seen on the plot, from the increase in surface area of the blue level above 2.50cm G.L.. Another surface swelling event occurred between November 1994 and November 1995. The plot of the November 1995 data shows peaks emerging on the right hand side of the plot. The emergence of these peaks can been seen by comparing the September 1994 plot with that from November 1994. A distinct channel is evident in the September 1994 plot which led out to the right hand apex of the triangle. The elevation of this channel was as low as 1.80cm above G.L. (as indicated by the black surface), but by November the channel surface began to rise, with elevations of between 2.0 and 2.2cm above G.L. Despite these swelling events on KM4C there was a net volume loss of 2.637cm^3 between November 1994 and November 1995.

Site KM4F is presented in Figure 5.29. As with KM4C, swelling episodes occurred between September 1994 and November 1994 and between November 1994 and November 1995. These can be seen on the lower apex of the surface plot for November 1994 where two distinct peaks appeared. As with KM4C, the beginning of this episode must have been between September 1994 and November 1994 and continued until November 1995. These swelling episodes on both bolt sites offer an important clue as to the duration of swelling events on limestone platforms. It is clear that these peaks began to form between September 1994 and November 1994 and were still present a year later.

Table 5.34 Volumetric erosion rates from KM4 (cm^3/yr).

Inter-survey Period	KM4B	KM4C	KM4D	KM4E	KM4F	KM4G
29-Dec-93 to 6-Apr-94	-0.356	-0.677	-0.182	2.676	0.450	1.015
6-Apr-94 to 6-Sep-94	1.539	0.985#	4.308	0.144	2.520	2.437
6-Sep-94 to 24-Nov-94	0.224	-0.577	0.332	2.579	-0.178	4.312*
24-Nov-94 to 25-Nov-95	2.637	0.243	4.314	1.367	-0.868	↓
Gross Total Erosion cm^3	4.400	1.228	8.954	6.767	2.970	7.764
Net Erosion cm^3	4.044	-0.026	8.772	6.767	1.924	7.764
Annual Rate cm^3/yr	2.307	0.644	4.696	3.549	1.558	4.072

* 6/9/94 to 25/22/95 # 6/4/94 to 24/11/94

Volume data from KM5 are presented in Table 5.35. Figure 5.30 shows surface plots for KM5A. A total of 15.648cm^3 was eroded from KM5A at an annual rate of 7.202 cm^3/yr. Again there were episodes of surface swelling, most noticeably between December 1993 and April 1994, and between November 1995 and March 1996. Minor swelling also occurred between November 1994 and February 1995. Surface plots from KM5C are shown in Figure 5.31. At this site significant surface swelling occurred between December 1993 and April 1994, when a net volume gain of 0.726cm^3 was measured, and between November 1994 and February 1995 when total gain of 2.228cm^3 was recorded. This large volume gain can be clearly seen by comparing the November 1994 and February 1995 surfaces. There was a significant increase in the surface area of elevations shaded blue for the February 1995 plot. As with other examples, the morphology on KM5A and KM5C was one of raised peaks. Volume gains on KM5C were offset by erosion between April 1994 and November 1994, and February 1995 to March 1996 so that the net change was only 0.332cm^3, while the gross was significantly larger at 3.286cm^3.

Erosion volume data from KM6 are not as detailed as for other profiles because re-measurement was often prevented by algae growth. KM6A was re-measured a number of times and shows the highest sediment yield of any bolt site at Kaikoura. It had an equivalent annual rate of erosion of 42.782cm^3/yr. An annual rate of loss of 1.407cm^3/yr from KM6B is likely to be a minimum since the measurement of this site occurred at the beginning and end of a winter period

Table 5.37 contains volume erosion data from KM7. On KM7B there was a total loss of 13.369cm^3 at an annual rate of 6.092cm^3/yr. KM7C is illustrated in Figure 5.32. The net volume of material eroded from this site was greater than the gross volume gain indicating that the surface of this bolt site had a higher volume at the end of the measurement period than at the beginning because of swelling after the November 1994 reading. At the top apex of the March 1996 plot there is larger area shaded light blue (1.6 to 1.7 G.L.) compared with the December 1993 plot where the black surface 1.3 to 1.4 G.L. is more in evidence. Overall the surface yielded at total of 1.207cm^3 at an annual rate of 0.549cm^3/yr.

Table 5.35 Volumetric erosion rates from KM5 (cm^3/yr).

Inter-survey Period	KM5A	KM5C	KM5F	KM5G
29-Dec-93 to 5-Apr-94	0.563	-0.726	0.998	0.316
5-Apr-94 to 22-Nov-94	6.678	0.665	2.914*	2.493*
22-Nov-94 to 23-Feb-95	3.136	-2.228	-	-
23-Feb-95 to 25-Nov-95	1.882	-	-1.393	0.577
25-Nov-95 to 1-Mar-96	3.388	2.621#	2.513	2.357
Gross Total Erosion cm^3	15.648	3.286	6.425	5.743
Net Erosion cm^3	15.648	0.332	5.032	5.743
Annual Rate cm^3/yr	7.202	1.512	2.957	2.643

*5/4/94 to 23/2/95 # 23-2-95 to 1-3-96

Table 5.36 Volumetric erosion rates from KM6 (cm^3/yr).

Inter-survey Period	KM6A	KM6B	KM6D	KM6G
28-Dec-93 to 4-Apr-94	16.643	-	-	-
4-Apr-94 to 25-Nov-94	14.339	2.668	1.122	-
25-Nov-94 to 25-Feb-95	23.100	-	2.923	-
25-Feb-95 to 26-Feb-96	38.397	-	3.513	1.575
Gross Total Erosion cm^3	92.480	2.668	7.557	1.575
Net Erosion cm^3	92.480	2.668	7.557	1.575
Annual Rate cm^3/yr	42.782	1.407	3.986	1.566

Table 5.37 Volumetric erosion rates from KM7 (cm^3/yr).

Inter-survey Period	KM7B	KM7C	KM7F	KM7G	KM7H
22/11/93 to 4/4/94	0.803	-1.685	-	-	-
4/4/94 to 5/9/94	0.873	1.207*	0.502	1.185	0.427
5/9/94 to 23/11/94	2.105	-	0.950	0.572	0.502
23/11/94 to 26/11/95	5.717	-1.053	2.192	2.921	0.436
26/11/95 to 2/3/96	3.871	-0.191	0.414	2.721	1.713
Gross Total Erosion cm^3	13.369	1.207	4.058	7.400	3.078
Net Erosion cm^3	13.369	-1.723	4.058	7.400	3.078
Annual Rate cm^3/yr	6.092	0.549	2.083	3.798	1.580

* 4/4/94 to 23/11/94

SURFACE PLOTS SHOWING CHANGES ON KM1A

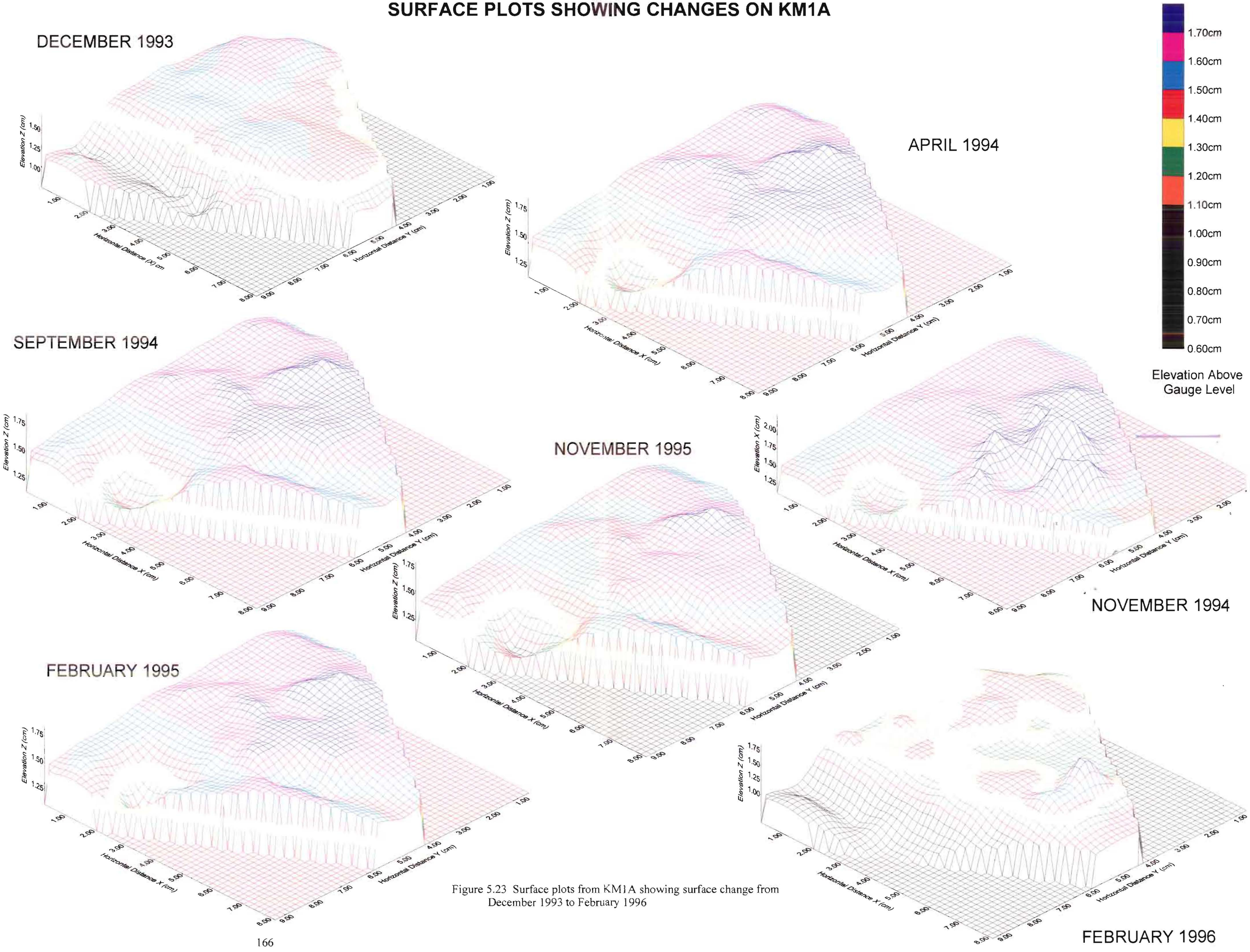

Figure 5.23 Surface plots from KM1A showing surface change from December 1993 to February 1996

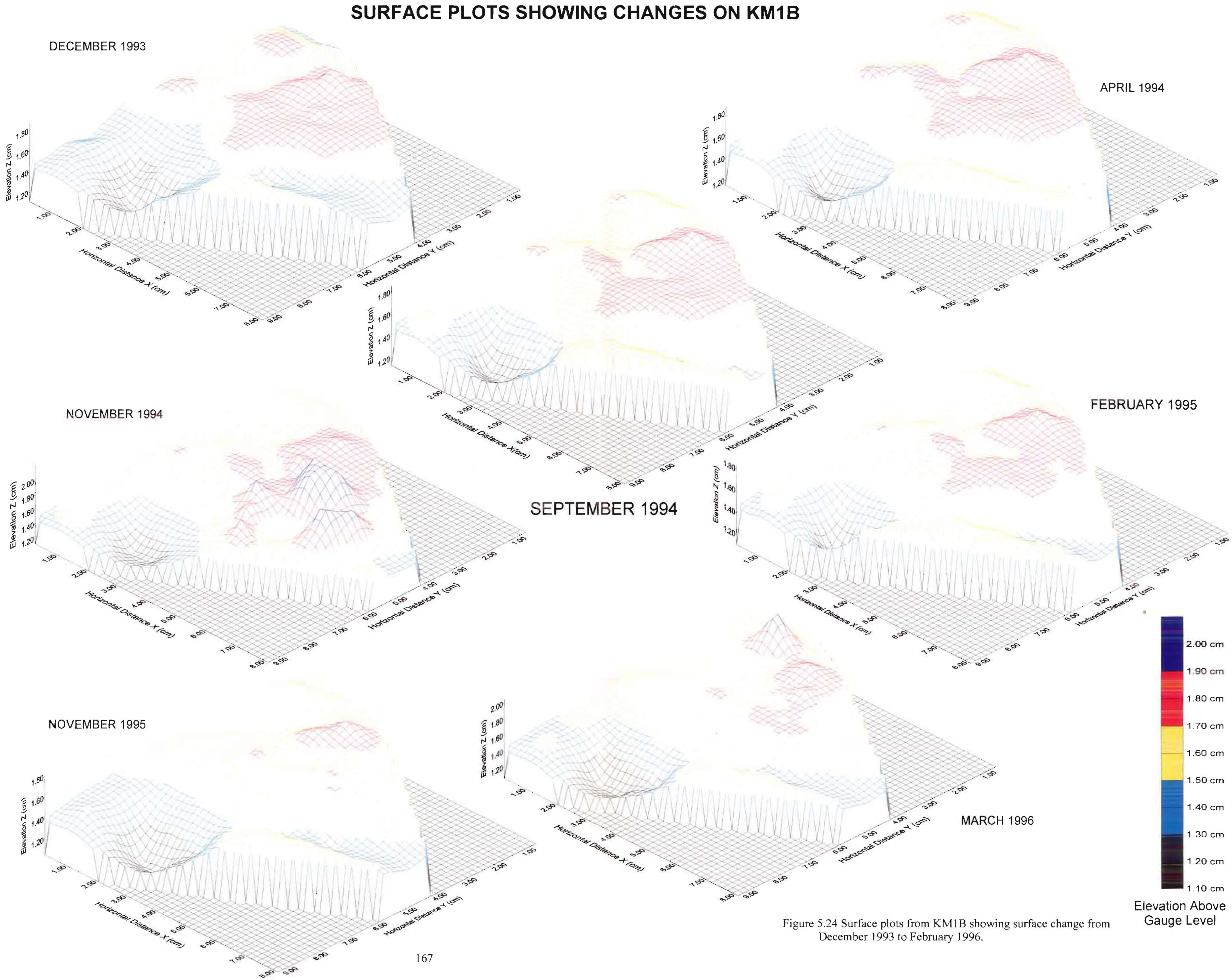

Figure 5.24 Surface plots from KM1B showing surface change from December 1993 to February 1996.

SURFACE PLOTS SHOWING CHANGES ON KM2A

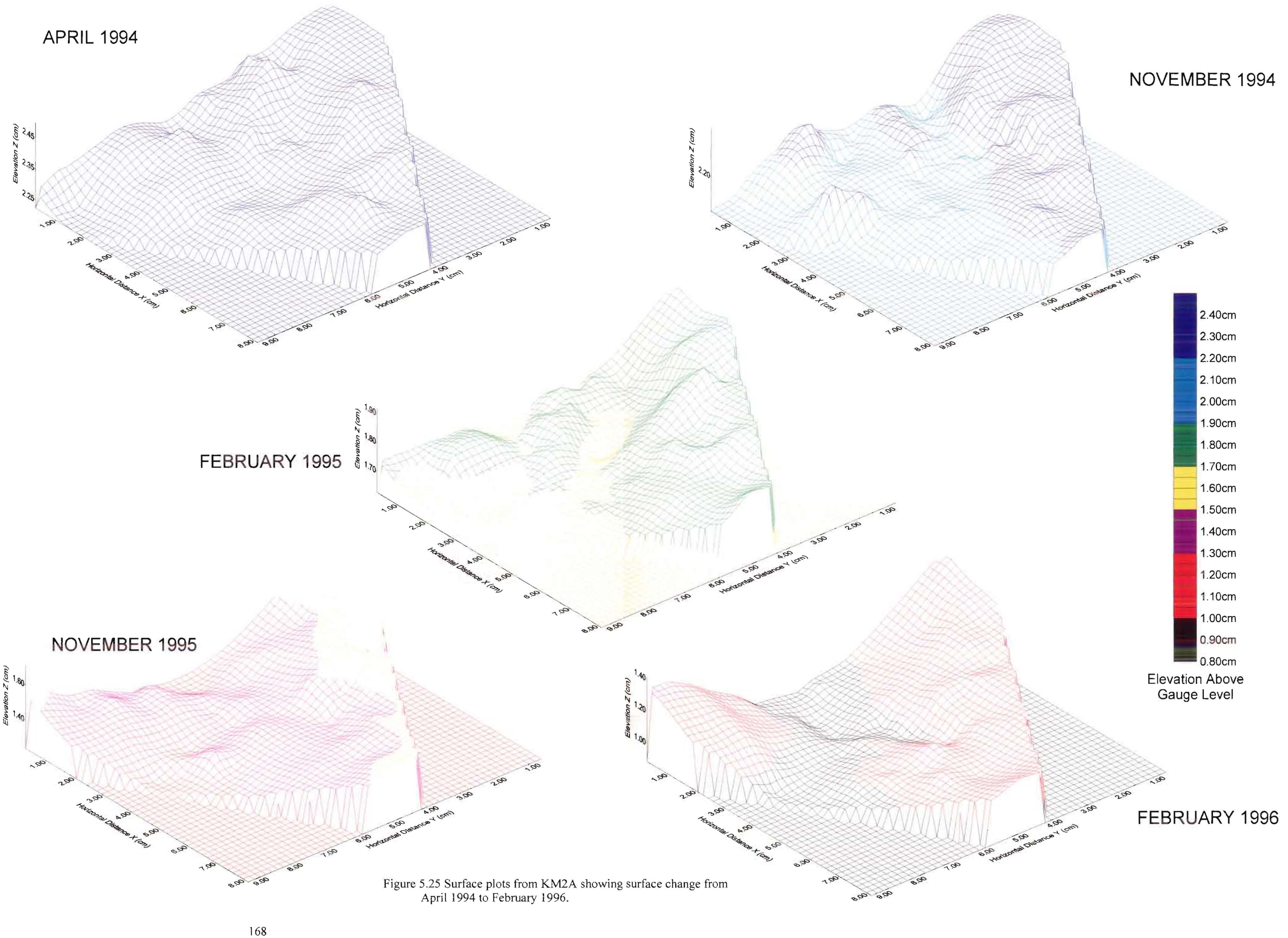

Figure 5.25 Surface plots from KM2A showing surface change from April 1994 to February 1996.

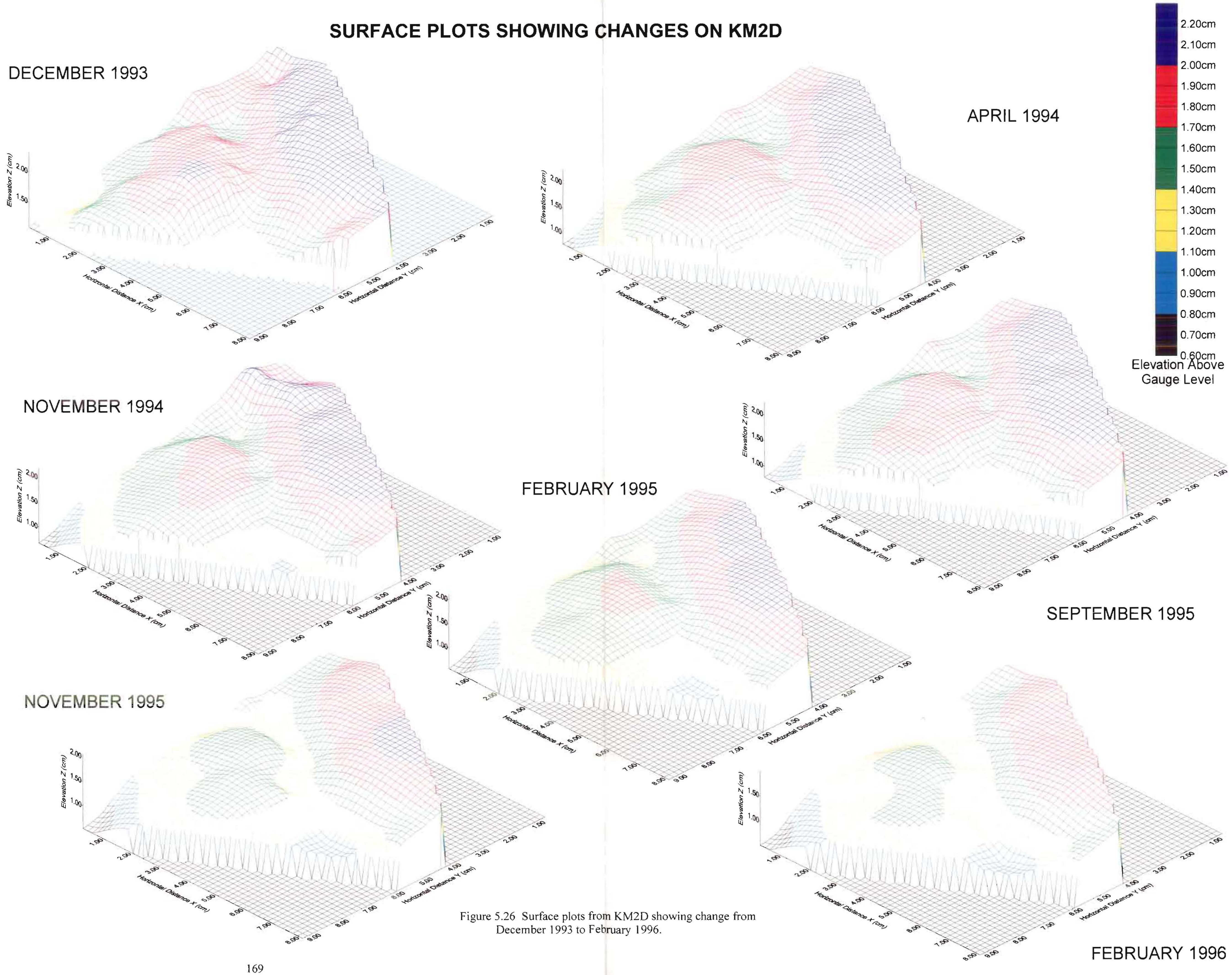

Figure 5.26 Surface plots from KM2D showing change from December 1993 to February 1996.

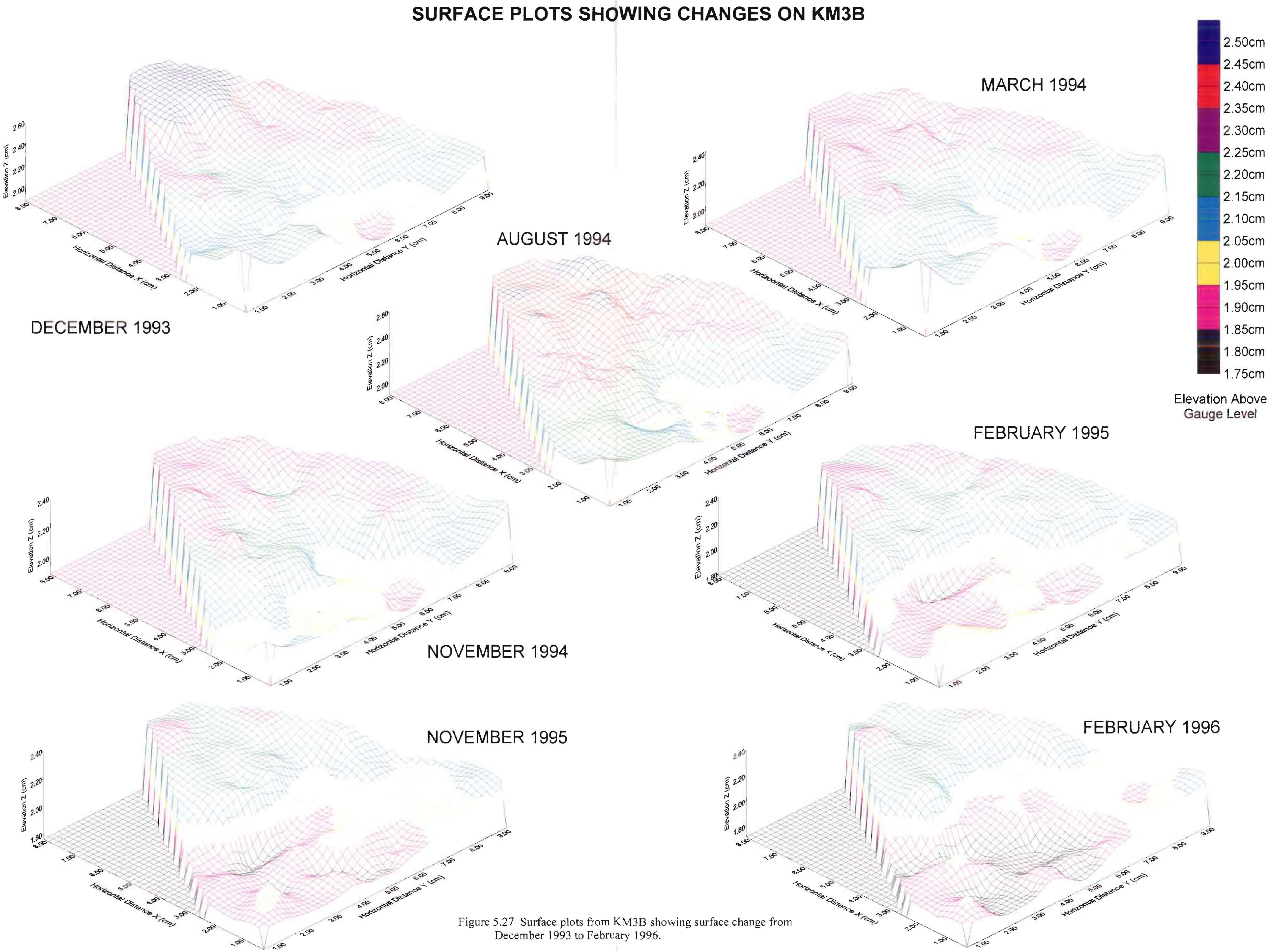

Figure 5.27 Surface plots from KM3B showing surface change from December 1993 to February 1996.

SURFACE PLOTS SHOWING CHANGES ON KM4C

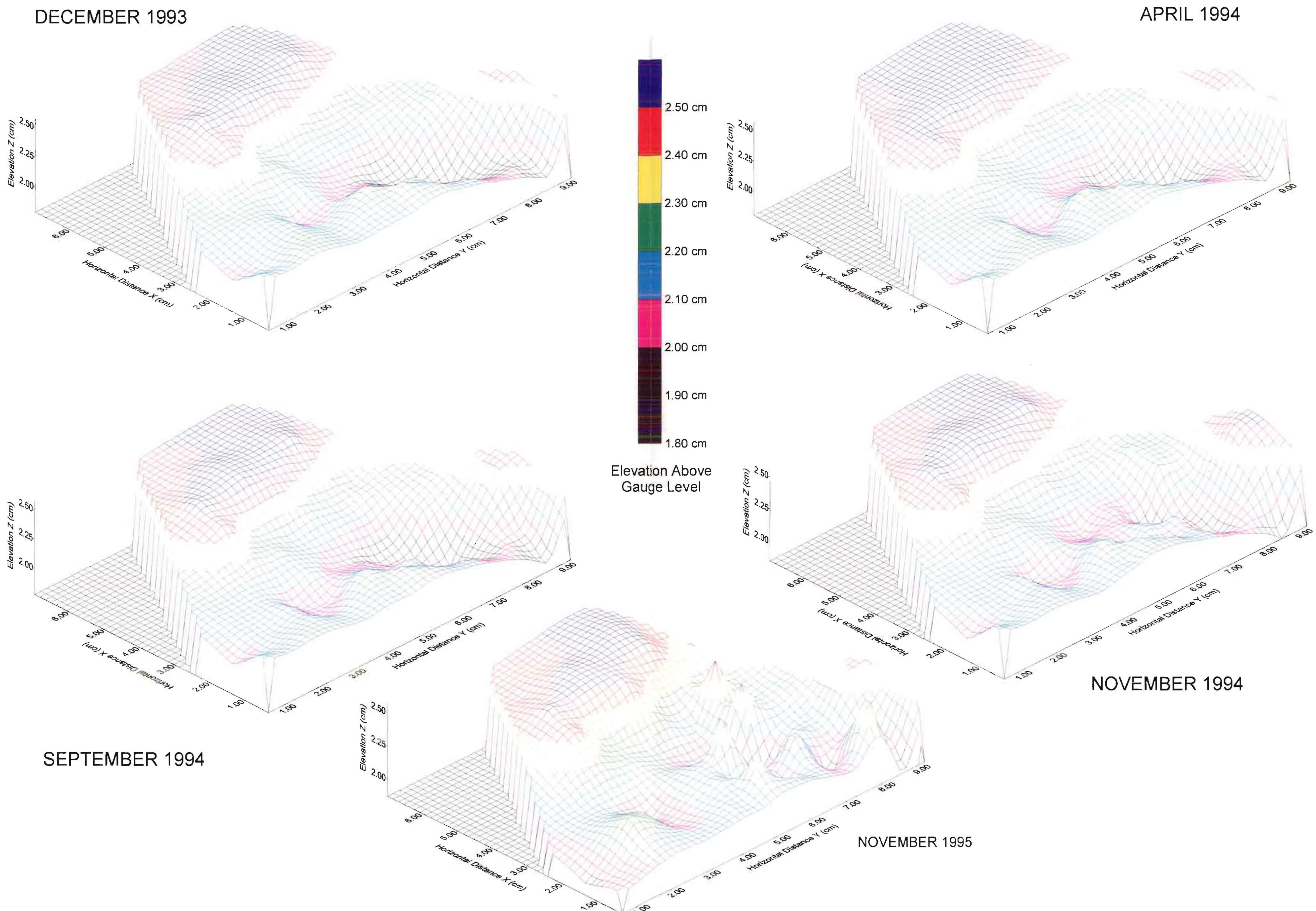

Figure 5.28 Surface plots from KM4C showing surface change from December 1993 to November 1995.

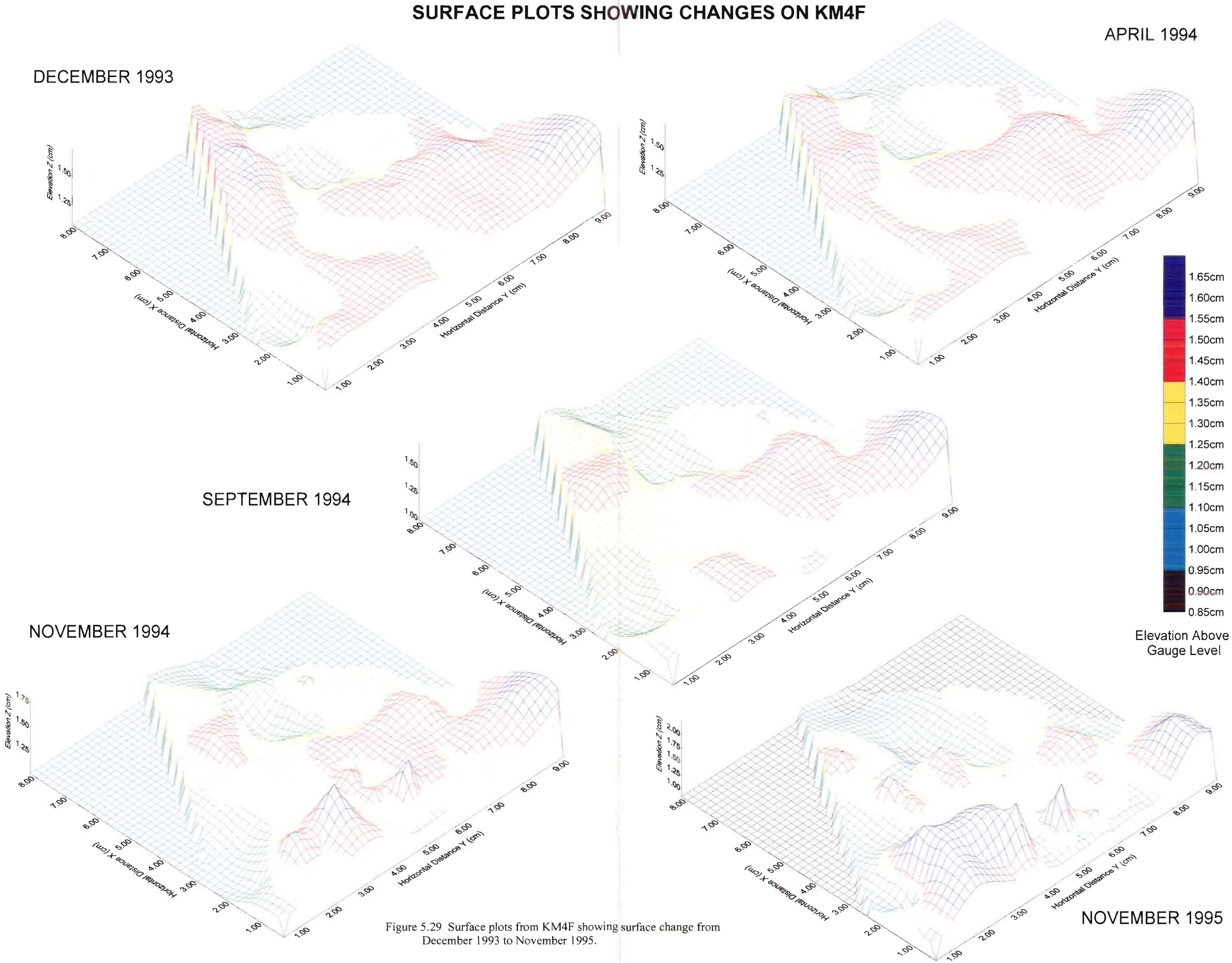

Figure 5.29 Surface plots from KM4F showing surface change from December 1993 to November 1995.

SURFACE PLOTS SHOWING CHANGES ON KM5A

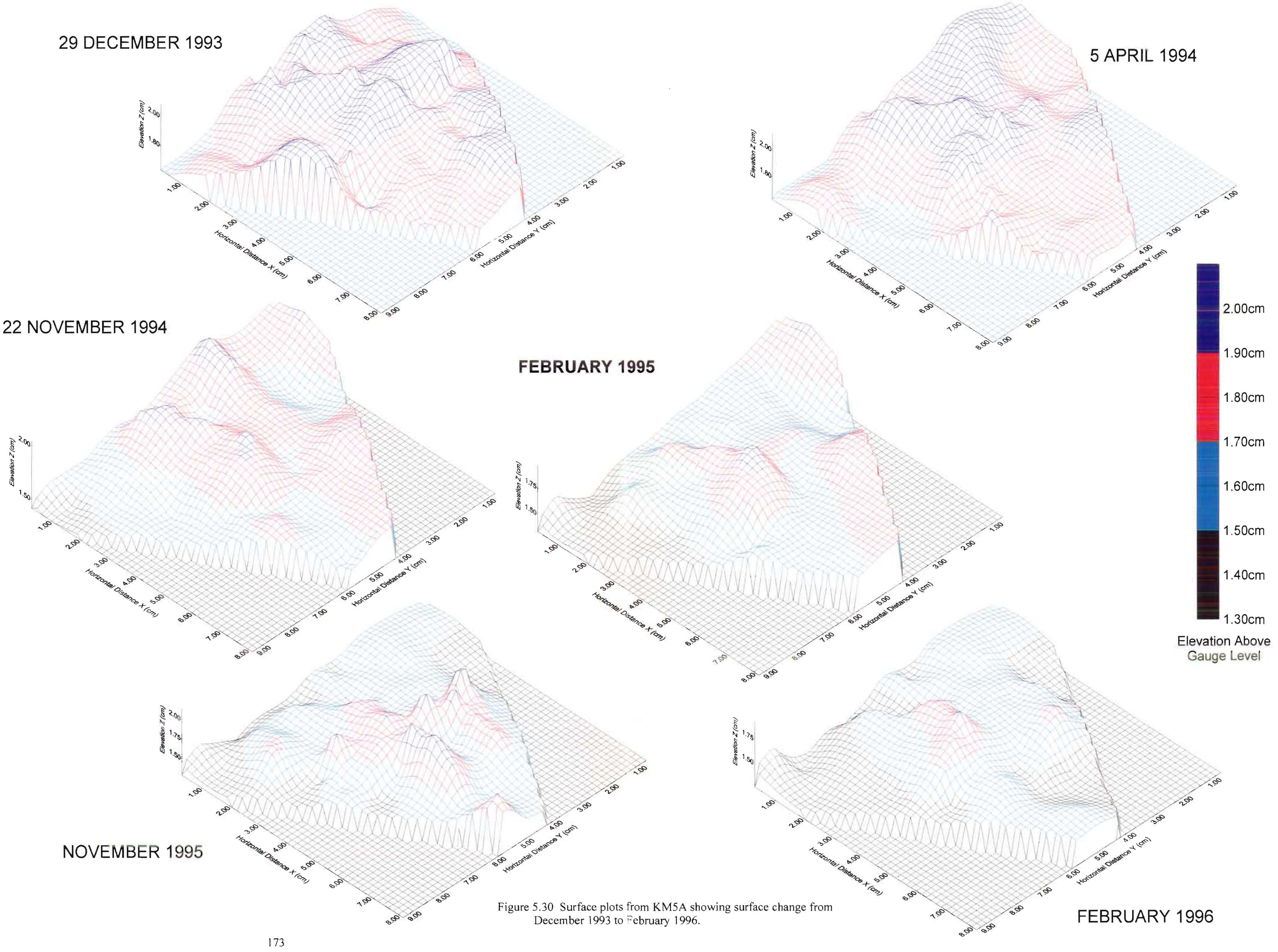

Figure 5.30 Surface plots from KM5A showing surface change from December 1993 to February 1996.

SURFACE PLOTS SHOWING CHANGES ON KM5C

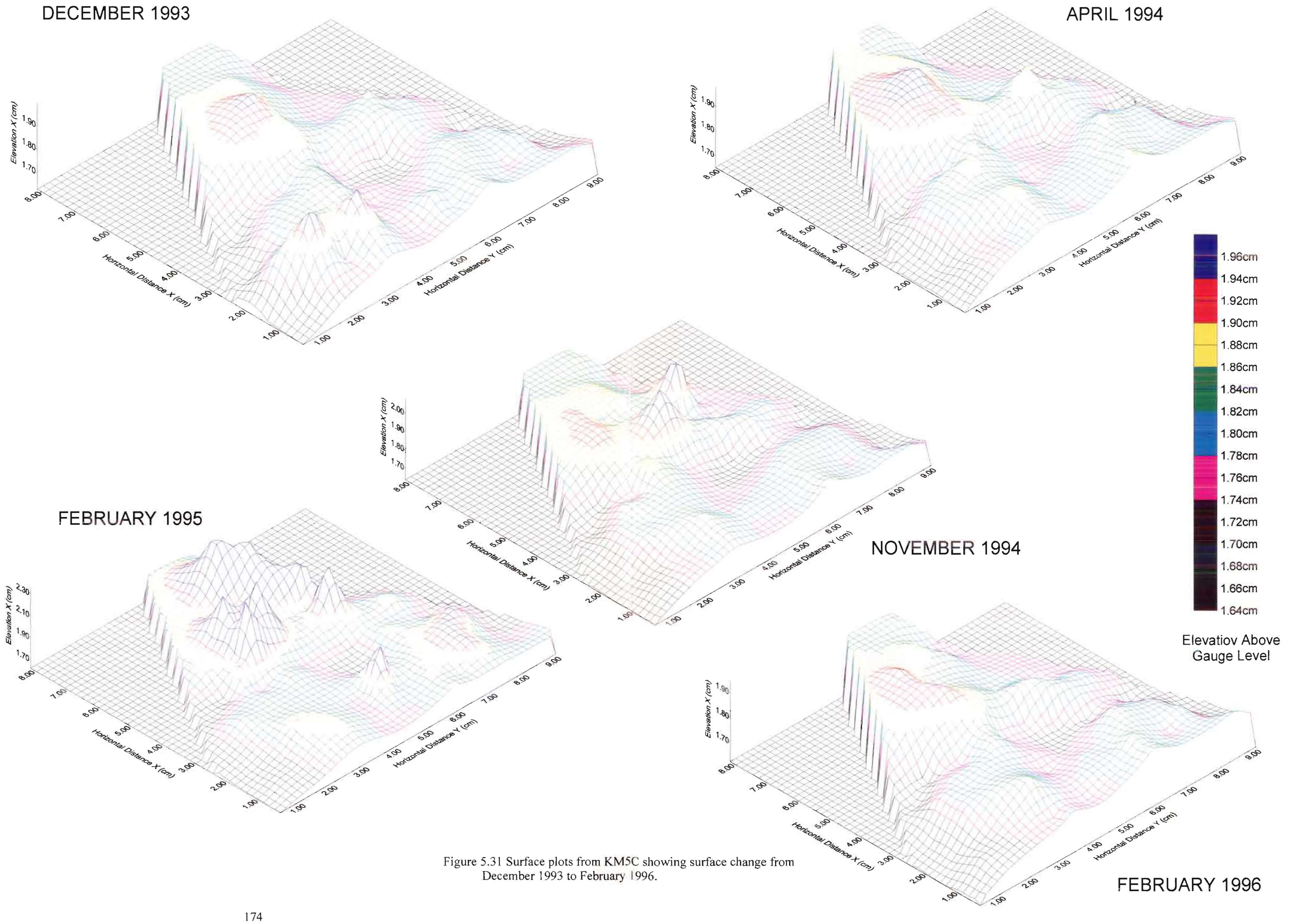

Figure 5.31 Surface plots from KM5C showing surface change from December 1993 to February 1996.

SURFACE PLOTS SHOWING CHANGES ON KM7C

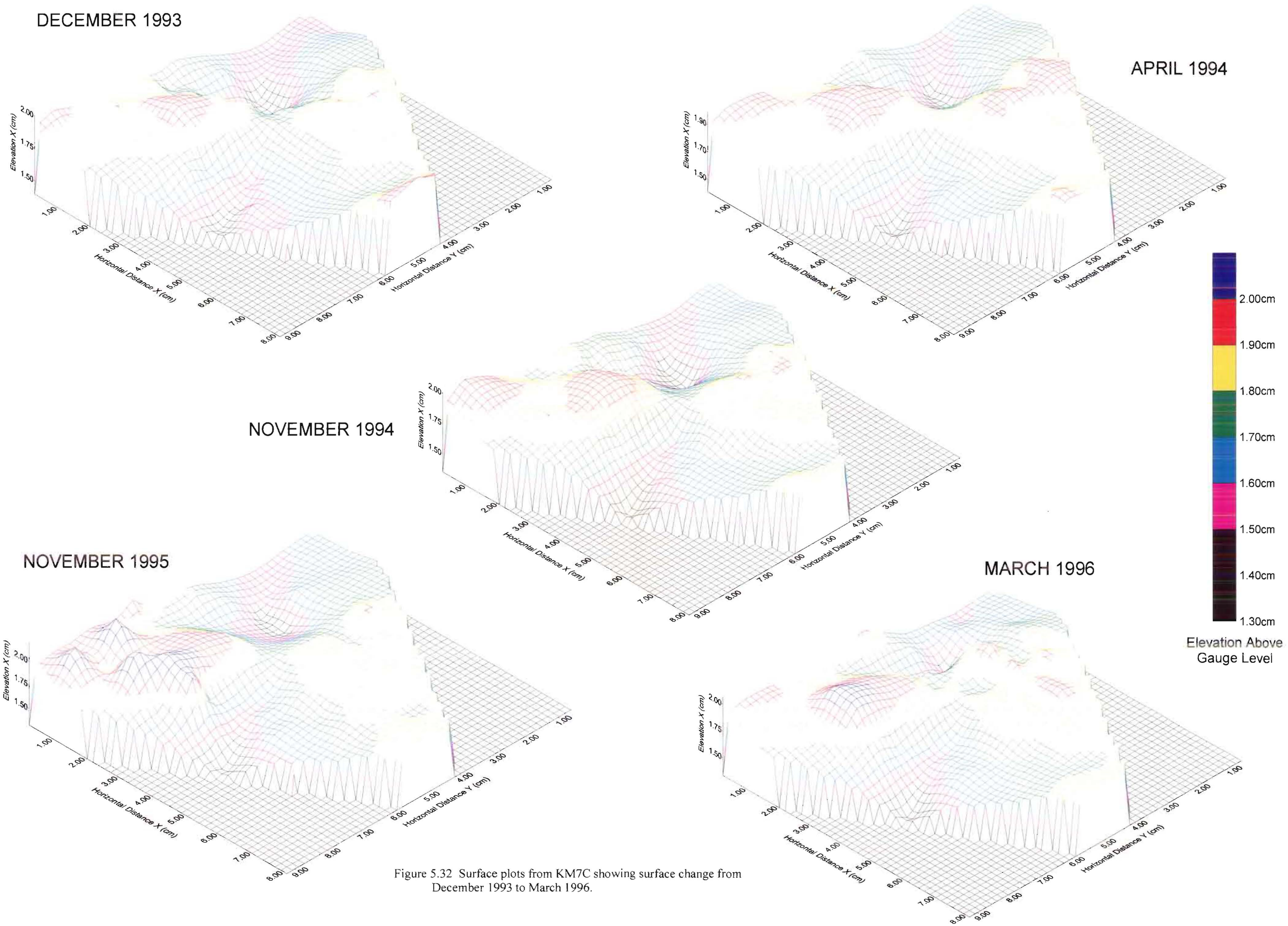

Figure 5.32 Surface plots from KM7C showing surface change from December 1993 to March 1996.

SUMMARY VOLUME DATA

Average annual rates of erosion by profile, lithology and platform type are presented in Table 5.38. Mean profile erosion varied from 2.804cm^3/45.4cm^2/yr on KM4 to 13.836cm^3/45.4cm^2/yr on KM6. These yields are expressed as a volume per time per area of a bolt site. As with linear erosion data the order of magnitude differences between Type A and Type B mudstone platforms are repeated. These data can be used to calculate the sediment volume yield from shore platforms at Kaikoura.

Table 5.38 Summary volume data

Platform Type	Profile	Average annual rate cm^3/yr/45.4cm^2
Type B	KM1	4.308
Type A	KM2	13.836
Type B	KM3	3.555
Type A*	KM4	2.804
Type B	KM5	3.579
Type A	KM6	12.435
Type A*	KM7	2.820
Grand Mean		6.191
*Limestone (Type A)		2.812
Mudstone		7.543
Type A Mudstone		13.135
Type B Mudstone		3.814

5.2.8 INTERPRETATION OF VOLUME CHANGE

From the erosion, swelling and volumetric data present in Section 5.2 some interpretation of processes operating on shore platforms can be made. Erosion occurs in two ways. The first is continual lowering of the surface which is most common on Type A platforms. The second process is one where the surface swells up and then flakes off, this is often repeated, but the net effect is lowering of the surface. This is found on Type B mudstone platforms and limestone platforms. It is proposed that the first process of continued surface lowering is a result of wetting and drying which causes the rock surface to dissolve. Wetting and drying causes repeated swelling and shrinkage which dislodges particles. The second means of erosion is caused by salt weathering. The growth and re-growth of salt crystals in the lattice of the rock pushes the surface of the rock up until it flakes away.

5.2.9 A SEDIMENT BUDGET FOR SHORE PLATFORMS ON THE KAIKOURA PENINSULA

Data from Table 5.39 can be used to calculate gross denudation of platforms on the Kaikoura Peninsula. This was achieved by extrapolating the volume data to the total area of the inter-tidal surface area of the peninsula. Such an exercise provides an estimation of the contribution of platform lowering to the littoral sediment budget of the Kaikoura Peninsula. Kirk (1977) reported the inter-tidal surface area of the peninsula as 0.77km^2. Given that there are significant differences in erosion rates between platform types and different lithologies it was deemed necessary to calculate the surface areas of Type A, Type B and of limestone and mudstone shore platforms. This was achieved by digitising a rectified 1:10000 aerial photograph of the peninsula using GIS software ARC INFO. The results of this are presented in Table 5.39.

The total inter-tidal surface area is 740579m^2, of this there are 211023m^2 of Type B mudstone platforms, 23084m^2 of Type A mudstone platforms, a total of 441864m^2 for all mudstone platforms and 298716m^2 of limestone shore platforms. Using these areas and the mean volumes of material eroded annually from each type of platform, the annual volume of material removed can be calculated. These results are also in Table 5.40. From Type B mudstone platforms 179m^3 of material was eroded annually, 668m^3 from Type A mudstone platforms and 185m^3 from limestone platforms. The total sediment yield from the inter-tidal surface of the Kaikoura Peninsula was 1032m^3/yr. Kirk (1977) also estimated the total inter-tidal erosion from micro-erosion meter measurements. This was achieved by deriving the quantity of material eroded per metre width of each profile annually, taking the average of all profiles, multiplying by the inter-tidal surface area of the peninsula and dividing by the average width. A total of 1226.6m^3/yr was calculated using this method. The result of 1032m^3/yr from this study compares well with Kirk's (1977) estimate. Table 5.30 also shows the percentage of material eroded from each platform type and lithology. Significantly, mudstone platforms account for 60 per cent of the inter-tidal area and contribute 82 per cent of the volume eroded annually. Type A mudstone platforms make up 31 per cent of shore platforms but yield 65 per cent of the volume eroded from the peninsula each year. This is significant in that it illustrates the difference in erosion rates between Type A and B platform proposed at the beginning of this chapter. While the results in Table 5.39 are interesting, it must be remembered that the calculated volumes eroded from shore platforms are an underestimate because erosion at larger scales, unmeasured with the TMEM has not be accounted for. It is the purpose of the next section to do this.

Table 5.39 Extrapolated volume erosion data for inter-tidal shore platforms at Kaikoura.

	Number of Bolt Sites	Total Platform Area m^2	Percentage of Area	Mean Erosion $cm^3/yr/45.4cm^2$	Percentage of Volume Eroded	Total m^3/yr
Type B Mudstone	16	211023	28.4	3.814	17.3	179
Type A Mudstone	8	230841	31.2	13.135	64.7	668
All Mudstone	24	441864	59.6	19.949	82.1	847
Limestone	11	298716	40.4	2.813	17.9	185
Grand Total	35	740579	100.0	6.191	100.0	1032

5.3 LARGER SCALE EROSION

This section presents results from two methods employed to assess erosion at scales larger than can be measured using the micro-erosion meter. Such an attempt was necessary because Kirk (1977) and Trenhaile (1980, 1987) both made the point that the micro-erosion meter technique cannot provide data on the amount of erosion caused by large scale block disintegration, or as Trenhaile (1980:17) called it "gross rates of downwasting". Two methods were employed to assess the contribution of quarrying of large blocks on the Kaikoura Peninsula to platform erosion.

5.3.1 THE EROSION FRAME AND DATA

It was recognised that the micro-erosion meter does not provide data on larger scale block disintegration of shore platforms. To address this problem an erosion frame (Fig 5.33) was constructed. The erosion frame was first used by Campbell (1970) to measure slope wash. It consists of a rectangular grid of aluminium bars which could be positioned on four permanently installed steel stakes (Goudie 1990). A depth gauge rod is placed in holes drilled in the frame and is used to measured the elevation of the surface. The erosion frame used at Kaikoura was modified and constructed with only three legs and the ends were machined in the same way as those of the micro-erosion meter. This allowed the same type of bolts from the MEM to be used. The frame has an area of $0.25m^2$ and was constructed to these dimensions to allow easy handling and transport. To facilitate the collection of data over a wider area five masonry bolts were installed instead of only three at each single erosion frame site. These bolts were arranged in a pattern that allowed the frame to be rotated 180° on the central bolt, doubling the area and allowing a total of 181 readings in an area of $0.5m^2$ (Fig 5.33).

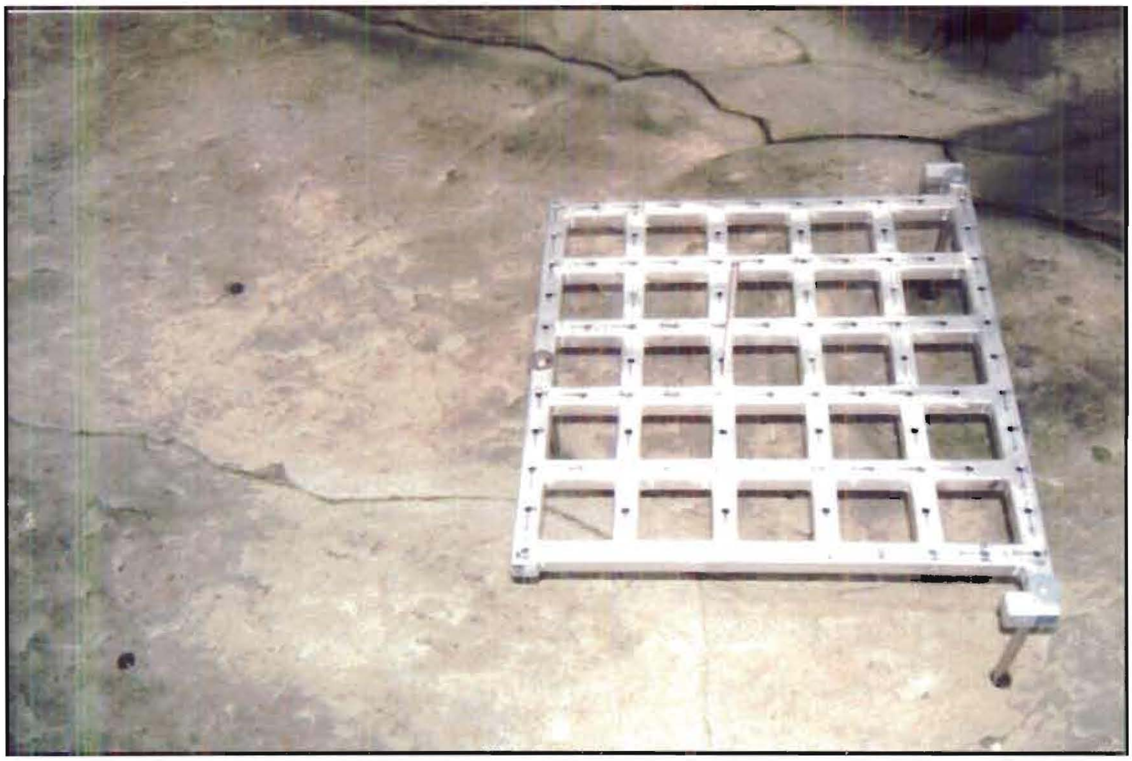

Figure 5.33 The erosion frame constructed for use at Kaikoura, and bolt positions.

As with micro-erosion meter bolt sites erosion frame sites were arranged in profiles across shore platforms. Five profiles were established, each with three bolt sites. These were located at the seaward edge of the platform the middle and on the landward margin of the platform. The location of these, which were fixed using G.P.S., are contained in Appendix Five. Three were placed on mudstone platforms and two on limestone platforms. Erosion frame sites were located next to KM3, KM4, KM5, KM6 and KM7. The accuracy of this technique is clearly much less than the micro-erosion meter. From repeated use it was estimated to be accurate to ±2mm. This was considered to be acceptable since it was intended to measure erosion occurring at the scale of centimetres rather than millimetres.

Measurement of erosion frame sites occurred only twice during the study period; in August 1994 and then in October 1996. Two sites, KB3C and KB5B did not yield data, KB3C was not accessible when visited in October 1996 because of waves washing over the bolt site and KB5B could not be found because of algae growth.

The erosion frame data required some form of screening to separate out larger scale erosion from that measured using the traversing micro-erosion data. This is because micro-scale erosion measured with the TMEM could be detected with the erosion frame. Since it is a question of scale of erosion then measurements that exceed TMEM and MEM results were considered to be physical disaggradation of fragments having sizes measured in tens of centimetres. Given that inter-survey erosion rates were as high as 11.240mm/yr on KM5E, 6.086mm/yr on KM4E and 4.894mm/yr on KM3A, erosion frame results less than 25mm were regarded as "micro-erosion" and for convenience values above 25mm were called "cobble erosion". Another better reason for using 25mm as a demarcation was because this is the maximum travel in the probe of the traversing micro-erosion meter.

Table 5.40 shows that only seven instances of cobble erosion were recorded on two erosion frame sites, KB1B and KB2A. A total of seven recorded instances of cobble erosion represents 0.3 per cent of all measurements, given that 13 bedstead sites were measured and there are 181 measurement positions at each site. If data from the erosion frame are extrapolated into volumes, by assuming that each piece eroded was a cube, then Type B platforms at Kaikoura yielded $279m^3$/yr and limestone platforms $27m^3$/yr. Relative to the volume calculations from the TMEM data erosion of $279m^3$/yr from cobble erosion, is 61 per cent of erosion on Type B platforms. On limestone shore platforms erosion of $27m^3$/yr, is 14.5 per cent of total erosion. Significantly no cobble erosion was measured on Type A platforms. From this it is assumed that cobble erosion does not contribute to erosion on Type A platforms at Kaikoura. These results suggest erosion at the scale measured with the erosion frame is of varying significance, depending on the underlying lithology. Some caution is needed in assessing these results, since volume calculations based on erosion frame data are unlikely to be accurate because the assumption that all pieces removed are cubes is unrealistic.

Table 5.40 Erosion frame data

Erosion Frame Profile	Bolt Site	Bolt Site	Bolt Site
KB1 29August 1994 to 13 October 1996	KB1A	KB1B	KB1C
	mm eroded	mm eroded	mm eroded
	-	52	-
	-	32	-
	-	39	-
No. of cobble erosion events	0	3	0
KB2 5 September 1994 to 16 October 1996	KB2A	KB2B	KB2C
	mm eroded	mm eroded	mm eroded
	30	-	-
	30	-	-
	25	-	-
	30	-	-
No. of cobble erosion events	4	0	0
KB3 21 November 1994 to 15 October 1996	KB3A	KB3B	KB3C
	mm eroded	mm eroded	mm eroded
	-	-	-
No. of cobble erosion events	0	0	0
KB4 4 September 1994 to 10 October 1996	KB4A	KB4B	KB4C
	mm eroded	mm eroded	mm eroded
	-	-	-
No. of cobble erosion events	0	0	0
KB5 25 November 1994 to 14 October 1996	KB5A	KB5B	KB5C
	mm eroded	mm eroded	mm eroded
	-	-	-
No of cobble erosion events	0	0	0

5.3.2 BLOCK EROSION

Larger scale "block erosion", as it has been termed by Trenhaile (1980, 1987) refers to the removal of rocks from platforms of sizes measured in metres. For the purposes of this study block erosion describes erosion debris larger than 256mm along the A axis. This size has been chosen based on the Udden-Wentworth size class for sediments. Determining the rate at which block erosion operates is particularly difficult. Instead, the contribution of this form of erosion was assessed relative to that measured with the micro-erosion meter and erosion frame. To do this, six study sites were chosen based on the location of four profiles. KM2, KM3, KM4, KM5, KM6 and KM7 were selected since these represent both lithologies, Type A and B platforms and a variety of exposures to the Kaikoura wave environment. At each site a visual survey was carried out to identify the presence of boulders on each platform. The area covered was 100m along shore from the profile line in both direction so that the area covered was 200 metres long by the width of the platform. In the case of KM4 and KM7, which are both less than 200m wide, the entire width was considered. As a boulder was found its general position on the platform was noted and the size of it was measured on the A, B, and C axis using a steel tape.

The first significant result was that at KM2, KM4, KM5 and KM6, no blocks were found. At KM3 19 blocks were found and measured in the area covered. Table 5.41 contains the size of measured blocks. The largest measured 3.97m in the A axis, 3.61m in the B axis and 1.63m in the C axis (Figure 5.34). Two others also had A axes in excess of 3m. Table 5.41 also contains the volume of each block calculated using the three axis measurements. The sum of all volumes was 56.962m^3. It is very difficult to assess the volume of material eroded by block erosion each year. Such an attempt would be complicated by the fact that larger blocks persist on platforms for some time. In the case of the four largest blocks in Table 5.41, these were observed in December 1993 and were still in the same positions in February 1996. Assuming this as a "residence" time the this block represents erosion at 19m^3/yr. Extrapolating this for the total area of Type B platforms then the an annual rate of erosion from block erosion would be 236m^3/yr. This is higher than the 179m^3/yr yielded by micro-erosion and less than 279m^3/yr from cobble erosion on Type B platforms at Kaikoura.

On KM7 two boulders were found, the dimensions of which are given in Table 5.42. The largest is shown in Figure 5.35. As with blocks on KM3 both of these were observed in December of 1993 and were still present at the end of the study period in February 1996. The total volume of these block was 1.520m^3. Extrapolating this value for the total area of limestone platforms then the an annual rate of erosion from block erosion would be $583m^3/yr$. This is significantly larger when compared with the volume of $185m^3/yr$ yielded from micro-erosion in Table 5.39.

No attempt was made to precisely mark the location of blocks on the platform, but the general trend on KM3 was for the largest boulders to be on the seaward edge of the platform and the smaller boulders to be closer to the backshore cliff. This pattern suggests that larger blocks originate from the erosion of the seaward cliff and smaller ones from erosion of the backshore cliff. Both blocks on KM7 were located at the landward part of the platform under an eroding cliff. Of course the location of a particular size of block on a platform does not clearly identify from where it originated. This point is important because an attempt to assess the relative contribution of each scale of erosion is complicated by considering where that material originated from. Block erosion can be derived from cliff retreat as well as surface lowering, but micro-erosion and cobble erosion as measured, can only be derived from surface lowering. It may not be valid to compare contributions of different scales of erosion.

Table 5.41 Dimensions of boulders found on KM3

Sample	A Axis (m)	B Axis (m)	C Axis (m)	Volume m^3
1	3.97	3.61	1.63	23.361
2	3.42	2.15	0.52	3.824
3	3.05	2.09	1.21	7.713
4	2.85	1.81	0.59	3.044
5	2.41	1.90	0.47	2.152
6	2.38	1.88	0.41	1.835
7	2.38	1.38	0.69	2.266
8	2.34	1.62	1.01	3.829
9	2.33	1.81	0.47	1.982
10	2.19	1.66	0.69	2.508
11	1.67	1.23	0.47	0.965
12	1.64	0.98	0.42	0.675
13	1.57	0.59	0.56	0.519
14	1.56	1.23	0.21	0.403
15	1.35	0.81	0.30	0.328
16	1.24	1.09	0.19	0.257
17	1.18	0.45	0.32	0.170
18	1.17	0.57	0.38	0.253
19	1.12	0.75	0.21	0.176
20	1.04	0.81	0.49	0.413
21	0.89	0.56	0.23	0.115
22	0.86	0.38	0.26	0.085
23	0.83	0.45	0.24	0.090
Total Volume m^3				56.962

Table 5.42 Dimensions of boulders found on KM7

Sample	A Axis (m)	B Axis (m)	C Axis (m)	Volume m^3
1	1.77	0.91	0.63	1.014
2	1.42	0.85	0.42	0.506
Total Volume m^3				1.520

Figure 5.34 The largest block on KM3 measuring 3.97m by 3.61m by 1.63m.

Figure 5.35 The largest block on KM7 measuring 1.77m by 0.91m by 0.63m.

Summary volume erosion data are shown in Table 5.43. This shows the relative contribution of each scale of erosion to shore platform erosion (both cliff and surface lowering). The occurrence of blocks on platforms at Kaikoura appeared to be limited, but extrapolating results for the inter-tidal area of the peninsula showed that cobble and block erosion was the most significant scale of erosion on Type B mudstone platforms and limestone platforms. The total volume of material eroded annually at Kaikoura has is estimated to 2156m^3/yr. When all platforms were grouped together the largest contribution came from micro-scale erosion (1032m^3/yr) and second was block erosion (818m^3/yr) followed by cobble erosion (306 m^3/yr).

Table 5.43 Summary volume erosion data for the inter-tidal area of the Kaikoura Peninsula.

	Micro-erosion (m^3/yr)	Cobble Erosion (m^3/yr)	Block Erosion (m^3/yr)	Grand Total (m^3/yr)
Limestone	185	27	582	794
Type A Mudstone	668	0	0	668
Type B Mudstone	179	279	236	694
Total	1032	306	818	2156

5.4 BACKSHORE AND LOW TIDE CLIFF RECESSION

The investigation of cliff erosion, both at the backshore and at the low tide cliff, forms an integral part of this thesis. It was shown in Chapters Two and Three that measured rates of backshore cliff retreat are necessary to test a number of models used to predict and describe shore platform development. The question of whether or not the low tide cliff retreats was also discussed, as were the difficulties in attempting to measure it. In order to assess rates of retreat of both cliffs, aerial photograph interpretation was employed. To this end aerial photographs of the Kaikoura Peninsula taken on 10 December 1942 were obtained from New Zealand Aerial Mapping and an aerial photograph taken on 7 December 1994 was obtained from Air Logistics New Zealand Ltd. Both sets of photographs were printed at a scale of 1:10000.

It was intended to render these photographs into digital form and utilise a image processing software package called ERDAS to assess changes in the positions of cliff lines. This technique required ground control points to be identified in the photographs and the precise position of these entered into the program, which then rectifies the image to remove distortion. Commonly used points include buildings or road intersections. Nine ground control points were identified in the 1994 photograph and located using differentially corrected G.P.S. A lack of human development of the peninsula made it impossible to locate these points in the 1942 photographs. The lack of ground control points was compounded by the fact that the 1942 photographs of the Kaikoura Peninsula occur on two prints as opposed to only one in 1994, thus requiring more than nine ground control points for 1942 depending on the degree of commonality of points on each print. The use of ERDAS had to be abandoned and another technique was used. This relied on comparing the seven study profiles between the two photographs. Measurements were taken using digital callipers and made to an accuracy of 0.01mm. In the case of KM6 it was not possible to identify a point common to both photographs and instead a photograph taken on the 7 May 1974 was used. This had been used by Kirk (1975c) in his assessment of coastal change at Kaikoura.

Assessment of low tide cliff erosion on Type B platforms relied on the same technique as for the backshore retreat. The retreat of the seaward edge of Type A platforms was also included in the analysis. The problem with this is that the error inherent in air photograph interpretation is probably greater than the rate of retreat of the low tide cliff where retreat is occurring. If backshore cliff retreat occurs in tens of centimetres per year, and accepting Edward's (1941) view that a platform is maintained because the high tide cliff retreat rates exceeds low tide cliff retreat, then any rate of retreat of the low tide cliff probably occurs at an order of magnitude less than that of the high tide cliff. The ability to detect this with traditional air photograph interpretation techniques seems low. Alternatively, accepting Trenhaile's (1974a) parallel retreat model, then low tide retreat must occur at a rate similar to that of the backshore cliff. This should be detectable in air photographs taken 52 years apart.

The results of measurement of backshore, low tide cliff and seaward edge erosion on platforms at Kaikoura Peninsula are presented in Table 5.44. In the case of KM6 the recession rate was determined from profile surveys carried out in 1973 and 1994. The lack of ground control points in the 1942 photographs made it difficult to compare shoreline positions with the 1994 photographs. Backshore erosion rates varied from no change at KM4 to 1.01m/yr on KM6. At KM4 the platform is backed by a stable cobble and pebble beach. The high rate of retreat on KM6 is because of erosion of loosely consolidated lagoon deposits behind the platform.

In Table 5.44 details of backshore characteristics of each profile are recalled from Table 4.4. At KM1 the annual rate of retreat is 0.10m/yr, but this rate must be viewed cautiously, since a sea wall was built, (and subsequently failed) between 1942 and 1994. Debris from it still remains today. This has no doubt stopped back shore recession for a period of time and subsequently distorted the rate of retreat. The rate of retreat at KM2 has been 0.67m/yr since 1942. This rate is rapid because of the presence of easily eroded lagoon and beach deposits which have been removed, and only a pebble beach remains. At the same location Kirk (1975c) calculated a retreat rate of 0.24m/yr between 1942 and 1974. This was a period dominated by the presence of Wairepo Lagoon (Figure 4.1), which is likely to account for the marked difference in retreat rates. At KM3 the rate of retreat between 1942 and 1994 has been 0.11m/yr. Kirk (1975c) calculated recession rates in mudstone cliffs of 0.24m/yr, although not at the location of KM3. The rate of retreat at KM5 was 0.23m/yr between 19442 and 1995. This compares well with findings of Kirk (1975c) who calculated 0.24m/yr. KM7 is the only limestone platform with an active cliff backing it and here the rate of retreat was 0.05m/yr. Kirk (1977c) measured rates of change in nearby limestone cliffs at 0.05 and 0.10m/yr. Results of low tide cliff retreat assessment are also shown in Table 5.44. There was no measurable difference in the position of low tide cliffs on any of Type B platforms nor on the seaward edge of Type A platforms of the study profiles. The implication of this is considered in the next section.

Table 5.44 Backshore and low tide cliff erosion rates at Kaikoura calculated from aerial photography interpretation.

Profile	Backshore Erosion 1942 to 1994 (m)	m/yr	Backshore	Low Tide Cliff and Seaward Edge Erosion
KM1	5.27	0.10	Pebble & cobble beach	No Change
KM2	35.01	0.67	Pebble beach & road	No Change
KM3	6.18	0.11	Cliff	No Change
KM4	No Change	0.00	Pebble & cobble beach	No Change
KM5	4.65	0.23	Hillslope	No Change
KM6	18.71#	0.91#	Lagoon deposit	No Change
KM7	2.76	0.05	Cliff	No Change

Note: # = Measured from surveyed profile.1974 to 1994 (20.58 years).

5.4.1 DO THE SEAWARD EDGES OF PLATFORMS RETREAT?

There is doubt concerning the reliability of the air photography interpretation as a means of assessing low tide cliff retreat. Another method to investigate low tide cliff retreat rates was used. Initially it involves accepting that low tide cliffs do retreat and that there has been no inheritance. Next, is necessary to predict the total amount of retreat of the landward cliff since platform development began, using the measured rate of cliff retreat from aerial photograph interpretation. This is done by multiplying the retreat rate by the amount of time sea level has been at the elevation it is today. Shulmeister and Kirk (1993) report that sea level reached its present position on the North Canterbury coast 6000 years B.P. The measured widths of platforms can then be subtracted from the total retreat of the landward cliff to predict the amount of retreat of the low tide cliff. Table 5.45 shows total predicted backshore cliff recession for KM3, and KM5 in the last 6000 years. These profiles have been used because they are the only two Type B profiles. Included in this table are the widths of those platform profiles. Subtracting the widths from the total recession of the backshore cliff predicts the total amount of low tide cliff recession in the last 6000 years (Table 5.45). This method predicts that the low tide cliffs of KM3, and KM5 could have retreated 575, and 1315m, respectively in the last 6000 years. It is then possible to use these results to estimate the rate of low tide cliff retreat, as is also shown in Table 5.45. Calculated retreat rates in the case of KM3 are an order of magnitude less than the backshore cliff retreat rates but are the same order on KM5.

Table 5.45 Predicted platform retreat

Profile	Retreat Rate of Backshore cliff (m/yr)	Total Predicted Recession (m)	Modern Width (m)	Total low Tide Cliff Recession (m)	Low Tide Cliff Erosion Rate m/yr	Total Low Tide Cliff Retreat 1942 to 1994 (m)
KM3	0.11	660	85	575	0.095	4.94
KM5	0.23	1380	65	1315	0.219	11.39

If the predicted rates of retreat of the low tide cliffs are used to estimate the total recession during the 52 year period of the aerial photography record, then it should be possible to estimate the retreat that would have occurred in that time interval. Table 5.44 shows that the total amount of predicted erosion in the last 52 years on the low tide cliffs of KM3, and KM5 was 4.94, and 11.39m respectively. These changes should be detectable in the aerial photographs but are not. Referring back to Table 5.45, these predicted changes in the position of the low tide cliff are not to be found.

Two different conclusions can be drawn from this analysis. First, based on the validity of the methodology, low tide cliff recession occurs at the range of rates predicted in Table 5.45. The lack of evidence of it in the aerial photographs is difficult to explain, but may be as a result of inaccuracies in the technique. The second conclusion is that because neither actual nor predicted low tide cliff retreat can be detected in the aerial photographs, then it is not occurring at rates above the detection limit. The minimum detectable rate of change with the scale of the air photograph used is 0.01m. There is further evidence to support this view. If the position of the backshore cliff is located at 6000 years B.P. and the depth of water at this position today is noted, then the total amount of erosion that has occurred can be evaluated. The position of KM3 at 6000 years B.P. was 575m seaward and 1315m for KM5. From Figures 4.18 and 4.25 the depth of water 575m off KM3 is -18m, and more than -18m, 1315m off KM5. This shows that a considerable amount of submarine erosion must have taken place in the last 6000 years, something that tends not to support the view that low tide cliff retreat has occurred. However, while it is possible for this amount of erosion to take place it is doubtful that it could be achieved in only 6000 years. Horikawa and Sunamura (1970) showed that the equilibrium time need to develop the offshore profile in Pliocene mudstones in the Byobugaura area of Japan was 30000 years. Based on the above evidence either of two conclusions can be made. First there has been no low tide cliff recession in the 52 years between 1942 and 1994. Or second that there has been, but at less than the detectable rate.

5.5 CONCLUSIONS

This chapter has presented measured rates of erosion on shore platforms on the Kaikoura Peninsula. Surface lowering rates on platforms were shown to vary widely. The range of actual erosion between measurement periods was 8.193mm, between 0.057 and 8.250mm. The range of data for total erosion measured was 19.804mm, between 0.070 to 19.874mm. Micro erosion data were positively skewed with standard deviations of 1.071 for actual erosion between measurements and 2.190 for total erosion between the first and last measurements. In terms of equivalent annual erosion rates Type A mudstone platforms at Kaikoura eroded at a rate of 1.983mm/yr, Type B mudstone platforms at 0.733mm/yr and limestone platforms at 0.875mm/yr. The grand mean lowering rate for shore platforms at Kaikoura was 1.130mm/yr. Rates of surface lowering were found to be in close agreement with other studies at Kaikoura (Kirk 1977; Stephenson and Kirk 1996) and from elsewhere around the world. From this it is apparent that rates of surface lowering on shore platforms are now much better known.

A number of findings have been made with regard to erosion on shore platforms. Surface lowering was shown to be different by an order of magnitude on mudstone Type A and B platforms, with Type A eroding faster than Type B platforms. This difference between platform type was not statistically significant. Considering the demarcation between the two types based on compressive strength reported in Chapter Four then it is concluded that the rate of erosion is controlled by rock hardness. Erosion rates were also found to be higher during summer than winter, suggesting weathering plays a significant role in platform development.

Platform surface lowering rates were examined to investigate cross shore variations. A cross shore pattern similar to that found by Kirk (1977) would offer the first evidence to support the proposal that marine and subaerial processes are zonally distinct across platforms. Erosion rates did not display the same cross shore pattern found by Kirk (1977). Instead rates were higher on the inner landward margin of platforms and decreased seaward on five profiles. On the other two the pattern occurred in the opposite direction. The patterns found are not grouped by platform type (A and B).

Surface swelling was observed on all bolt sites at Kaikoura. This phenomenon has also been noted by Kirk (1977) and Mottershead (1989). This study presented the first detailed examination of it. It is proposed that swelling is caused by salt crystal growth in the lattice of rocks, and wetting and drying causing expansion and shrinking. Surface swelling up to 8.882mm was observed and values of 4 and 5mm were common. In one instance swelling over 92.5 per cent of a bolt site surface was recorded. The duration of swelling was more difficult to measure; but it was shown how some swelling persisted over 697 days, while other events lasted between 86 and 168 days. Shorter term swelling was found to occur superimposed on longer term events. It was noted that future investigations of swelling will require measurements at closer intervals - perhaps even on a daily basis. The magnitude and frequency of swelling were greater on Type B mudstone platforms than on Type A mudstone platforms. Swelling was of a similar nature on Type A limestone platforms to Type B mudstone platforms.

The analysis of both erosion and swelling led to the proposal that both were linked to season. The occurrence and magnitude of both appeared higher during the summer than winter. This was supported by the observation that erosion rates are higher in summer. To test this Chi Square tests were used to see if there was an association between season and swelling and erosion. Tests were carried out on individual bolt sites, and on each profiles; 74 per cent of bolt sites and all profiles were shown to have the occurrence of erosion and swelling controlled by season. A seasonal control indicates subaerial weathering in the form of salt weathering and wetting and drying is a major erosional process. Summer provides better conditions for these processes with a wider range of temperatures than in winter.

For the first time, traversing micro-erosion meter data were plotted to provide three dimensional representation of bolt surfaces using a computer software program called SURFER. This clearly illustrated surface lowering and swelling. For the first time erosion rates from the TMEM were expressed as volumes. This was taken further to calculate the amount of material eroded each year from platform surfaces. From micro-erosion, over a $1000m^3/yr$ is removed from the inter-tidal surface of the Kaikoura Peninsula. The calculation of volume of material eroded also supported the view that two types of erosive processes produce two forms of erosion. This was shown by the differences between gross and net volume totals. If the gross volume is large and the net volume is small then the surface has been affected by swelling. For example, on KM1B the gross volume eroded was $4.359cm^3$ and the net volume was $1.898cm^3$. This site was eroded more by salt weathering than by wetting and drying. The end effect is only a small amount of real surface lowering relative to Gauge Level, despite the site having $4.359cm^3$ of material eroded from it. Other sites showed no difference between net and gross erosion.

From all TMEM data some interpretation of processes of erosion was made. Erosion on Type A platforms was a continual lowering of the surface. The interpretation given to this was erosion is a result of wetting and drying which causes the rock surface to dissolve. On Type B platforms the process is one where the surface swells up and then flakes off, this is often repeated but the net effect is lowering of the surface. This means of erosion was proposed to be caused by salt weathering. It is the growth of crystals that cause swelling.

Larger scales of erosion were investigated and shown to be as important as erosion measured using the traversing micro-erosion meter on Type B mudstone and limestone shore platforms. It was noted that better data are required to fully assess the contribution of this scale of erosion to platform development. It was also noted that quantifying the contribution of boulder erosion to platform development is very difficult. Expressing it as rate or volume per time is complicated by the long residence time on platforms of very large boulders. Over a total of 2156m^3/yr of material was eroded from shore platforms at Kaikoura.

Cliff recession around the Kaikoura Peninsula was measured from aerial photographs taken 52 years apart. At some site no cliff retreat was measured and at other rates of retreat varied from 0.05m/yr to 0.91m/yr: depending on the type of backshore, limestone cliffs in the former and lagoon deposits in the case of the latter. These aerial photographs were used to try and determine whether or not the low tide cliff on shore platforms erodes. Measurements taken from the aerial photographs indicated that no erosion occurred, but concern was expressed because the rate of erosion might be less than what could be detected with the measurement technique. Further analysis using the total predict retreat of the backshore cliff provided conflicting evidence both for and against low tide cliff retreated. Based on this two conclusions were drawn. 1) Either that the low tide cliff on Type B platforms do not retreat on shore platforms at Kaikoura or 2) retreat occurs at rates less than what is detectable.

This chapter has used morphological data to interpret processes operating on shore platforms at Kaikoura. The warning of Mii (1962) about using morphology to do this has not been forgotten. Processes of erosion inferred above require further investigation. This is because measurements of erosion do not of themselves indicate the process or processes responsible for rock removal. In particular an examination of marine processes is required because no evidence was found in the erosion data for it and a large part of the literature reviewed in Chapters Two and Three indicated it should be. The proposals made above concerning the role of subaerial weathering will be reassessed after both marine and weathering processes have been examined in Chapter Six.

6. PROCESSES OF EROSION

6.1 INTRODUCTION

This chapter is concerned with identifying processes causing erosion on shore platforms at Kaikoura. It presents investigations of processes proposed by other researchers as causing the development of shore platforms. Surprisingly in Chapter Five it proved not to be possible too adduce evidence that marine processes of erosion are developing platforms at Kaikoura. Given that waves can be observed on shore platforms and that erosion of the platforms has also been demonstrated, the question that needs to be answered is, do marine processes cause erosion? There is also a need to determine which weathering processes occur. In Chapter Five it was proposed that subaerial weathering is an erosional agent on shore platforms at Kaikoura; this was based on the interpretation of morphological change. Heeding the warning sounded by Mii (1962) that morphology is an ambiguous indicator of process, then direct investigation of weathering processes is necessary to further evaluate the proposition that subaerial weathering causes erosion on platforms at Kaikoura.

6.2 WAVE PROCESSES

Waves occur on shore platforms when the tide permits. This is an observable fact, but do they cause erosion? Previous investigations of the role of waves in shore platform development have relied on deep water wave data and assumed a causal role in erosion (Sunamura 1978a, 1983, 1990, 1991; Trenhaile 1983a; Trenhaile and Layzell 1983; and Tsujimoto 1987). No attempt has been made to directly assess the competency of waves to cause erosion on platform surfaces. This section presents both deep water wave data and the results of measuring waves on shore platforms.

6.2.1 OFFSHORE WATER WAVE DATA

During the period 1 June 1996 to 9 July 1996 the National Institute of Water and Atmospheric Research Ltd under contract from CANDAC-PERRY Ltd, deployed a Wave Rider buoy 8 km east of the Kaikoura Peninsula, located at 42°23′00″ S 173°51′00″ E. The depth of water below the wave rider was 82m. Data were averaged at 20 minute intervals and included significant wave height, maximum wave height and period. The data from this instrument were made available to the author by CANDAC-PERRY Ltd.

Figure 6.1 displays daily mean significant wave height from the Wave Rider data. This has been generated by averaging the 20 minute interval data to derive a mean significant wave height for each day. Mean significant wave height varied through the deployment period from a maximum of 3.58m on 2 June 1996 to a minimum of 0.94m on 27 June 1996. No data were recorded on 13 June 1996 due to instrument failure. The average significant wave height for the deployment period was 1.78m. In terms of the sea state code presented in Table 4.1, 13 per cent of the record can be described as sea state three (slight) when waves were between 0.5 and 1.25m in height. Sea state four (moderate) occurred 74 per cent of the time when waves were between 1.25 and 2.5m. For the remaining 13 per cent of the record, sea state five (rough) occurred and waves were between 2.5 and 4.0m high.

Figure 6.2 displays mean maximum wave height for each day derived by averaging the 20 minute interval maximum wave height data. Included in Figure 6.2 are maximum wave heights recorded on each day. Mean maximum wave height ranged from a maximum of 5.4m on 2 June 1996 to a minimum of 1.4m on 27 June 1996. The largest maximum wave height was 7.5m recorded on 2 June 1996. The smallest maximum wave height was 1.4m recorded on 27 June 1996. Average maximum wave height during the deployment period was 4.06m.

Mean daily wave period and daily maximum wave period data are presented in Figure 6.3. Mean daily period ranged from 5.2 seconds on 3 July to 8.5 seconds on 2 June 1996, with the average for the period being 6.8 seconds. Maximum wave periods ranged from 5.9 seconds on 3 July to 9.7 seconds on 2 ,6 and 7 June 1996.

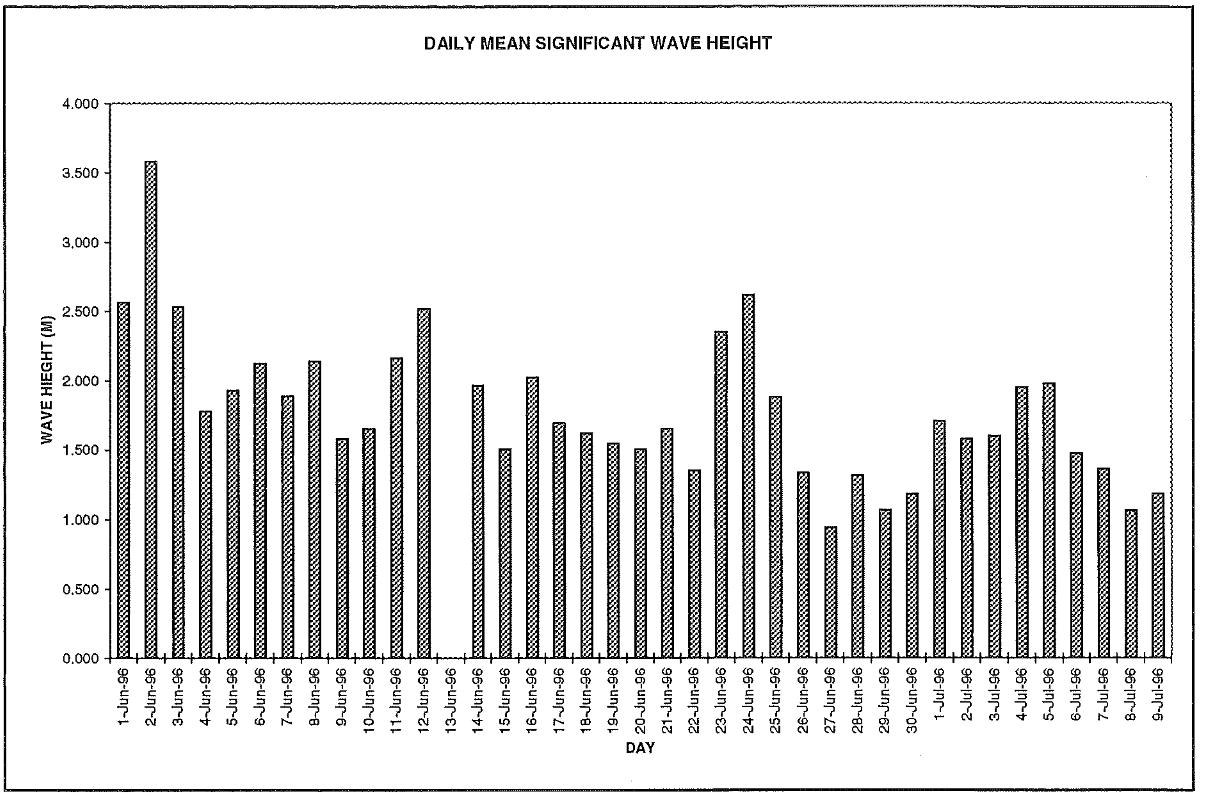

Figure 6.1 Wave rider data showing daily mean significant wave height from June to 9 July 1996 (CANDAC-PERRY Ltd).

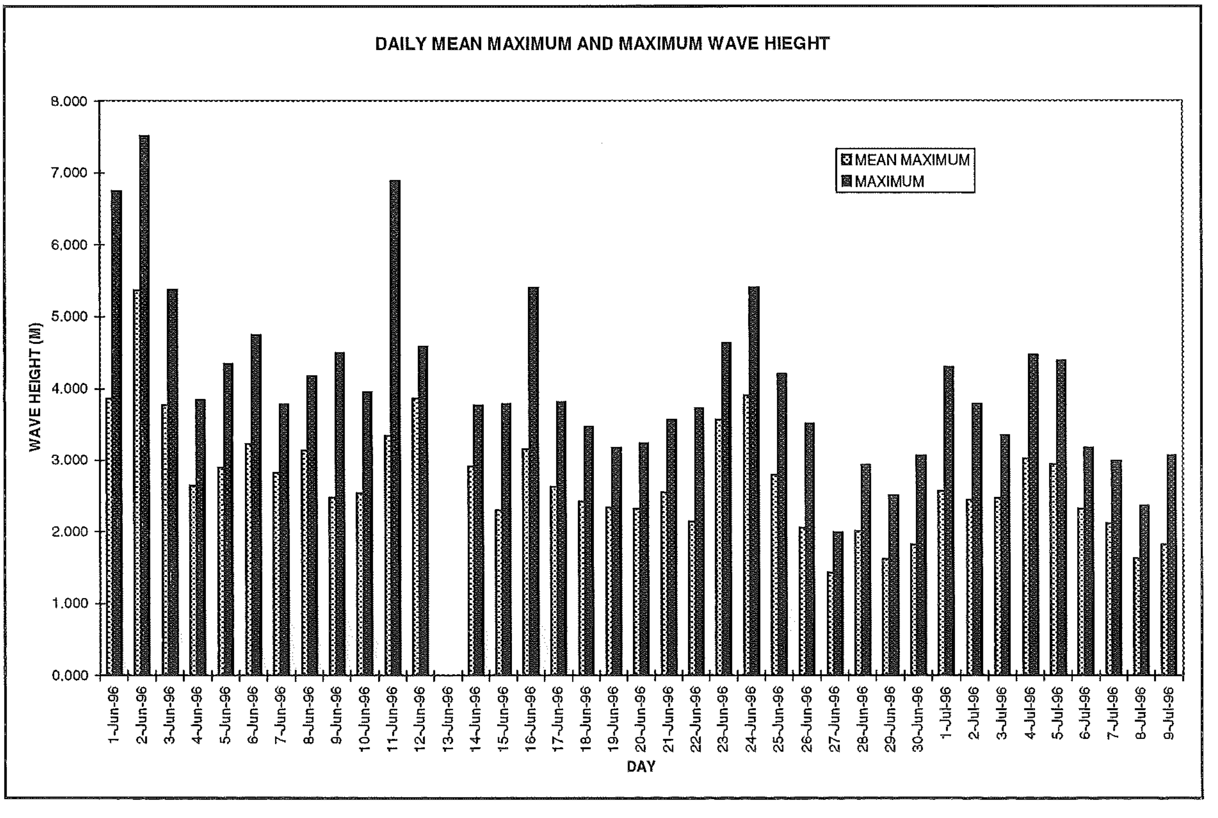

Figure 6.2 Wave rider data showing daily mean maximum and maximum wave height (CANDAC-PERRY Ltd).

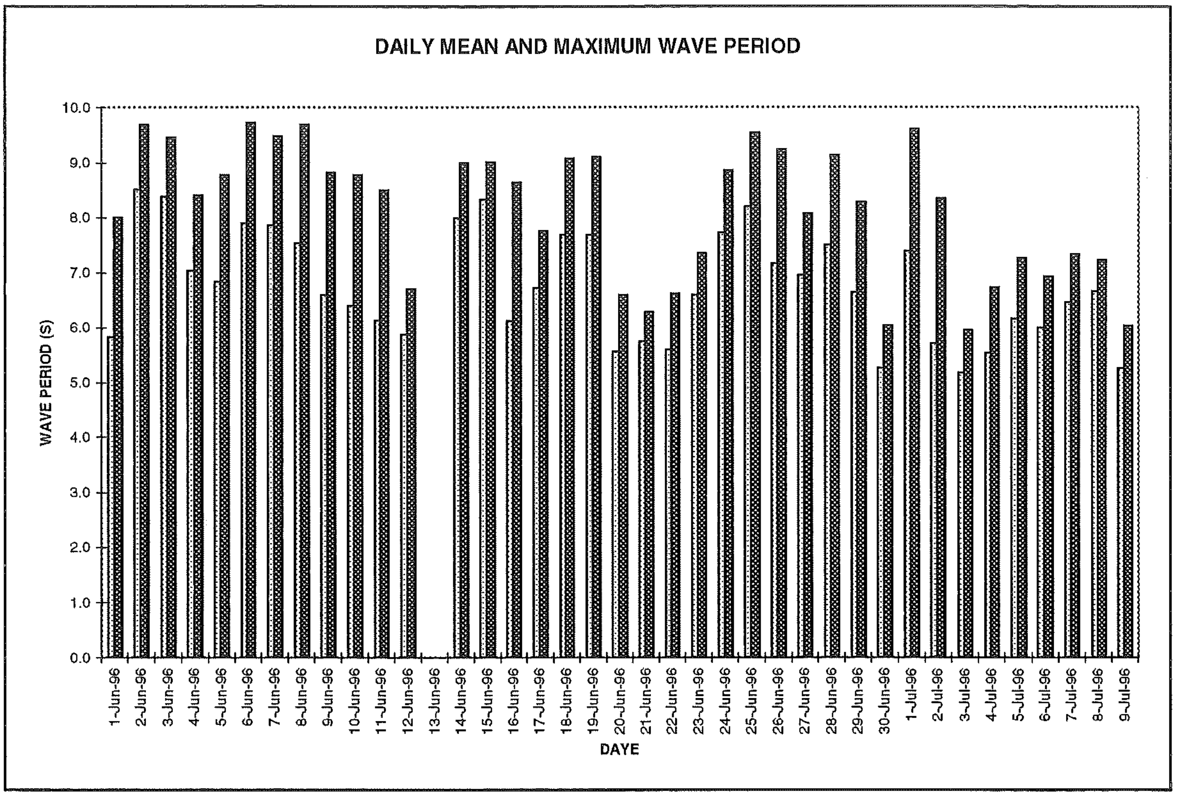

Figure 6.3 Wave rider data showing daily mean and maximum wave periods (CANDAC-PERRY Ltd).

WAVE ENERGY FLUX

Wave energy flux was calculated from the offshore data using daily mean significant wave height and daily maximum wave height. Calculations were made using a computer software package, Automated Coastal Engineering System 1.05 (ACES) developed by the Coastal Engineering Research Center. This software package is designed to calculate wave energy flux using the equation:

$$\bar{P}_o = \bar{E}_o C_{go}$$

6.1

where: $\bar{P}_o$ = wave energy flux (N.m/s per m of crest)

$\bar{E}_o$ = deep water average energy density given by:

$$\bar{E}_o = \frac{\rho g H_o^{\ 2}}{8} \qquad \textbf{6.2}$$

where: $\bar{E}_0$ = average energy density ($N.m/m^2$)

ρ = density of sea water (1005kg)

g = acceleration due to gravity (9.81m/s)

H_o^2 = deep water wave height (m)

C_{go} = wave group velocity (m/s)

Wave energy flux will be used to examine the amount of deep water wave energy delivered onto shore platforms after consideration has been given to onshore wave data. Figure 6.4 shows daily wave energy flux calculated from mean significant wave height and daily maximum wave height. From mean significant wave height, wave power ranged from 5900 to 106700N-m/s-m of crest and calculated from maximum wave height it ranged from 31400 to 5370002N-m/s-m of crest.

The data set collected during the six week deployment of the Wave Rider shows a range of wave condition was incident on shore platforms at Kaikoura. The wave environment was characterised by high energy swell and storm waves as well as periods of relative calm. A number of high energy storm events were recorded showing that waves were not trivial in a geomorphic sense. These storm events should be significant to shore platforms.

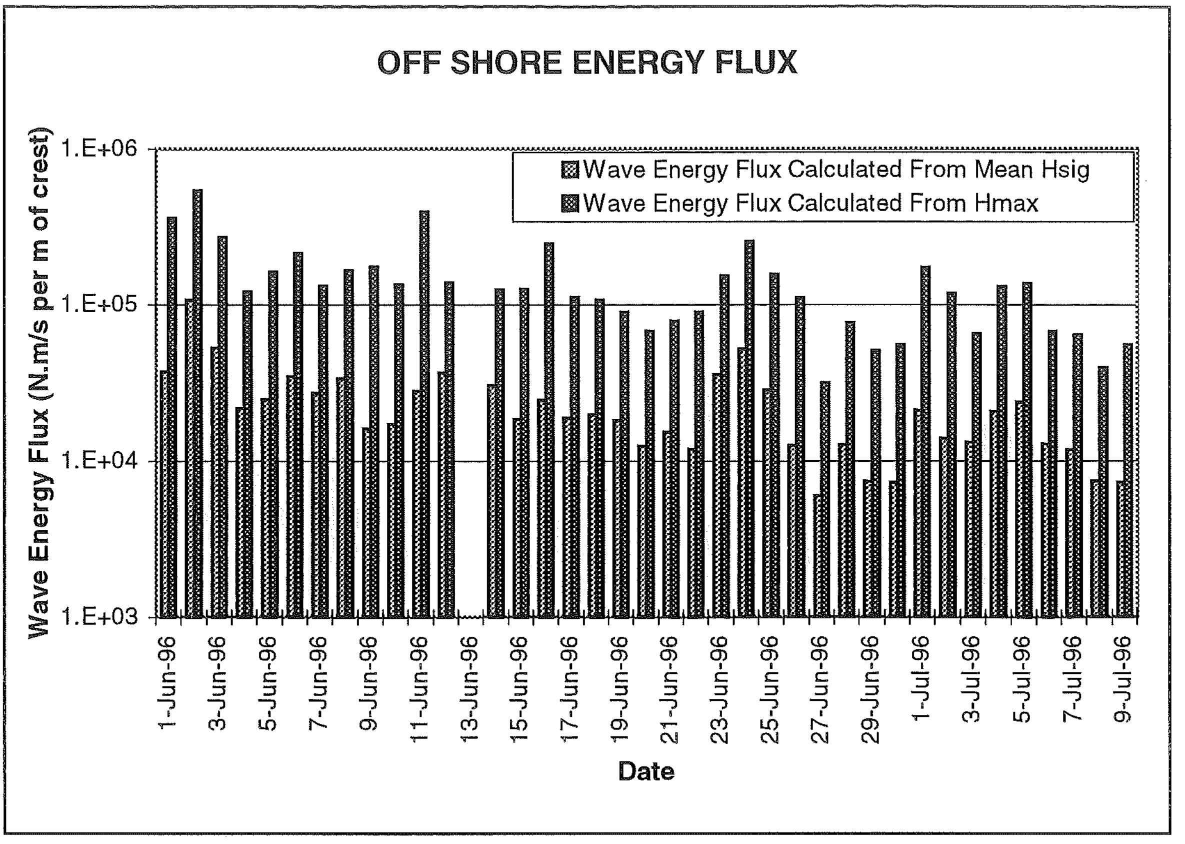

Figure 6.4 Offshore wave energy flux calculated from daily mean significant wave height and daily maximum wave height (CANDAC-PERRY Ltd).

6.2.1.1 WAVE BREAKING

It will be recalled from Chapter Two that doubts were raised concerning the role of breaking waves and associated hydraulic forces in shore platform erosion. It was argued that breaking waves never break directly on platforms surfaces, the low tide cliff or the landward cliff. Using the deep water wave data, the ACES program, offshore profile data and tidal data, it has been possible to calculate breaker height and depth of water at breaking. Using depth of breaking and profile data the position where wave breaking occurred in relation to a platform could also be calculated. Breaker heights and depths were calculated for three sites around the Kaikoura Peninsula. These three sites correspond to where waves were measured on platforms, KM2, KM3 and KM5. Three assumptions were made during this analysis:

1) all waves were incident on the three study sites;
2) the offshore topography sloped uniformly; and
3) waves reach the platforms at high tide.

Figure 6.5 presents breaker depths and heights calculated from significant wave heights recorded by the Wave Rider buoy off KM2. Maximum breaker height was 4.39m on 2 June 1996. This wave broke in a depth of water of 5.15m. Using the profile data from KM2 tidal data and assuming that this breaker occurred at the peak of the high tide then the wave broke 279m from the seaward edge of KM2. The seaward edge of all three platforms was identified using tidal data for the period 1 June to 9 July 1996. The elevation of the lowest low tide during that period was marked on each profile. The smallest calculated breaking wave occurred on 27 June 1996 and was 1.45m high. This wave broke in 1.62m of water, 3m from the seaward edge of KM2. All other predicted breaker heights and depths of breaking occurred between 279 and 3m offshore. From this analysis it is clear that no breaking waves impacted directly on KM2 during the period 1 June 1996 to 9 July 1996.

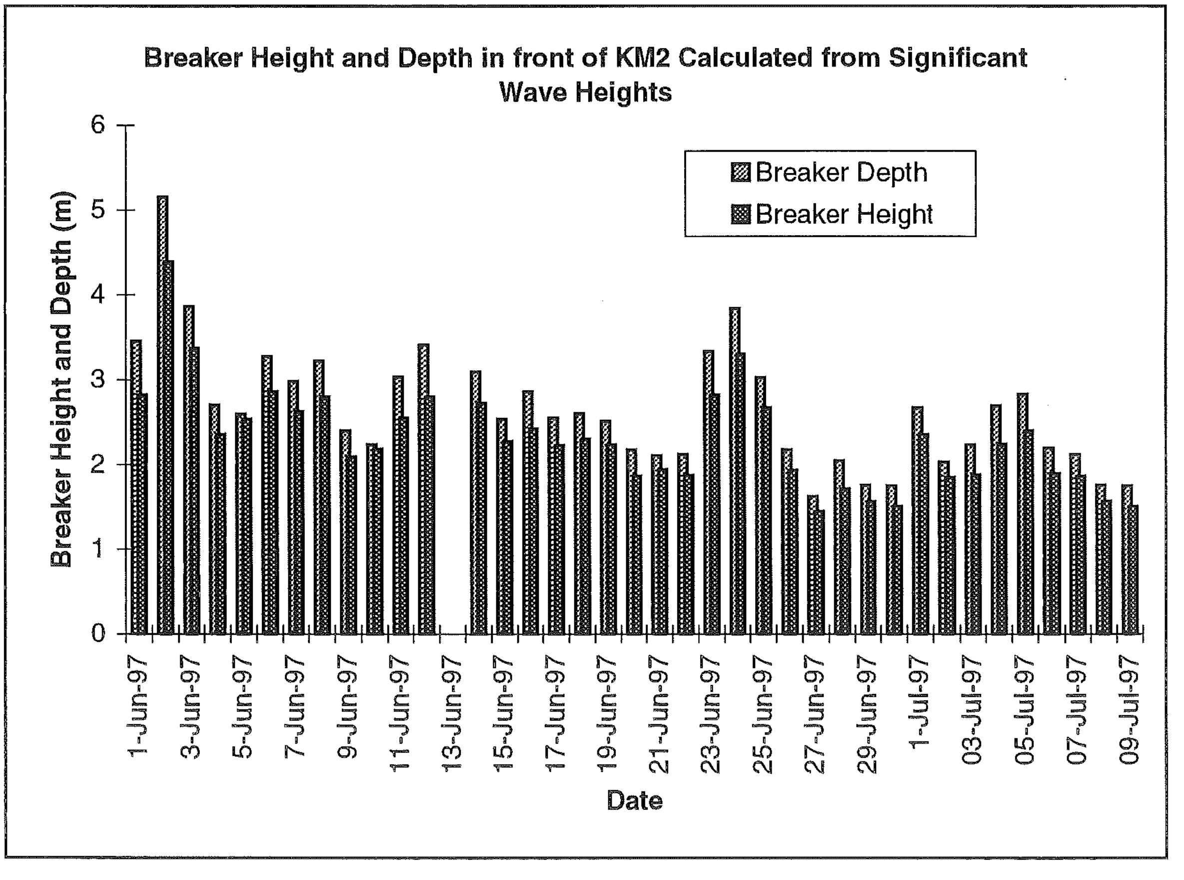

Figure 6.5 Breaker depth and height in front of KM2 calculated from deep water significant wave height.

Figure 6.6 presents calculated breaker depths and height off KM2 calculated from maximum wave heights recorded by the Wave Rider buoy. Maximum breaker height was 8.16m on 2 June 1996. This wave broke in a depth of water of 10.04m, 477m from the seaward edge of KM2. The smallest calculated maximum breaking wave occurred on 27 June 1996 and was 2.76m high. This wave broke in 3.14m of water, 149.5m from the seaward edge of KM2. All other predicted breakers occurred between these two distances, offshore.

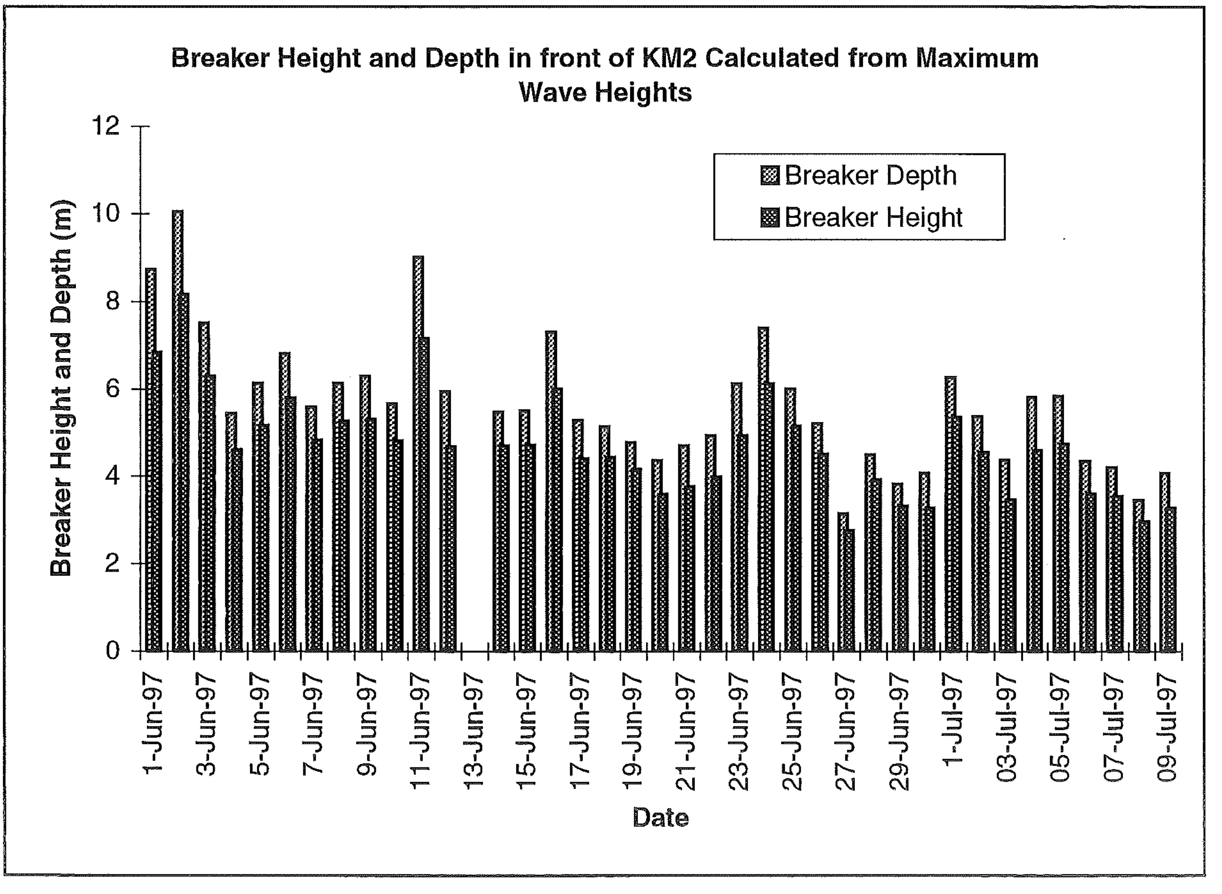

Figure 6.6 Breaker depth and height in front of KM2 calculated from deep water maximum wave height.

Figure 6.7 presents calculated breaker depths and height seaward of KM3 using mean daily significant wave heights recorded by the Wave Rider buoy. Maximum breaker height was 4.5m on 2 June 1996; this wave broke in a depth of water of 4.7m. Using the profile data from KM3 and assuming that this breaker occurred at the peak of the high tide, this wave broke 32m from the seaward edge of KM3. The smallest calculated breaking wave occurred on 27 June 1996 and was 1.49m high; this wave broke in 1.43m of water. Profile data showed that this wave broke on the seaward edge of KM3.

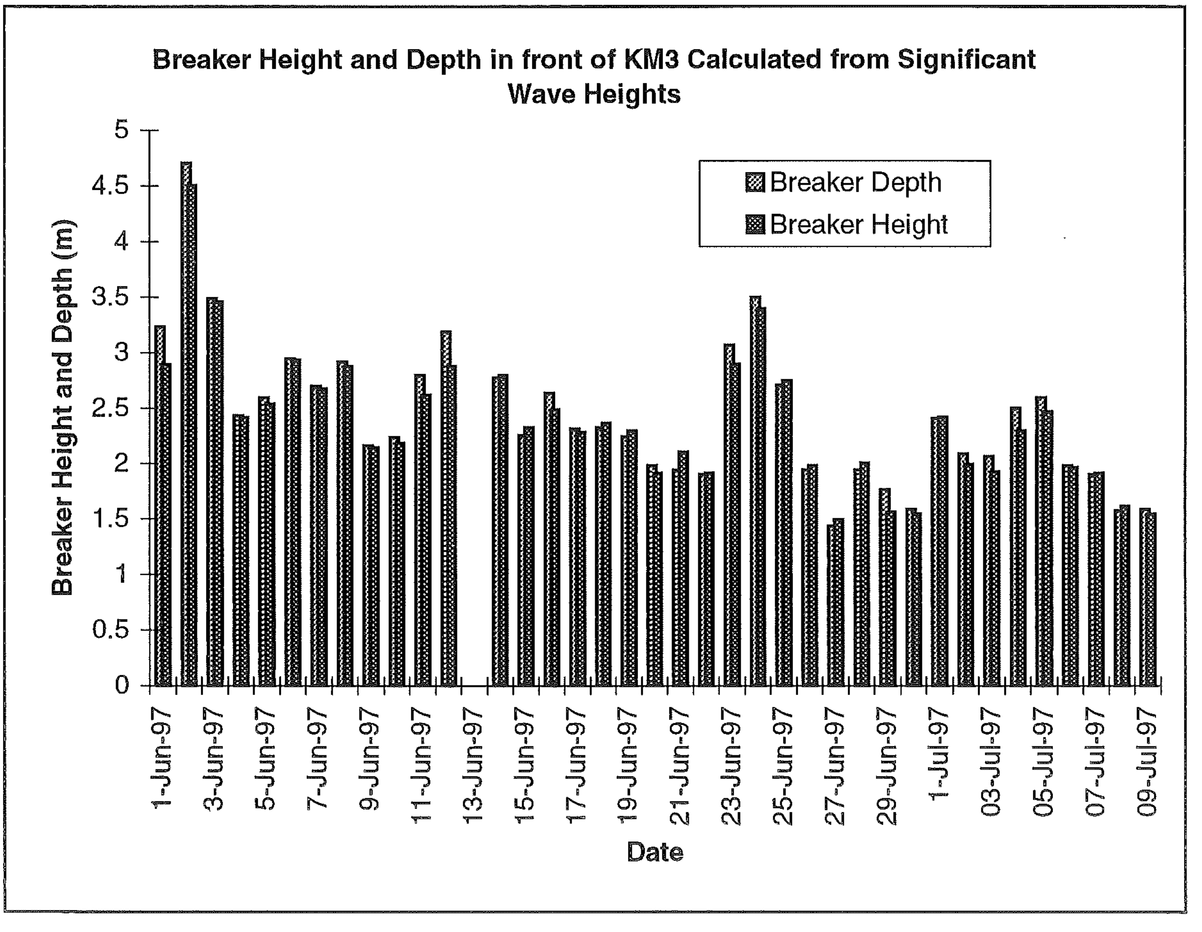

Figure 6.7 Breaker depth and height in front of KM3 calculated from deep water significant wave height.

It is interesting to consider on what days during the wave record waves broke on the seaward edge of KM3. To do this it was first necessary to identify the lowest tidal elevation in the period 1 June to 9 July, (which was 1.428m above the Kaikoura tide gauge). This elevation was considered to mark the seaward edge of the platform. It was then necessary to identify the highest tide elevation for each day, and this was compared with the depth of breaking on each day, if the depth of breaking was less than the depth of water at high tide then the wave was deemed to have broken on the platform. That is, the depth of breaking was subtracted from the tide elevation. If this result was less than 1.428m then the wave broke seaward of the platform edge. Alternatively if it broke above 1.428m then it broke on the platform. Results are presented in Table 6.1. Waves were able to break on KM3 on 10 days in the wave record. On these days breaker height was between 1.540 and 2.000m and the tide elevation was 3.298m above the Kaikoura gauge. This result shows that it is the smallest waves that break on this platform and only on the highest tides.

Table 6.1 Predicted occurrence of breaking waves on KM3 between 1 June 1996 and 9 July 1996. The seaward edge of KM3 was identified as being 1.428m above the Kaikoura tide gauge. Waves that broke above this elevation broke on the seaward edge on this platform (as shown in bold type.

Date	Calculated Breaking Depth (m)	Breaker Height (m)	High Tide Elevation Above Gauge (m)	Depth of Breaking (m)	Wave Type
1-Jun-97	3.23	2.89	3.572	0.342	Broken
2-Jun-97	4.70	4.50	3.562	-1.138	Broken
3-Jun-97	3.48	3.45	3.481	0.001	Broken
4-Jun-97	2.43	2.41	3.45	1.020	Broken
5-Jun-97	2.59	2.53	3.608	1.018	Broken
6-Jun-97	2.94	2.93	3.547	0.607	Broken
7-Jun-97	2.69	2.67	3.530	0.840	Broken
8-Jun-97	2.91	2.87	3.601	0.691	Broken
9-Jun-97	2.16	2.14	3.567	1.407	Broken
10-Jun-97	2.23	2.18	3.543	1.313	Broken
11-Jun-97	2.79	2.61	3.589	0.799	Broken
12-Jun-97	3.18	2.87	3.594	0.414	Broken
13-Jun-97	No Data	No Data	No Data	No Data	No Data
14-Jun-97	2.77	2.79	3.418	0.648	Broken
15-Jun-97	2.25	2.32	3.3445	1.094	Broken
16-Jun-97	2.63	2.48	3.391	0.761	Broken
17-Jun-97	2.31	2.28	3.325	1.015	Broken
18-Jun-97	2.32	2.36	3.284	0.964	Broken
19-Jun-97	2.24	2.29	3.210	0.970	Broken
20-Jun-97	1.98	1.91	3.174	1.194	Broken
21-Jun-97	1.94	2.1	3.140	1.200	Broken
22-Jun-97	1.90	1.91	3.140	1.240	Broken
23-Jun-97	3.06	2.89	3.245	0.185	Broken
24-Jun-97	3.49	3.39	3.386	-0.104	Broken
25-Jun-97	2.70	2.74	3.452	0.752	Broken
26-Jun-97	**1.94**	**1.98**	**3.462**	**1.522**	**Breaking**
27-Jun-97	**1.43**	**1.49**	**3.501**	**2.071**	**Breaking**
28-Jun-97	**1.94**	**2.00**	**3.591**	**1.651**	**Breaking**
29-Jun-97	**1.76**	**1.56**	**3.633**	**1.873**	**Breaking**
30-Jun-97	**1.58**	**1.54**	**3.828**	**2.248**	**Breaking**
1-Jul-97	2.4	2.41	3.733	1.333	Broken
02-Jul-97	**2.08**	**1.99**	**3.721**	**1.641**	**Breaking**
03-Jul-97	**2.06**	**1.92**	**3.550**	**1.490**	**Breaking**
04-Jul-97	2.49	2.29	3.418	0.928	Broken
05-Jul-97	2.59	2.46	3.362	0.772	Broken
06-Jul-97	1.98	1.96	3.342	1.362	Broken
07-Jul-97	**1.90**	**1.91**	**3.364**	**1.464**	**Breaking**
08-Jul-97	**1.57**	**1.61**	**3.315**	**1.745**	**Breaking**
09-Jul-97	**1.58**	**1.54**	**3.298**	**1.718**	**Breaking**

In Figure 6.8 calculated breaker depths and height off KM3 are presented using maximum wave height. Maximum breaker height was 8.37m on 2 June 1996. This wave broke in a depth of water of 9.45m, 141m from the seaward edge of KM3. The smallest calculated maximum breaking wave was on 27 June 1996 and was 2.83m high. This wave broke in 2.81m of water, 12m from the seaward edge of KM3. No waves among the maximum wave height data broke directly on KM3.

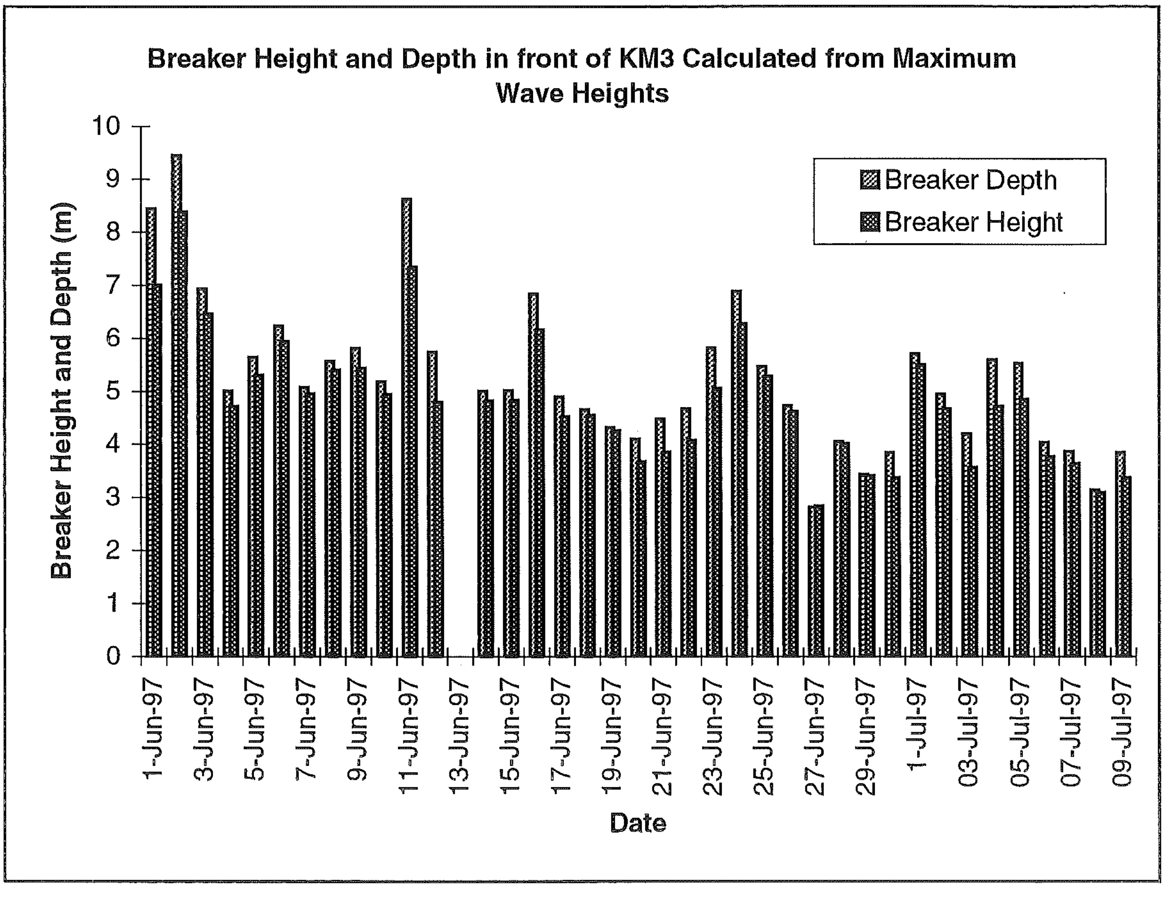

Figure 6.8 Breaker depth and height in front of KM3 calculated from deep water maximum wave height.

Figure 6.9 presents breaker depths and height seaward of KM5 calculated from mean daily significant wave heights. Maximum breaker height was 4.39m on 2 June 1996. This wave broke in a depth of water of 5.15m, 21m from the seaward edge of KM5. The smallest calculated breaking wave occurred on 27 June 1996 and was 1.52m high. This wave broke in 1.26m of water on the seaward edge of KM5. As with KM3, the same analysis was carried out to identify when waves broke on the seaward edge of KM5. Waves broke on KM5 on 15 days in the wave record. On these days breaker heights were between 1.52m and 2.45m and the tide elevation was above 3.298m on the Kaikoura gauge.

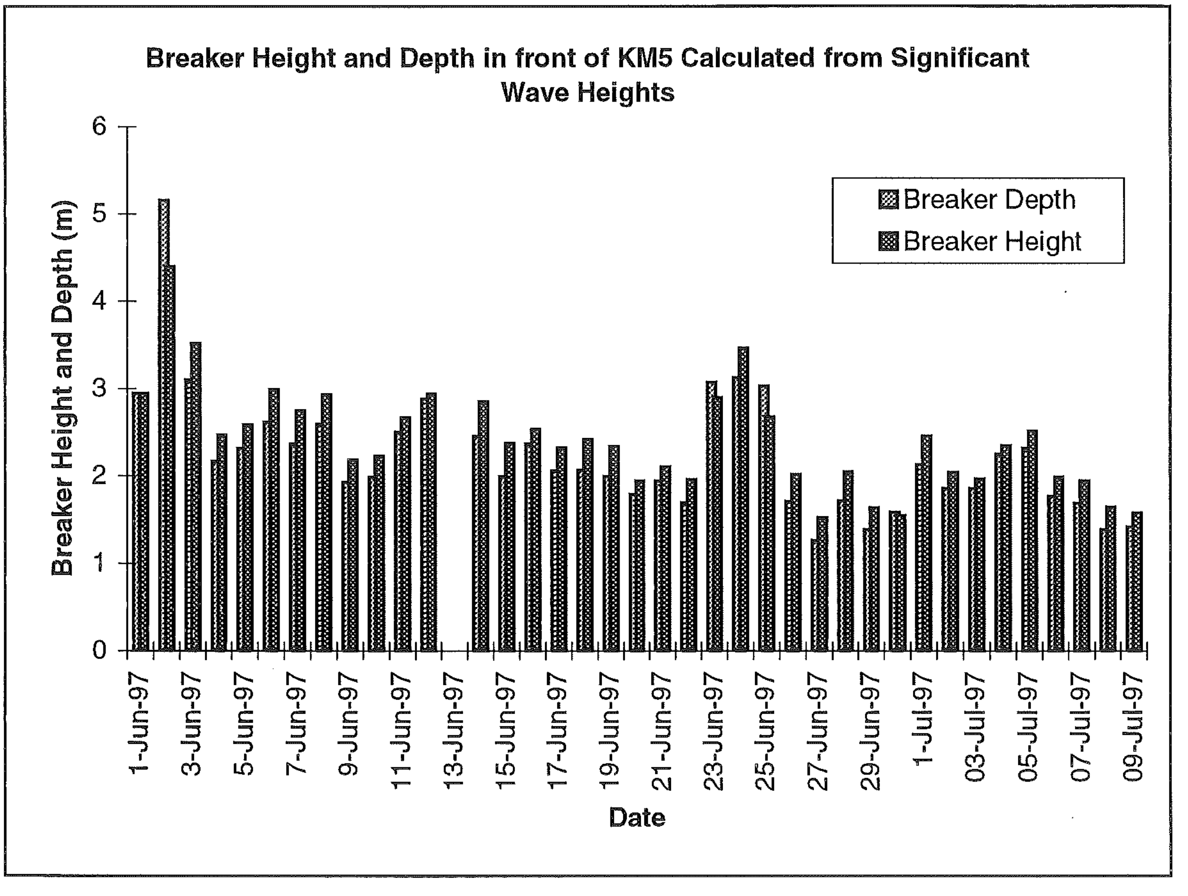

Figure 6.9 Breaker depth and height in front of KM5 calculated from deep water significant wave height.

Table 6.2 Predicted occurrence of breaking waves on KM5 between 1 June 1996 and 9 July 1996 (as shown in bold type.

Date	Calculated Breaking Depth (m)	Breaker Height (m)	High Tide Elevation Above Gauge (m)	Depth of Breaking (m)	Wave Type
1-Jun-97	2.94	2.94	3.572	0.632	Broken
2-Jun-97	5.15	4.39	3.562	-1.588	Broken
3-Jun-97	3.09	3.51	3.481	0.391	Broken
4-Jun-97	2.16	2.46	3.45	1.29	Broken
5-Jun-97	2.31	2.58	3.608	1.298	Broken
6-Jun-97	2.61	2.98	3.547	0.937	Broken
7-Jun-97	2.36	2.74	3.53	1.17	Broken
8-Jun-97	2.59	2.92	3.601	1.011	Broken
9-Jun-97	**1.92**	**218**	**3.567**	**1.647**	**Breaking**
10-Jun-97	**1.98**	**2.22**	**3.543**	**1.563**	**Breaking**
11-Jun-97	2.5	2.66	3.589	1.089	Broken
12-Jun-97	2.87	2.93	3.594	0.724	Broken
13-Jun-97	No Data	No Data	No Data	No Data	No Data
14-Jun-97	2.45	2.84	3.418	0.968	Broken
15-Jun-97	1.99	2.37	3.344	1.354	Broken
16-Jun-97	2.36	2.53	3.391	1.031	Broken
17-Jun-97	2.05	2.32	3.325	1.275	Broken
18-Jun-97	2.06	2.41	3.284	1.224	Broken
19-Jun-97	1.99	2.33	3.210	1.220	Broken
20-Jun-97	1.78	1.94	3.174	1.394	Broken
21-Jun-97	1.94	2.01	3.140	1.200	Broken
22-Jun-97	**1.69**	**1.95**	**3.140**	**1.450**	**Breaking**
23-Jun-97	3.06	2.89	3.245	0.185	Broken
24-Jun-97	3.11	3.45	3.386	0.276	Broken
25-Jun-97	3.02	2.67	3.452	0.432	Broken
26-Jun-97	**1.70**	**2.01**	**3.462**	**1.762**	**Breaking**
27-Jun-97	**1.26**	**1.52**	**3.501**	**2.241**	**Breaking**
28-Jun-97	**1.71**	**2.04**	**3.591**	**1.881**	**Breaking**
29-Jun-97	**1.38**	**1.63**	**3.633**	**2.253**	**Breaking**
30-Jun-97	**1.58**	**1.54**	**3.828**	**2.248**	**Breaking**
1-Jul-97	**2.12**	**2.45**	**3.733**	**1.613**	**Breaking**
02-Jul-97	**1.85**	**2.03**	**3.721**	**1.871**	**Breaking**
03-Jul-97	**1.85**	**1.96**	**3.550**	**1.700**	**Breaking**
04-Jul-97	2.24	2.34	3.418	1.178	Broken
05-Jul-97	2.31	2.51	3.362	1.052	Broken
06-Jul-97	**1.76**	**1.98**	**3.342**	**1.582**	**Breaking**
07-Jul-97	**1.68**	**1.94**	**3.364**	**1.684**	**Breaking**
08-Jul-97	**1.38**	**1.64**	**3.315**	**1.935**	**Breaking**
09-Jul-97	**1.41**	**1.57**	**3.298**	**1.888**	**Breaking**

Figure 6.10 presents calculated breaker depths and height off KM5 using maximum wave heights recorded by the wave rider buoy. Maximum breaker height was 8.52m on 2 June 1996. This wave broke in a depth of water of 8.57m and broke 72m from the seaward edge of KM5. The smallest calculated breaking wave occurred on 27 June 1996 and was 2.88m high. This wave broke in 2.48m of water, 2m from the seaward edge of KM5.

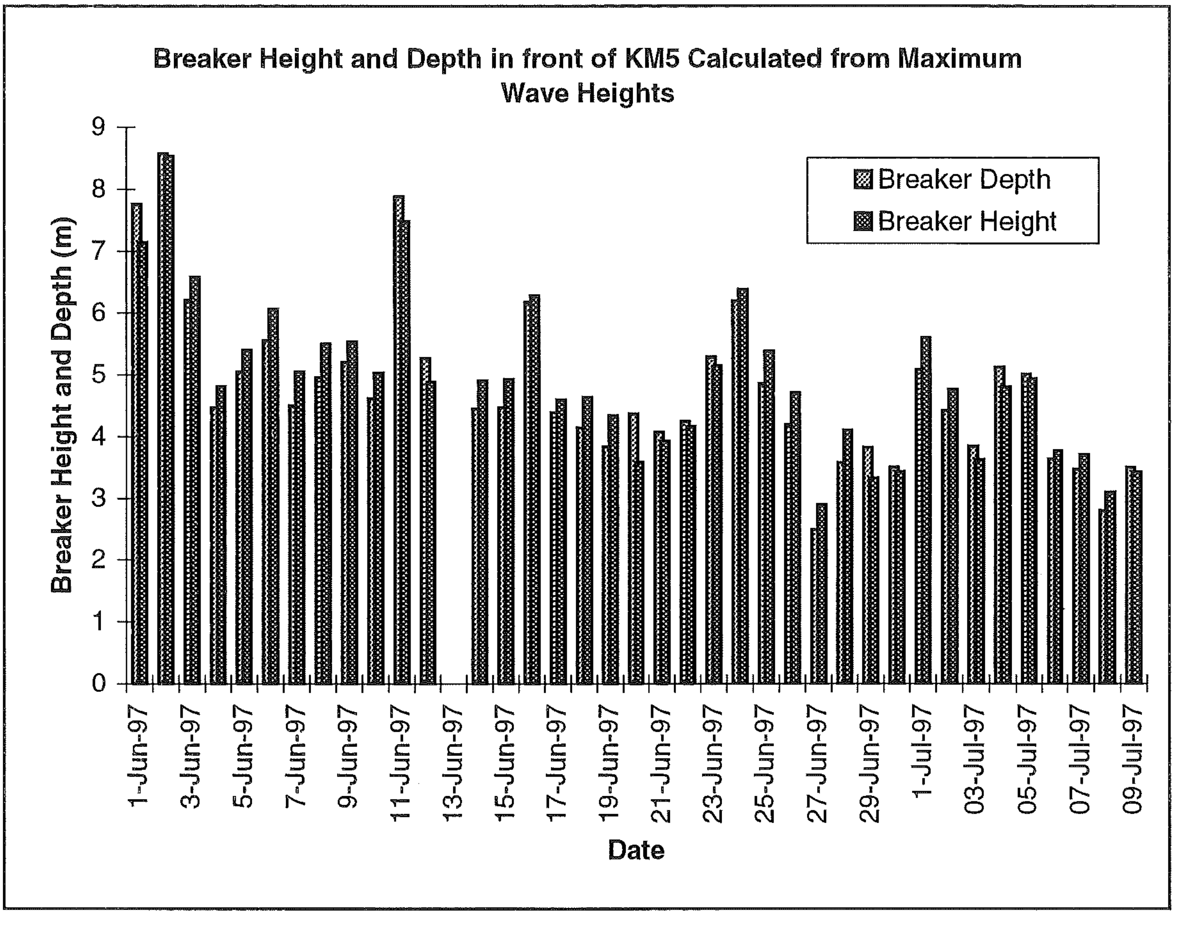

Figure 6.10 Breaker depth and height in front of KM5 calculated from deep water maximum wave height.

It has been shown above that there is a range of wave and tidal conditions when waves will break on Type B shore platforms at Kaikoura. Breaking can only happen at high tide since lower tides reduce water depth causing waves to break further from the shore. Clearly waves do not break directly on the landward cliff of shore platforms. Landward cliffs are never subjected to the impact forces of breaking waves. Nor were the low tide cliffs of KM3 and KM5 at Kaikoura subjected to impact forces of breaking wave either. This was because at high tide the platform edge is submerged producing a cushion of water which prevents impact pressure. It will be recalled from Chapter Two that it is necessary to entrap a cushion of air to generate true shock pressure. Trenhaile (1987) argued that because of this necessary pre-condition true shock pressures in the field occur infrequently. Data from Kaikoura have shown that these conditions are not only infrequent but that only the smallest waves can impact directly on the seaward edge of Type B platforms. No impact at all is possible on Type A platforms.

6.2.2 INSHORE WAVE DATA

To further investigate wave characteristics on shore platforms three pressure transducers were used to measure wave height, period and water depth across a platform profile. One was an Inter Ocean S4ADW directional wave recorder. This is a self contained unit with an internal data logger and power supply. The advantage of this is that it can be located any where on a platform. The other two other transducers were less versatile since they had cable connected to a shore-based Campbell 21X data logger with a 12v power supply. One of these was a Kainga 1000 Pressure Transducer with 45m of cable and the other was a Greenspan PS200 Pressure Transducer with 80m of cable. Both these transducers were purchased from the National Institute of Water and Atmospheric Research Ltd and were supplied calibrated.

All three instruments were arranged in profile across shore platforms with one at the outer edge, one in the middle and one at the landward edge. The Kainga and Greenspan pressure transducers were held in a cradle using hose clips and bolted to the rock surface using masonry expansion bolts (Fig 6.11). Because of the long distances across shore platforms the two cable instruments were always used on the inner two sites. The S4ADW wave recorder was mounted on a stainless steel pole with stays, as illustrated in Figure 6.12.

Two sites were selected to deploy the pressure transducers, these were adjacent to KM3 and on KM2. KM3 is a Type B platform exposed to easterly and southerly seas. KM2 is a Type A platform exposed to north easterly waves. These sites were selected because of their exposure to different wave approach directions and ease of access for deployment of the equipment. The transducers were deployed at low tide and recording began when they became submerged. Logging was stopped as each became exposed on the out going tide. A third site was chosen for deployment of the S4A to better represent wave approach from a southerly direction. This site was the seaward edge of the KM5 profile on Atia Point (Fig 4.1). The other two transducers could not be installed at this site. Between 14 June 1996 and 2 July 1996 the S4A wave recorder was deployed ten times (on five occasions on KM2, two on KM3 and three on KM5).

Figure 6.11 The Greenspan pressure transducer and cradle bolted to the platform at KM3. The transducer is 300mm long and 43mm in diameter.

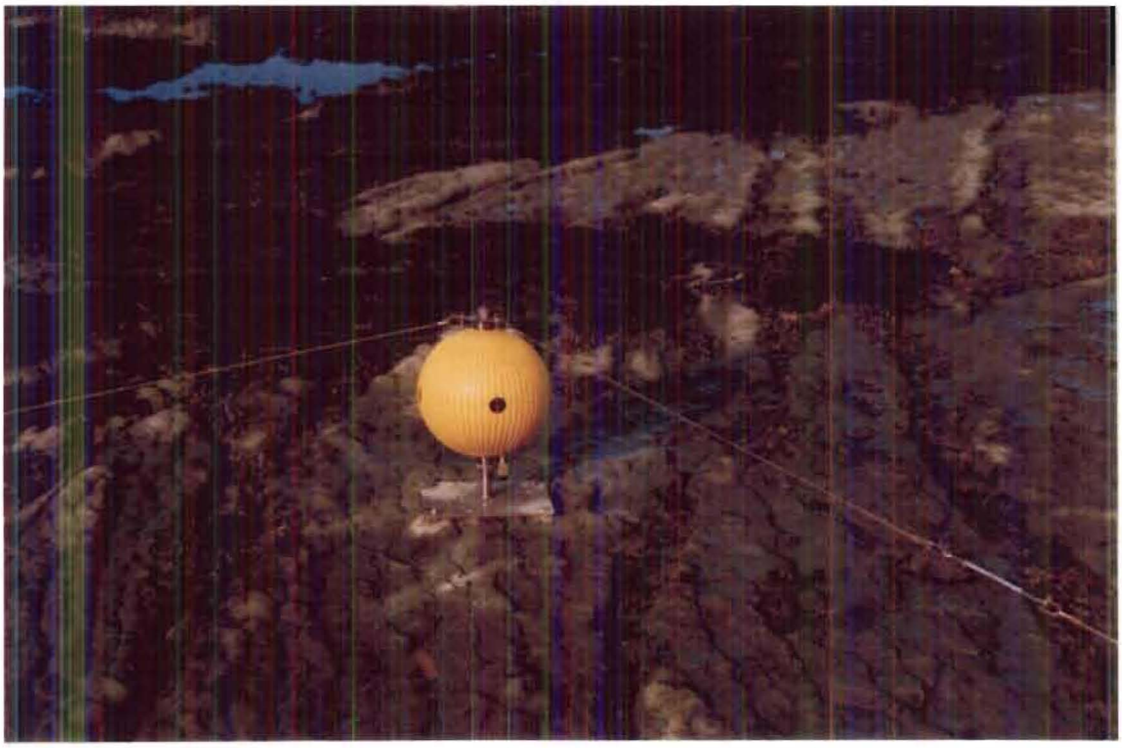

Figure 6.12 The S4A directional wave recorder bolted to the platform at KM2. The transducer port of the S4A is 100mm above the bed.

The S4A directional wave recorder has wave analysis software to process raw data. This software allows a number of wave parameters to be calculated, including:

1) Average wave height (H_{AVG}): the average wave height from the record calculated from: $H_{AVG} = 2.5\sigma_{\eta}$ (m).
2) Significant wave height (H_S): the average height of the highest one third of the waves in the record (m).
3) Maximum wave height (H_{MAX}): the highest recorded wave in the record (m).
4) Zero crossing period (T_z): the average of number of surface elevation up crossings of mean water level by per unit time (s).
5) Significant wave period (T_S): the period of the significant wave height (s).
6) Crest period (T_C): the average time between successive maxima in water elevations (s). A crest is defined as a point where the water level is momentarily constant and falling to either side (Pickrill 1976). Maximum elevations can occur below or above mean water level.
7) Period at maximum wave height (T_{HMAX}).
8) Spectral band width (ε): A measure of the width of the energy spectrum. Values range from 0 to 1. When the band width is narrow, values approach zero and when the width is wide, values are closer to 1. A wide spectrum contains waves of different periods. This occurs when short waves are carried on longer waves and the number of zero crossings is less than the number of crests. In a narrow spectrum the wave record is much simpler with each crest associated with a zero crossing (Pickrill 1976).

For descriptive purposes S4A data are presented using the eight variables explained above. Detailed analysis of wave characteristics on shore platforms will utilise H_S and associated T_S and H_{MAX} and associated T_{HMAX} to calculate wave energy and shear stress on platforms. It will be recalled from Chapter Three that Sunamura (1992, 1994) identified wave energy as the primary wave variable controlling shore platform development. Tsujimoto (1987) utilised H_{MAX} from deep water data to calculate pressure and shear stress exerted by waves on shore platforms. Wave data from each deployment are contained in Appendix Five. These data were used to generate Figures 6.13 to 6.23 which present wave data from the S4A deployments for discussion. All waves measured on shore platforms were broken waves.

Figure 6.13 presents wave data from a deployment on 21 June 1996 on KM2. Each block of time contains 1024 measurements that were used in Fast Fourier Transformation calculations carried out in the S4A software package. High tide occurred during this deployment at 20:25 (NZST). These data show that H_{AV} did not exceed 0.2m, H_S did not exceed 0.3m and H_{MAX} did not exceed 0.5m. The mode of H_{MAX} was 0.4m and accounted for 72 per cent of H_{MAX}

measurements. Wave height increased as the tide flooded, but the maximum wave height of 0.5m occurred between 20:55 and 21:04. T_Z periods ranged from 7.4 to 8.9, T_S from 7.7 to 9.7s, T_C from 6.4 to 7.1s and T_{HMAX} ranged from 7.6s to 9.3s. Spectral band width ranged from 0.47 to 0.62 indicating a moderate width (mean = 0.54) with some spread.

Figure 6.14 presents wave data from the 22 June 1996 on KM2. High Tide was at 09:05 (NZST). During this deployment maximum H_{AV} was 0.2m and the mean was 0.1m. Maximum H_S was 0.3m and the mean was 0.2m. The highest H_{MAX} value was 0.4m while the mean value was 0.3m. Wave heights increased as the tide flooded but maximum values for all three height parameters did not occur at the peak of the tide. Rather, maximum values occurred within the half hour period either side of high tide. T_Z periods ranged from 7.5 to 8.6, T_S from 7.9 to 9.2s, T_C from 6.6 to 7.1s and T_{HMAX} ranged from 7.7 to 8.9s. Spectral band width ranged from 0.45 to 0.59 indicating a moderate width with some spread (mean = 0.53).

Figure 6.15 presents wave data from the evening of the 23 June 1996 and early morning of the 24 June 1996, on KM2. High Tide was at 22:35 (NZST). During this deployment maximum H_{AV} was 0.3m and the mean was 0.2m. Maximum H_S was 0.4m and the mean was 0.3m. The highest H_{MAX} value was 0.6m while the mean value was 0.5m. Wave heights increased as the tide flooded and maximum values for all three height parameters occurred at the peak of the tide. T_Z periods ranged from 8.3 to 10.3, T_S from 9.2 to 12.0s, T_C from 6.4 to 7.3s and T_{HMAX} ranged from 8.7 to 11.1s. Spectral band width ranged from 0.60 to 0.73, indicating a wider spectral width than during the previous two deployments (mean = 0.67).

Figure 6.16 presents wave data from the morning of the 24 June 1996 on KM2. High Tide was at 10:40 (NZST). During this deployment maximum H_{AV} was 0.2m and the mean was 0.1m. Maximum H_S was 0.3m and the mean was 0.2m. The highest H_{MAX} value was 0.5m while the mean value was 0.3m. Wave heights increased as the tide flooded but maximum values for all three height parameters occurred an hour before the peak of the tide. T_Z periods ranged from 8.6 to 11.1s, T_S from 9.5 to 11.3s, T_C from 6.5 to 7.3s and T_{HMAX} ranged from 9.0 to 10.5s. Spectral band width ranged from 0.66 to 0.77 indicating a moderate spectral width (mean = 0.71).

Figure 6.17 presents wave data from the evening of the 24 and early morning if the 25 June 1996 on KM2. High Tide was at 23:40 (NZST). During this deployment maximum H_{AV} was 0.3m, the mean was 0.2m, and maximum H_S was 0.4m. The highest H_{MAX} value was 0.6m while the mean value was 0.5m. Wave heights increased as the tide flooded but maximum values for all three height parameters occurred 40 minutes before the peak of the tide and again at high tide. T_Z periods ranged from 7.7 to 10.6s, T_S from 8.3 to 11.8s, T_C from 6.3 to 7.5s and T_{HMAX} ranged from 8.0 to 11.2s. Spectral band width ranged from 0.58 to 0.73m indicating a moderately wide spectral width (mean = 0.65).

Figure 6.18 presents wave data from the 25 June 1996 on KM2. High Tide was at 11:20 (NZST). During this deployment, maximum H_{AV} was constant at 0.2m. Maximum H_S was 0.4m and the mean was 0.3m. The H_{MAX} was also constant at 0.5m. Wave heights increased as the tide flooded and maximum values for all three height parameters occurred at the peak of the tide. T_Z periods ranged from 7.9 to 9.9s, T_S from 8.7 to 12.1s, T_C from 6.3 to 7.8s and T_{HMAX} ranged from 8.3 to 11.5s. Spectral band width ranged from 0.58 to 0.71 indicating a moderately wide spectral width (mean = 0.64).

The S4A was deployed two times on KM3 when waves were arriving from a southeast direction. Figure 6.19 contains wave data from the 14 June 1996 on KM3. High Tide was at 15:45 (NZST). During this deployment maximum H_{AV} was 0.5m and the mean was 0.4m. Maximum H_S was 0.8m and the mean was 0.6m. The highest H_{MAX} value was 1.1m and the mean value was 0.8m. Wave heights increased as the tide flooded but the highest maximum values for all three height parameters occurred 40 minutes before the peak of the tide. T_Z periods ranged from 9.5 to 12.3s, T_S from 10.5 to 14.7s, T_C from 6.9 to 7.7s and T_{HMAX} ranged from 10.0 to 13.3s. Spectral band width ranged from 0.65 to 0.79, indicating a moderately wide spectral width (mean = 0.71).

Figure 6.20 contains wave data from the 15 June 1996 on KM3. High Tide was at 04:45 (NZST). During this deployment maximum H_{AV} was 0.3m and the mean was 0.2m. Maximum H_S was 0.5m and the mean was 0.35m. The highest H_{MAX} value was 0.7 m and the mean value was 0.48m. Wave heights increased as the tide flooded, the highest maximum values for all three height parameters occurred 52 minutes before the peak of the tide and persisted until 04:45. T_Z periods ranged from 9.0 to 10.5s, T_S from 9.8 to 11.9s, T_C to from 6.7 to 7.6s and T_{HMAX} ranged from 9.4 to 11.1s. Spectral band width ranged from 0.62 to 0.71, indicating a moderately wide spectral width (mean = 0.68).

Figure 6.21 contains wave data from the 1 July 1996 on KM5. High Tide was at 16:20 (NZST). During this deployment maximum H_{AV} was 0.2m and the mean was 0.16m. Maximum H_S was 0.4m and the mean was 0.27m. The highest H_{MAX} value was 0.6m and the mean value was 0.39m. Wave heights increased as the tide flooded; the highest maximum values for all three height parameters occurred at the peak of the tide. T_Z periods ranged from 7.8 to 8.8s, T_S from 8.2s to 9.5s, T_C from 6.4 to 7.1s and T_{HMAX} ranged from 8.0 to 9.1s. Spectral band width ranged from 0.48 to 0.62, indicating a moderately wide spectral width (mean = 0.57).

Figure 6.22 contains wave data from the 2 July 1996 on KM5. High Tide was at 04:45 (NZST). During this deployment maximum H_{AV} was constant at 0.1m. Maximum H_S was 0.2m and the mean was also 0.2m. The highest H_{MAX} value was 0.3m and the mean value was 0.2m. Wave heights increased as the tide flooded; the highest maximum values for all three height parameters occurred around the peak of the tide. T_Z periods ranged from 8.2 to 8.7s, T_S from 8.6 to 9.2s, T_C from 6.7 to 7.3s and T_{HMAX} ranged from 8.4 to 8.9s. Spectral band width ranged from 0.52 to 0.60 indicating a moderate spectral width (mean = 0.55).

Figure 6.23 contains wave data also from the 2 July 1996 on KM5 but on the second high tide of that day which was at 17:15 (NZST). During this deployment maximum H_{AV} was constant at 0.2m. Maximum H_S was 0.4m and the mean was 0.3m. The highest H_{MAX} value was 0.6m and the mean value was 0.4m. Wave heights increased as the tide flooded, but the highest maximum values for all three height parameters occurred before and after the peak of the tide. T_Z periods ranged from 7.0s to 8.4s, T_S from 7.4 to 8.4s, T_C from 6.3 to 6.9s and T_{HMAX} ranged from 7.2 to 8.2s. Spectral band width ranged from 0.45 to 0.50, indicating a moderate spectral width (mean = 0.47).

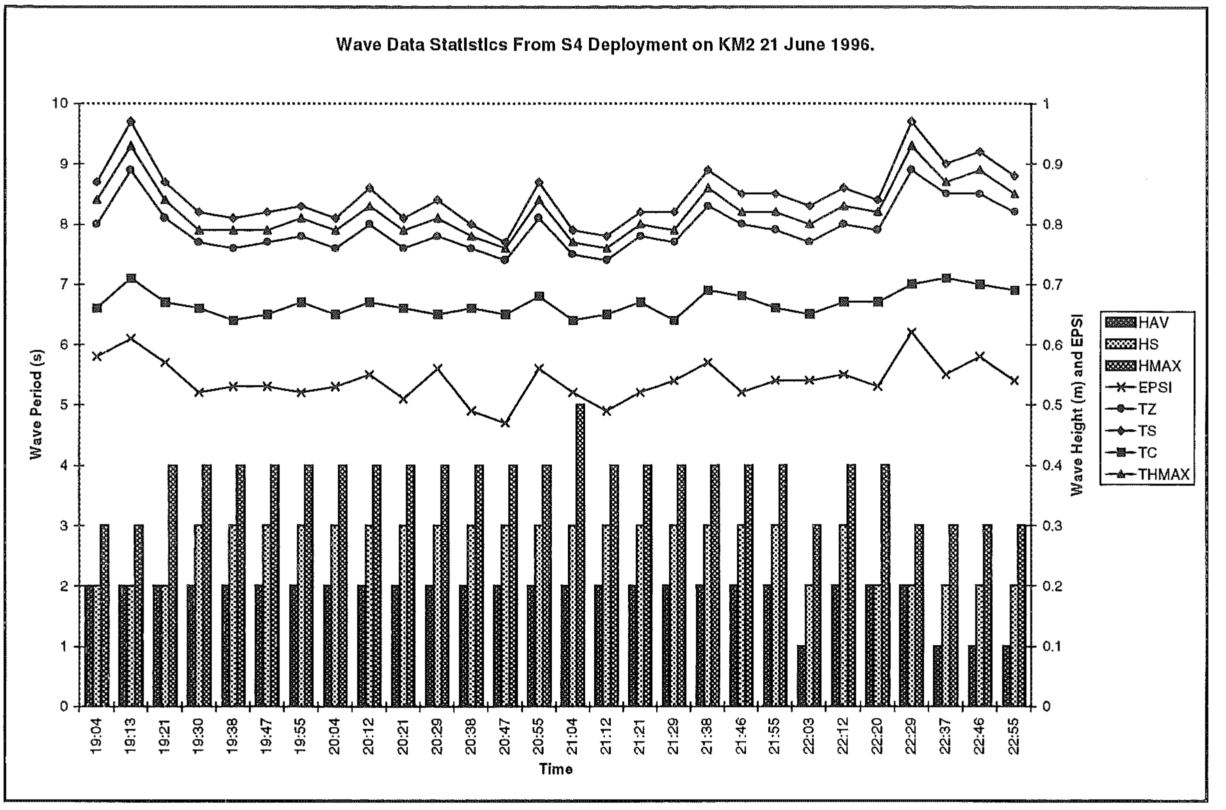

Figure 6.13 Wave data statistics resulting from the deployment of the S4A on the 21 June 1996 on KM2. High tide was at 20:25 (NZST).

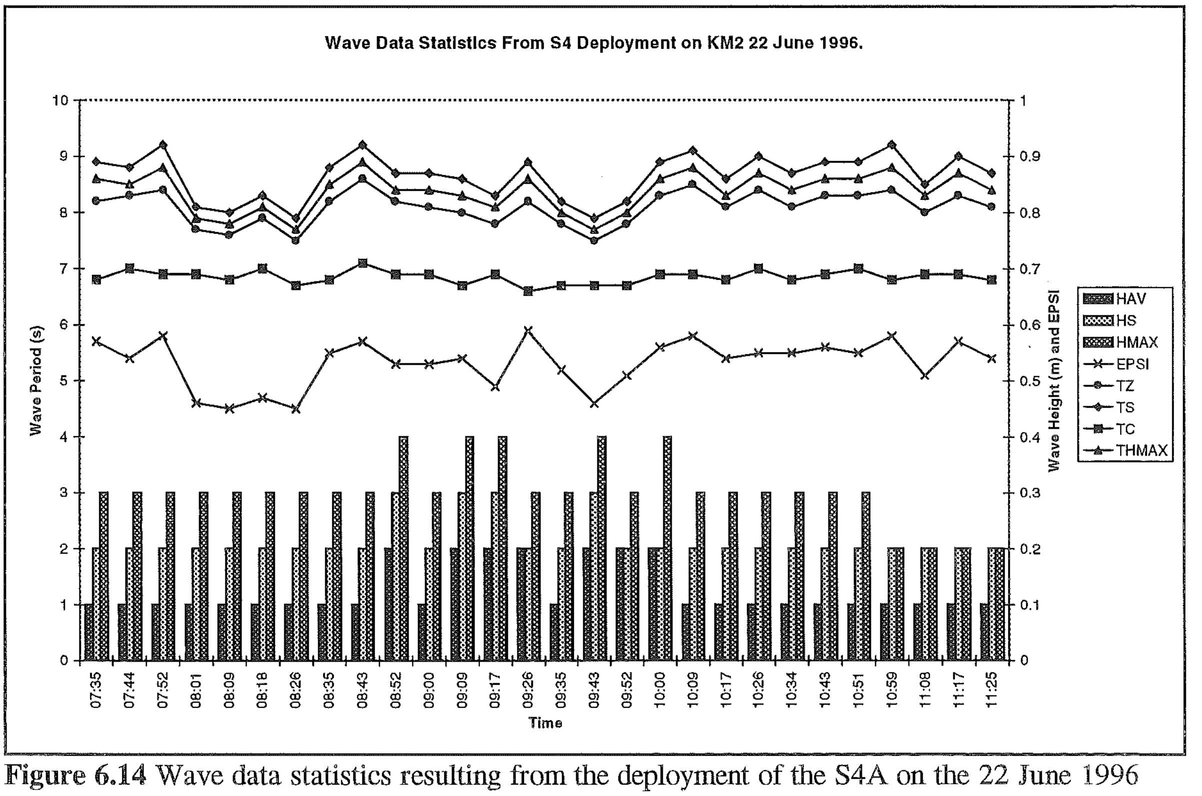

Figure 6.14 Wave data statistics resulting from the deployment of the S4A on the 22 June 1996 on KM2. High tide was at 09:05 (NZST).

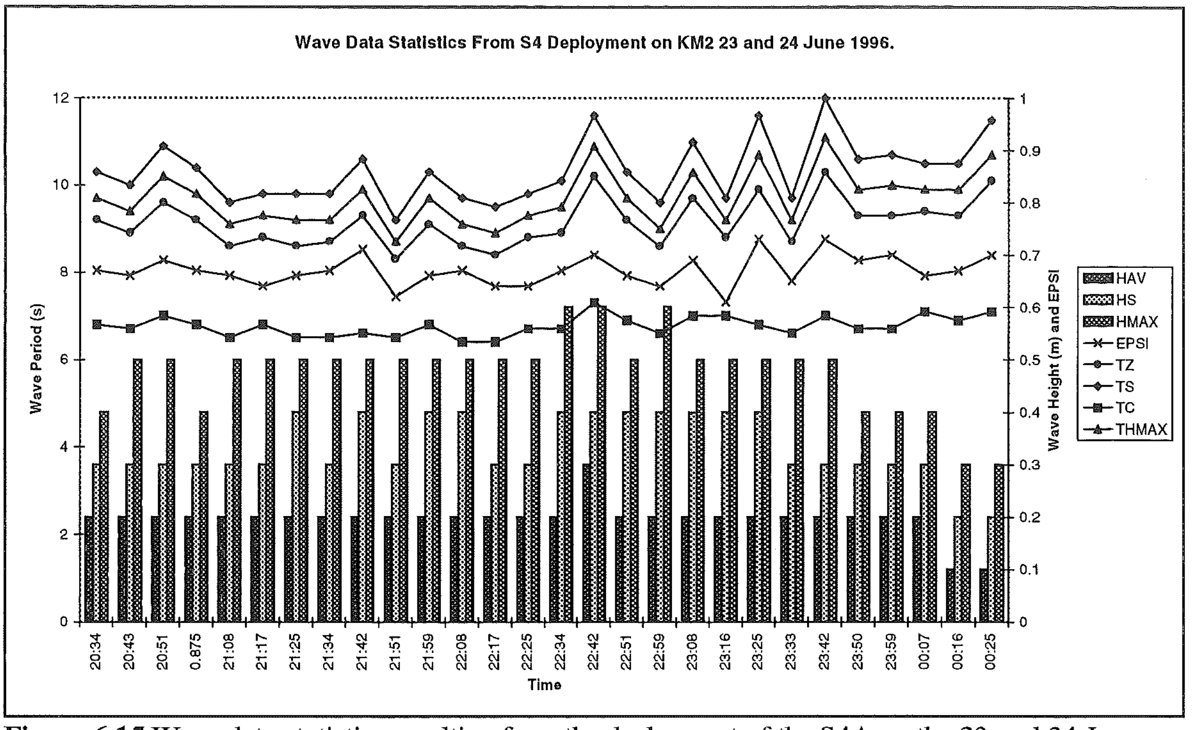

Figure 6.15 Wave data statistics resulting from the deployment of the S4A on the 23 and 24 June 1996 on KM2. High tide was at 22:35 (NZST).

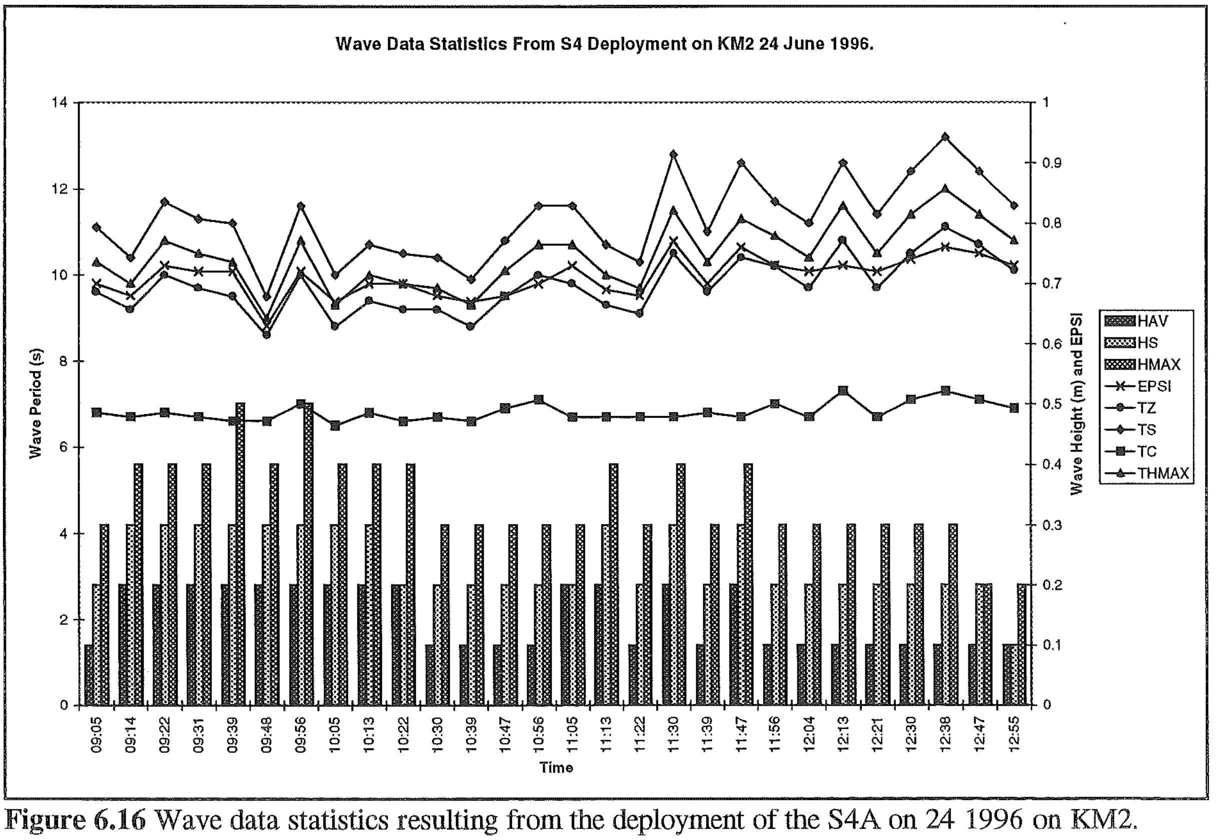

Figure 6.16 Wave data statistics resulting from the deployment of the S4A on 24 1996 on KM2. High tide was at 10:40 (NZST).

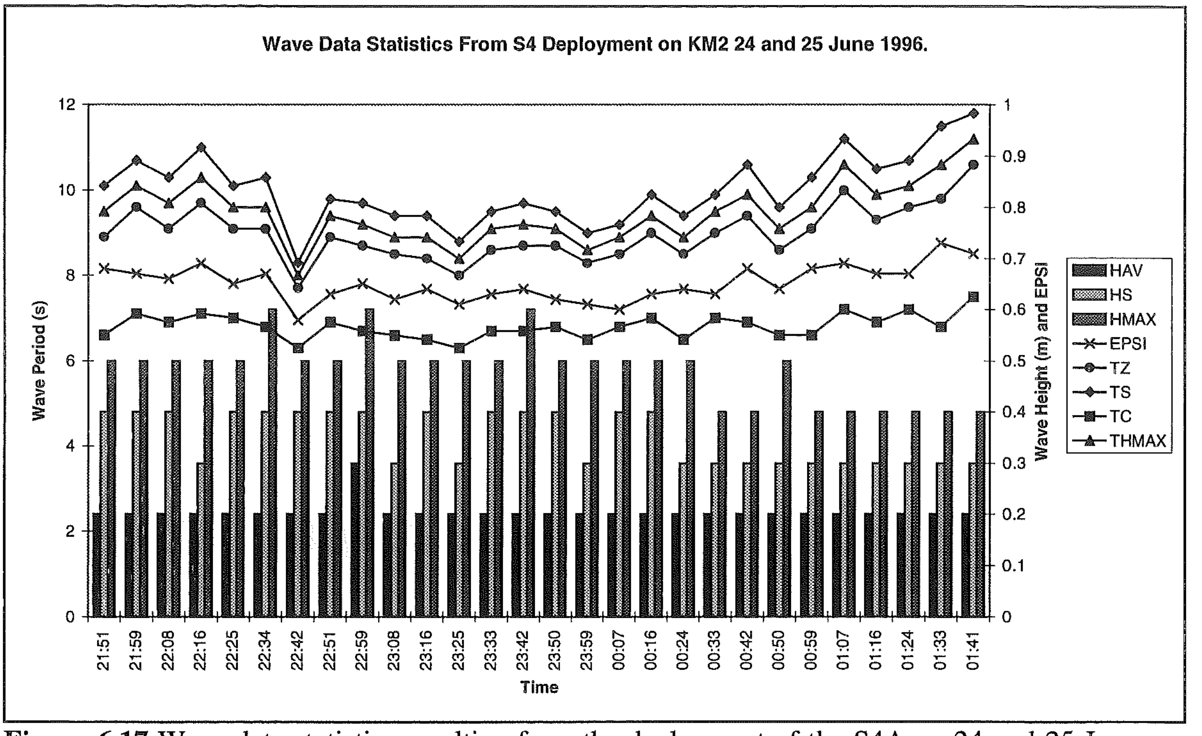

Figure 6.17 Wave data statistics resulting from the deployment of the S4A on 24 and 25 June 1996 on KM2. High tide was at 23:40 (NZST).

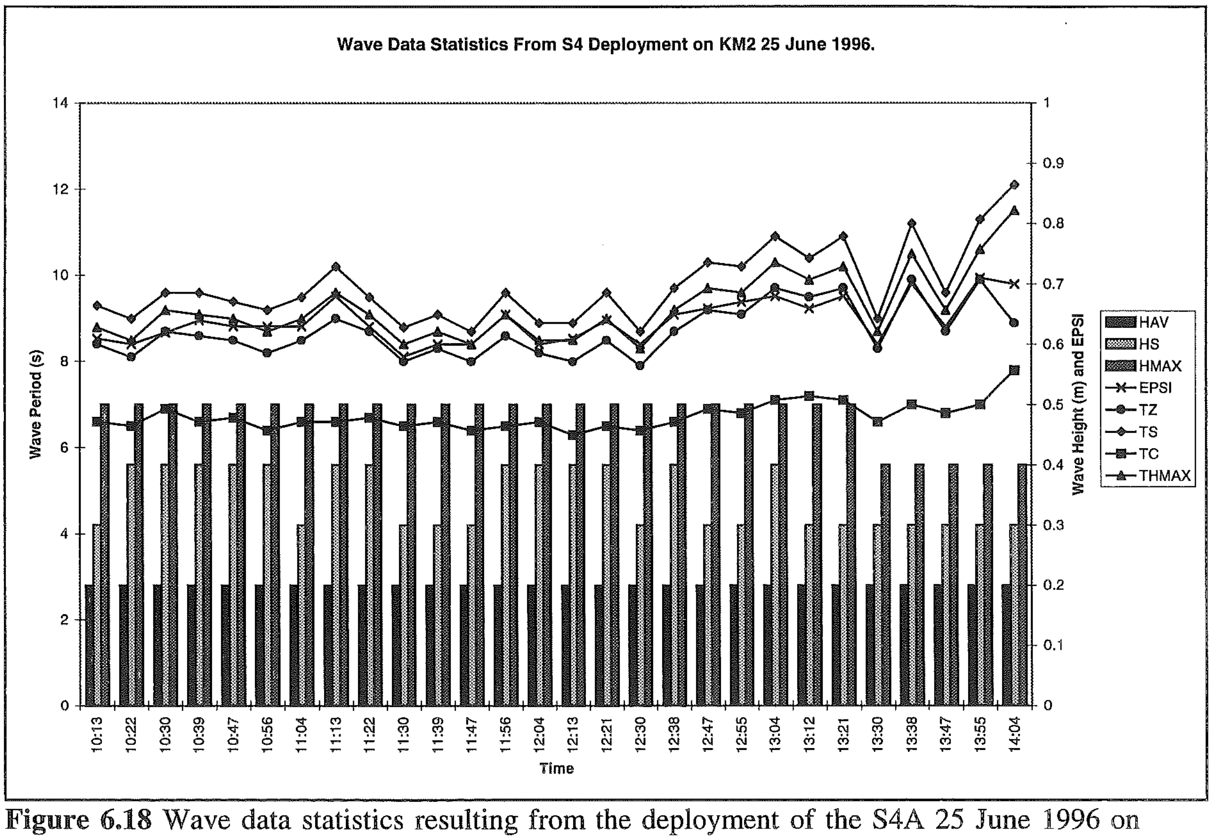

Figure 6.18 Wave data statistics resulting from the deployment of the S4A 25 June 1996 on KM2. High tide was at 11:20 (NZST).

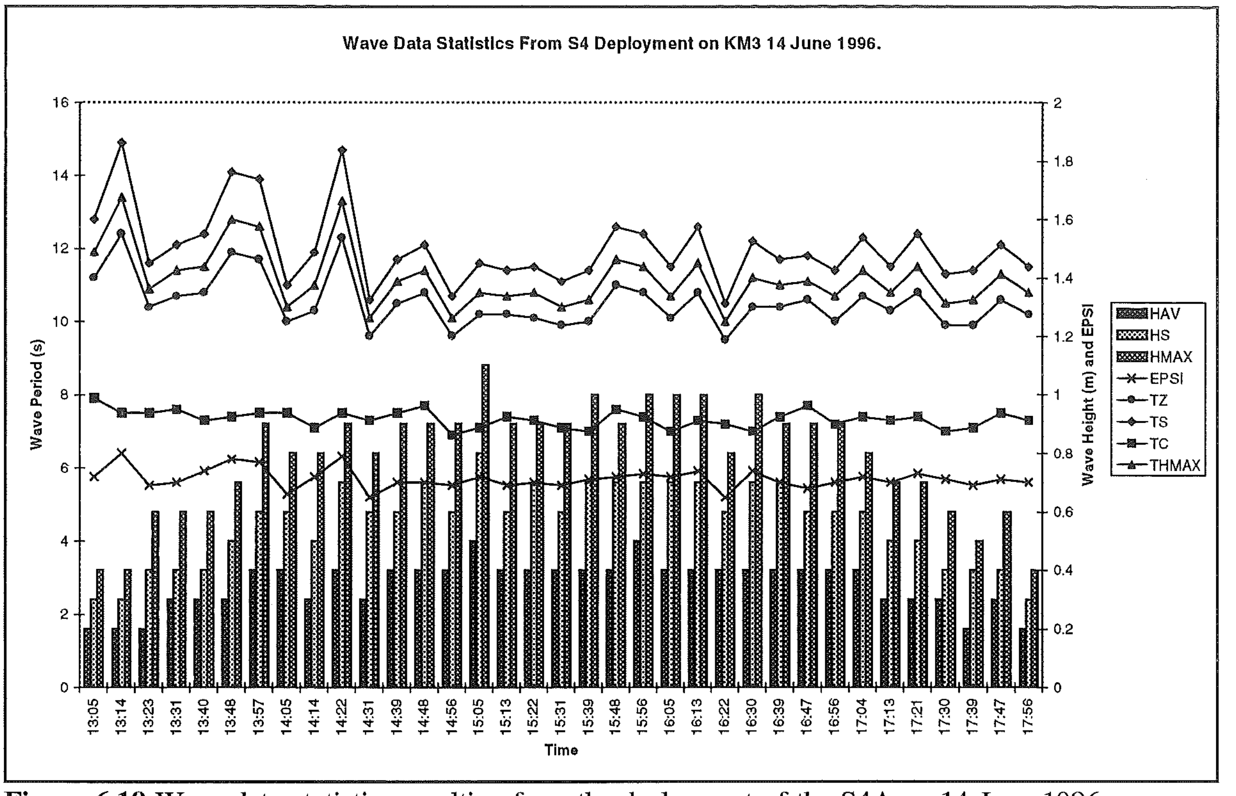

Figure 6.19 Wave data statistics resulting from the deployment of the S4A on 14 June 1996 on KM3, high tide was at 15:45 (NZST).

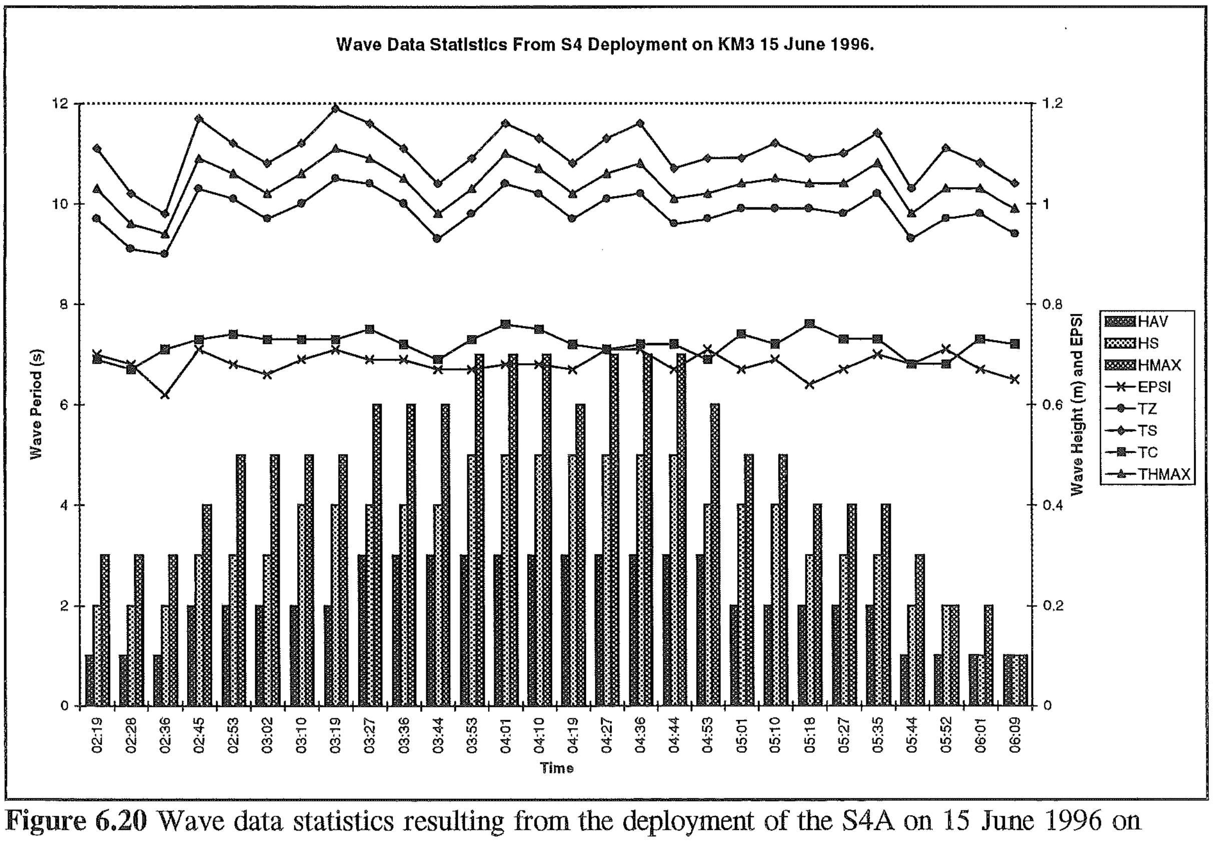

Figure 6.20 Wave data statistics resulting from the deployment of the S4A on 15 June 1996 on KM3. High tide was at 04:45 (NZST).

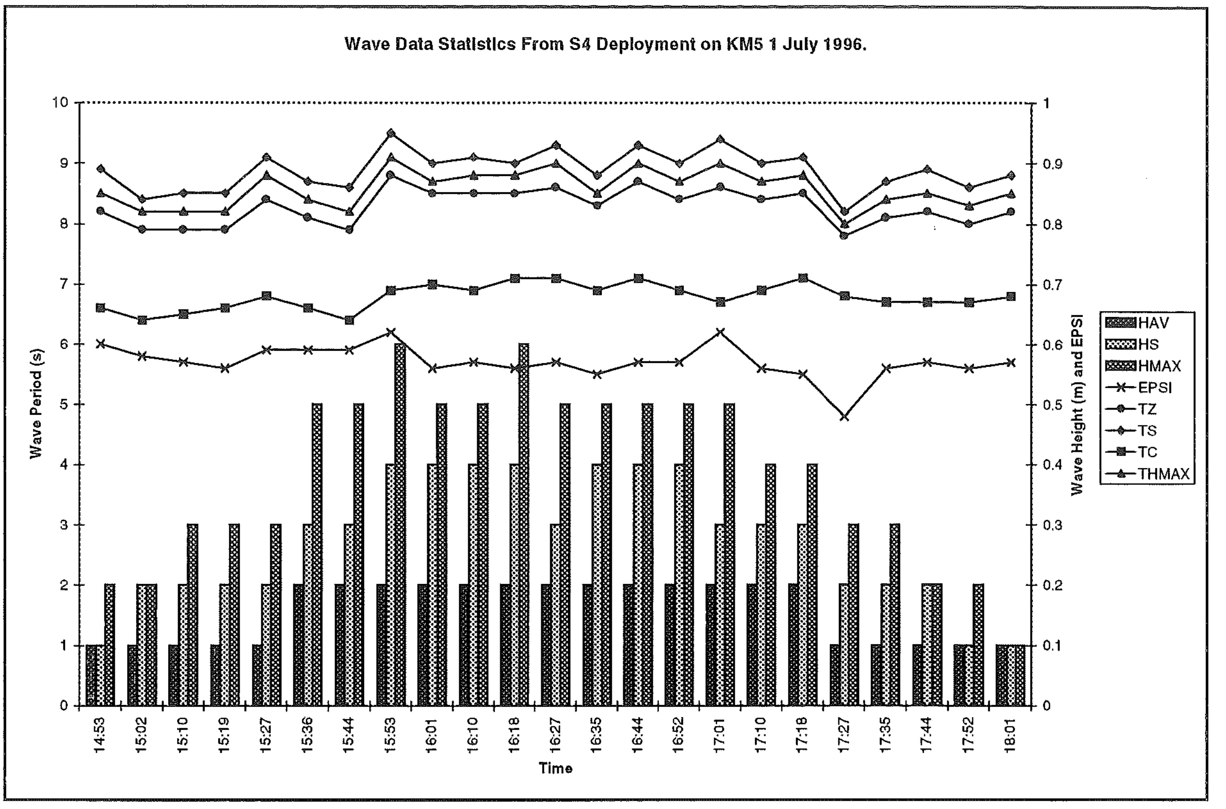

Figure 6.21 Wave data statistics resulting from the deployment of the S4A on 1 July 1996 on KM5 High tide was at 16:20 (NZST).

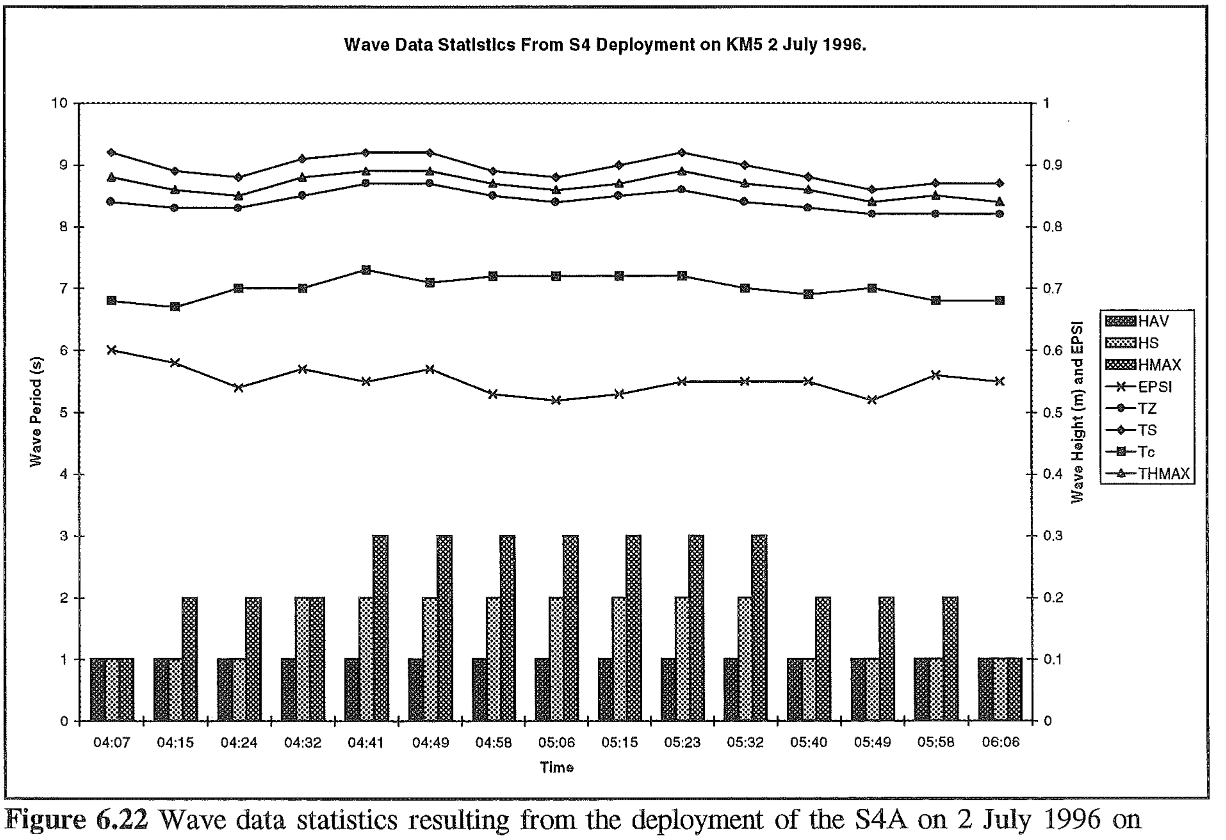

Figure 6.22 Wave data statistics resulting from the deployment of the S4A on 2 July 1996 on KM5. High tide was at 04:45 (NZST).

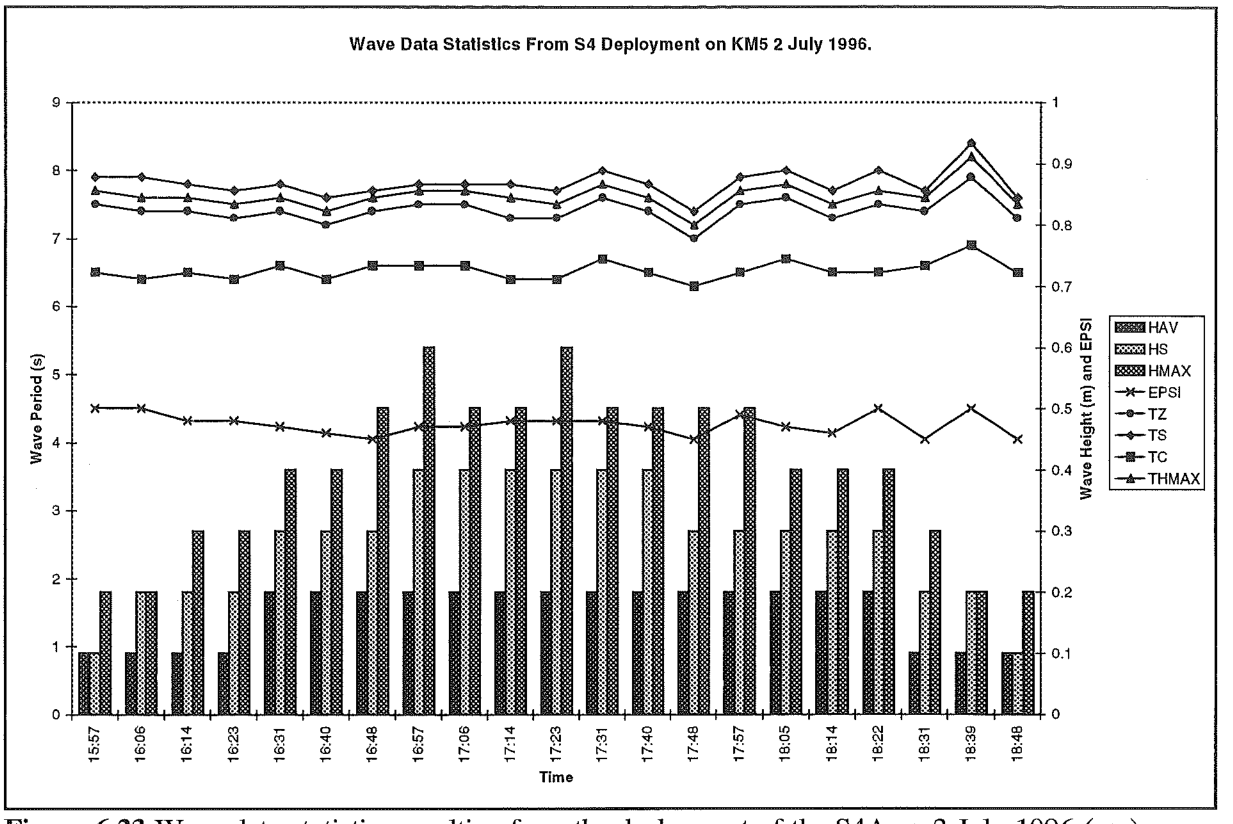

Figure 6.23 Wave data statistics resulting from the deployment of the S4A on 2 July 1996 (pm) on KM5. High tide was at 17:15 (NZST).

6.2.3 WAVE ATTENUATION IN SHOALING

In Chapters Two and Three attention was drawn to the lack of investigation of wave characteristics on shore platforms. With the S4A data it is now possible to evaluate how much offshore wave energy was delivered to the seaward edge of shore platforms. The wave data in Section 6.2.2 were used to calculate wave energy flux on shore platforms. This was calculated using both significant wave height and significant period, and maximum wave height and maximum period. Values for these were taken from each S4A deployment at high tide and entered into the ACES wave program. Since these waves were in shallow water the option within the program that deals with shallow water waves was used. This option calculates energy flux using second order approximations of cnoidal wave theory. Table 6.3 presents the results from these calculations. On KM2 energy flux ranged from 146N-m/s-m calculated from significant wave height and period to 1447N-m/s-m calculated from maximum wave height and period. Values for wave energy flux were higher on KM3 ranging from 918N-m/s-m calculated from significant wave height and period to 4835N-m/s-m calculated from maximum wave height and period. Wave energy flux on KM5 ranged from 135N-m/s-m calculated from significant wave height and period, to 1414N-m/s-m calculated from maximum wave height and period.

In order to assess the attenuation of offshore energy during shoaling the wave energy flux data from Table 6.3 were compared with offshore wave energy fluxes calculated at the corresponding high tide times. The results of this comparison are also presented in Table 6.3. Offshore energy flux (P_O) ranged from 8141 to 122601N-m/s-m during S4A deployments on KM2 compared with the ranged of 146 to 1447N-m/s-m on the platform (P_P). As a percentage of the offshore energy flux, platform energy fluxes were never more than 2.9 per cent and were as low as 0.3 per cent. On KM3 platform energy fluxes were higher as a percentage of offshore energy flux compared with KM2. As a percentage of the offshore energy flux, platform energy fluxes ranged from 4.0 per cent to 8.8 per cent on KM3. Platform energy fluxes on KM5 were as low as 0.4 per cent of the offshore energy flux and as high as 3.3 per cent. This analysis answers the question of how much energy arrives on shore platforms from deep water. Clearly a very large proportion of offshore wave energy is lost during shoaling and refraction; less than 10 per cent of the offshore energy arrived on platforms from deep water during field measurements. This represents a loss of energy by two or three orders of magnitude. The offshore wave environment during the study period was very energetic with a number of storm events in the record. Yet only a small proportion of that was delivered to platforms.

Table 6.3 Wave energy flux at high tide on shore platforms during S4A deployments. Comparison of offshore wave energy flux calculated from significant wave height (P_O H_S), and maximum wave height (P_O H_{MAX}), with wave energy flux on shore platforms calculated from significant wave height (P_P H_S), and maximum wave height (P_P H_{MAX}), measured at high tide during S4A deployments. Energy flux (P_P H_S and P_P H_{MAX}) on shore platforms is also presented as a percentage of the offshore energy flux.

Date	High Tide	H_S m	T_S s	H_{MAX} m	T_{HMAX} s	P_P H_S N-m/s-m	P_P H_{MAX} N-m/s-m	H_{OS} m	H_{OMAX} m	T_O s	P_O H_S N-m/s-m	P_O H_{MAX} N-m/s-m	P H_S % P_O H_S	P H_{MAX} % P_O H_{OMAX}
KM2														
21/06/96	20:25	0.3	8.4	0.4	8.1	236	400	1.4	2.1	5.8	11790	26000	2.0	1.5
22/06/96	09:05	0.3	8.6	0.4	8.3	146	327	1.2	1.9	5.7	8141	19943	1.8	1.6
23/06/96	22:35	0.4	11.6	0.6	10.9	347	961	2.6	4.2	7.1	47324	122601	0.7	0.8
24/06/96	10:40	0.2	9.5	0.3	10.1	154	346	2.9	4.1	7.2	58214	118159	0.3	0.3
	23:40	0.4	9.7	0.6	9.2	616	1447	2.0	2.6	8.3	33879	56579	1.8	2.6
25/06/96	11:20	0.4	9.5	0.5	9.1	616	960	1.7	3.5	7.3	21736	86147	2.8	1.1
KM3														
14/06/96	15:45	0.7	12.6	0.9	11.7	2073	4835	1.8	2.6	8.2	26970	54730	7.7	8.8
15/06/96	04:45	0.5	10.7	0.7	10.1	918	2062	1.6	2.5	8.3	20881	51934	4.4	4.0
KM5														
1/07/96	16:20	0.4	9	0.6	8.8	535.07	1413.84	2.0	2.9	6.6	25686	53262	2.1	2.7
2/07/96	04:45	0.2	9.2	0.3	8.9	135.16	540.63	1.6	2.4	8.4	31128	47822	0.4	1.1
2/07/96	17:15	0.4	7.8	0.5	7.6	535.5	880.26	1.9	2.9	4.8	16402	40330	3.3	2.2

6.2.4 ATTENUATION ACROSS THE PLATFORM

During S4A deployments between 14 June 1996 and 2 July 1996 both the Kainga 1000 and Greenspan transducers were also deployed either on KM2 or KM3. Unfortunately both transducers failed to record properly, due to manufacturers' faults. Both transducers were returned for repair. In July 1997 a second attempt was made to measure cross platform wave attenuation. On 1 and 2 July 1997 the Greenspan transducer was successfully deployed at the same time as the S4A, but the Kainga 1000 again failed. As a result the Greenspan transducer was located at the foot of the landward cliff on the KM3 profile and the S4A in the same positions as in 1996 at the seaward edge. No deep water wave data were available during these deployments. While the size of the data set collected is small and a larger number of deployments would be desirable, investigation of the degree of attenuation of wave energy cross the platform was considered viable.

Wave statistics were calculated from 20 minutes of wave recording centred over the peak of high tide. S4A wave statistics were computed using the S4A software. Wave statistics from the Greenspan pressure transducer were computed using an EXCEL® spread sheet designed by Mr Jonathon Allan, Department of Geography, University of Canterbury. The Greenspan transducer outputs the depth of water measured from the hydrostatic head; it does not include the dynamic component. In the spread sheet raw data of water depth were detrended to remove variations in water level due to tides. Detrended data were then analysed using the zero crossing method presented by Tucker (1967). A macro was used to carry out this analysis. The output was the following wave parameters: significant wave height (H_S); maximum wave height (H_{MAX}); and zero crossing period (T_z).

Table 6.4 presents the results of wave measurements on 1 July and 2 July 1997. At high tide significant wave heights on 1 July 1997 were 0.4m on the outer edge on KM3 and 0.08m on the inner site. Maximum wave heights were 0.6m on the outer edge of the platform and 0.14 on the inner position. On 2 July significant wave heights were 0.4m on the outer edge on KM3 and 0.11m on the inner site, and maximum wave heights were 0.6m on the outer edge of the platform and 0.14m on the inner position. Using these height parameters and zero crossing periods wave energy flux was calculated with the ACES programme. On the outer edge of KM3 wave energy flux calculated from H_{MAX} was 636N-m/s-m of wave crest on 1 July. This compared with 31N-m/s-m of wave crest at the landward cliff foot; 31N-m/s-m represents 4.9 per cent on the wave energy flux at the seaward edge of the platform. On this day wave energy flux calculated from H_{SIG} was 305N-m/s-m at the seaward edge and 17N-m/s-m at the cliff foot, or 5.6 per cent of the wave energy measured at the seaward edge. Wave energy flux calculated from H_{MAX} on 2 July 1997 was 617N-m/s-m of wave crest at the outer edge of the platform and 35N-m/s-m of wave crest at the cliff foot. That is, 5.7 per cent of the energy in the highest wave measured at the seaward edge reached the cliff foot. From H_{SIG} wave energy flux at the seaward edge of KM3 on 2 July was calculated to be 296N-m/s-m of wave crest while at the cliff foot it was 20N-m/s-m of wave crest; 20N-m/s-m of wave crest is 6.8 per cent of the energy flux at the seaward edge of the platform.

Table 6.4 Calculated wave parameters and wave energy flux from two deployments of the S4A wave recorder and Greenspan pressure transducer on KM3. The S4A was located at the seaward edge of the platform and the Greenspan transducer was located at the landward cliff foot.

Date	H_{SIG} Outer	H_{MAX} Outer	T_Z Outer	P_{OUT} H_{MAX} N-m/s-m	P_{OUT} H_{SIG} N-m/s-m	H_{SIG} Inner	H_{MAX} Inner	T_Z Inner	P_{INNER} H_{MAX} N-m/s-m	P_{INNER} H_{SIG} N-m/s-m	# %	* %
1/7/97	0.4	0.6	8.6	636	305	0.08	0.14	5.5	31	17	4.9	5.6
2/7/97	0.4	0.6	9	617	296	0.11	0.15	5.4	35	20	5.7	6.8

Inner H_{MAX} wave flux as a percentage of outer H_{MAX} wave flux

* Inner H_{SIG} wave flux as a percentage of outer H_{SIG} wave flux

As with wave attenuation from deep water to the platform edge, between 93 and 95 per cent of wave energy is lost in shoaling from the platform edge to the landward cliff. Wave energy at the cliff foot was found to be an order of magnitude less than that measured at the seaward edge of the platform. Wave energy flux in deep water was calculated to be in the order 5952 to 536772N-m/s-m of wave crest but at the cliff foot is was found to be in the order of 17 to 20N-m/s-m of wave crest. This shows that the amount of wave energy reaching the cliff platform junction where platform extension occurs is two to five orders of magnitude less than that in deep water.

6.2.5 DO WAVES CAUSE EROSION?

It was demonstrated in Sections 6.2.3 and 6.2.4 that there is a very large loss of wave energy from deep water to the landward cliff platform junction. This presents the question: do waves cause erosion on shore platforms, given that so much energy is lost during shoaling? Tsujimoto (1987) proposed that wave induced shear stress caused erosion on platforms. Further, he argued that because breaking waves exert the greatest pressures, then equation 2.19 should be adopted using breaker height. It has been clearly demonstrated in this study that waves very rarely break at the landward cliff foot or on platform surfaces. It is proposed that wave induced shear stress should be calculated using equation 2.20:

$$\tau = C_f \rho g H$$

where H is wave height measured on the platform and at the cliff foot.

Wave forces against the landward cliff of KM3 can be calculated using equation 2.3:

$$p_m = 0.5 \rho g h_b$$

Some modification of this equation was required. For the purposes of calculating the dynamic component of the wave force, d_b (depth of breaking) was replaced with the depth of water at the cliff foot d_c. This was because the depth of breaking required in equation 2.3 cannot be gained from the wave data. It has been demonstrated that most waves break offshore of platforms.

6.2.5.1 SHEAR STRESSES UNDER WAVES

Table 6.5 presents calculated shear stresses under waves measured using the S4A on profiles KM2, KM3, and KM5. Shear stresses have been calculated using both significant and maximum wave height. Values for shear stress ranged from 31N/m^2 under a wave 0.2m high to 1400N/m^2. Under a wave 0.9m high. Table 6.6 contains shear stresses calculated from wave data during S4A and Greenspan pressure transducer deployments on KM3 in July 1997. On the seaward edge of KM3 shear stress was 622N/m^2 and 934N/m^2 under wave heights of 0.4 and 0.6m respectively. Simultaneously, at the cliff foot, shear stress ranged from 124 to 233N/m^2.

Table 6.5 Wave induced shear stresses on the seaward edge of platforms KM2, 3 and 5 calculated from significant and maximum wave height data collected at high tide.

Date	H_SS4 (m)	H_{MAX}S4 (m)	Shear Stress N/m^2 H_S	Shear Stress N/m^2 H_{MAX}
21/06/96	0.3	0.4	467	622
22/06/96	0.3	0.4	467	622
23/06/96	0.4	0.6	622	934
24/06/96	0.2	0.3	311	467
	0.4	0.6	622	934
25/06/96	0.4	0.5	622	778
KM3				
14/06/96	0.7	0.9	1089	1400
15/06/96	0.5	0.7	778	1089
KM5				
1/07/96	0.4	0.6	622	934
2/07/96	0.2	0.3	311	467
2/07/96	0.4	0.5	622	778

Table 6.6 Wave induced shear stresses on the seaward edge (S4A) and at the landward cliff foot (GS) of platform KM3 calculated from significant and maximum wave height data collected at high tide.

Date	H_SS4	H_{MAX}S4	Shear Stress N/m^2 H_S	Shear Stress N/m^2 H_{MAX}	H_SGS	H_{MAX}GS	Shear Stress N/m^2 H_S	Shear Stress N/m^2 H_{MAX}
2/07/97	0.4	0.6	622	934	0.08	0.14	124	218
2/07/97	0.4	0.6	622	934	0.11	0.15	171	233

6.2.6 WAVE FORCES AT THE CLIFF FOOT

Using equation 2.3 and wave data collected at the landward cliff foot on KM3 the dynamic forces of waves were calculated assuming the profile presented a vertical cliff face. The results of these calculations are presented in Table 6.7. At high tide dynamic force ranged from 161 to 301N/m^2 against the cliff face.

Table 6.7 Wave dynamic force against the landward cliff on profile KM3 calculated from significant and maximum wave heights.

KM3	H_S	H_{MAX}	Dynamic Force H_S N/m^2	Dynamic Force H_{MAX} N/m^2
1/07/97	0.08	0.14	161	281
2/07/97	0.11	0.15	221	301

If waves are to cause erosion then wave induced shear stress on the platform and dynamic force against the cliff foot must exceed the resisting strength of the rock forming the platform (Sunamura 1992). Minimum compressive strength values of rock material forming profiles KM2 and KM3 are recalled from Chapter Four and compared with the maximum shear stress and dynamic force values in Table 6.8. Clearly wave forces never exceeded the compressive strength of the rock forming these platforms. Wave forces are less than compressive strength values by between four and five orders of magnitude.

Table 6.8 Compressive strength values from profiles KM2 and KM3 compared with wave induced shear stress on both profiles and dynamic force at the cliff base on KM3.

KM2 Minimum Compressive strength KN/m^2	Maximum Shear Stress KN/m^2	KM3 Minimum Compressive strength KN/m^2	Maximum Dynamic Force KN/m^2	Maximum Shear Stress KN/m^2
217545	0.934	47198	0.301	1.400

It is recognised above that the wave data set from Kaikoura is very small and the range of wave forces given is not categorical. Because of this further analysis was under taken in an attempt to predict the largest wave that may occur on the landward edge of KM2 and at the cliff foot of KM3 and KM5. This was done by using the relationship between breaker height and depth from CERC (1984):

$$\frac{db}{Hb} = 1.28 \qquad \textbf{6.3}$$

If the assumption is made that waves on shore platforms reform after breaking, then the maximum depth of water at the cliff foot at high tide can be used to predict the height of the maximum wave reaching the cliff foot. The highest water level during the period 1 June to 9 July was identified in tidal data. The deepest water occurred on 30 June when high tide peaked at 3.828m above the Kaikoura tide gauge. Table 6.9 shows the depth of water on the landward edge of KM2 and at the cliff foot on KM3 and KM5 and the maximum predicted wave height in that depth of water. Also included in Table 6.9 are maximum shear stress and dynamic wave force calculated from the predicted wave heights. Clearly the shear stress and dynamic wave force do not exceed the mechanical strength of the rock forming the platforms. The important point to be made from this analysis is that the largest wave that can arrive at the cliff foot on a shore platform is controlled by the depth of water in front of the cliff. In Chapter Two it was noted from Tsjimoto's (1987) work which empirically accounted for weathering, that wave induced shear stress causes erosion when the wave force equals 0.5 per cent of the compressive strength of rock. As shown in Table 6.9 shear stresses on KM2 and KM3 never reached this value.

Table 6.9 Predicted wave height at the landward edge of KM2 and at the cliff foot on KM3 and KM5 based on water depth at high tide. From these wave heights shear stress and dynamic wave force have been calculated.

Profile	Compressive strength KN/m^2	Water Depth (m)	Predicted Wave Height (m)	Shear Stress KN/m^2	Shear Stress as a Percentage of Compressive Strength	Dynamic Wave Force KN/m^2
KM2	21755	0.577	0.74	0.115	0.0005	n/a no cliff
KM3	47198	0.406	0.52	0.809	0.0017	1.06
KM5	n/a	0.578	0.74	0.115	n/a	2.14

The above analysis has shown that wave induced shear stress and dynamic force are less than the mechanical strength of the rocks forming the platforms on the Kaikoura Peninsula by wide margins. The conclusion drawn from this is that waves do not have enough energy to cause erosion at the landward cliff of platforms or to cause downwasting on platform surfaces. In terms of Sunamura's (1992) conceptual model (Figure 3.3) of platform erosion, F_W is less than F_R therefore erosion will not occur. The analysis so far has not considered those forces that act to reduce mechanical strength, in particular weathering, except through Tsujimoto's (1987) empirical consideration. Nor has it considered processes such as abrasion or the compression of air in joints. Weathering will be examined in Section 6.4 of this chapter.

6.3 TIDES

Trenhaile (1978) viewed waves as the cause of erosion and the tide as the control of the location at which the erosion occurred. Tide data from Kaikoura were collected and examined for two purposes related to this view. The first was to investigate the durations for which particular elevations on platforms were submerged and therefore subjected to wave action and conversely exposed to subaerial action. Secondly, it was desired to calculate the number of times tides inundate particular elevations. This was considered a useful starting point to estimate the number of wetting and drying cycles that occur in any given year. The significance of wetting and drying is considered in the next section.

With permission from the Kaikoura District Council a tide gauge was established at Kaikoura in association with the National Institute of Water and Atmospheric Research Ltd, in August 1994. The gauge was located on the New Wharf (Fig 4.1) and levelled relative to benchmarks so that platform elevations could be related to the tidal data. This gauge consists of a Unidata Starlogger model 6004A and a calibrated Kainga 1000 pressure transducer. The instrument samples at two second intervals and logs the mean water elevation at five minute intervals. The logger is supplied power from a 12v battery that is continuously trickle charged from mains power. This ensures that a cut in mains power will not cause the instrument to stop logging. Further power back up is supplied by batteries contained in the logger itself. Initially data were retrieved by downloading the logger to a laptop computer on site. Later, the National Institute of Water and Atmospheric Research Ltd installed a modem so that the logger can be downloaded remotely.

For the purposes of analyses, data from 1995 and 1996 were examined. To calculate the amount of time a particular elevation on shore platforms at Kaikoura was submerged data were entered into an Excel® spreadsheet. The spreadsheet was designed to count the number of loggings lower than specified elevations. Since each logging represented a period of five minutes a summation command allowed the total hours submerged to be calculated. The elevations of micro-erosion meter bolt sites were used to consider platform inundation. The number of tidal cycles at a bolt site was calculated by counting the number of high tides that exceeded the elevation of the bolt site. For bolt sites on the seaward edge of platforms with lower elevations it was necessary to count the number of times low tide remained above that elevation and subtract these from the total number of high tides.

Tables 6.10 to 6.16 present the results of the analyses described above. Duration of submergence varied from 0hrs/yr on KM3A to 7898.1hrs/yr on KM1G. After KM3A, KM7A was submerged the least amount of time: 13hrs in 1995 and 12.75hrs in 1996. Submergence time has also been translated into the percentage of each year submerged. This provides an indication of how often waves were able to act on platform surfaces at each elevation. Obviously there is a direct relationship between elevation and the number of hours submerged per year: the higher the elevation the less the submergence. This has important implications for the role of waves in platform development. Clearly waves do not cause erosion on KM3A and have little opportunity to do so on KM7A. With the exception of KM4A the inner margins of platforms at Kaikoura were submerged from between 0 to 33.3 per cent (KM6A 1996) of the year. Conversely the more seaward bolt sites were submerged for much longer periods. KM1G was submerged 87 per cent (7620.7 hours out of a possible total of 8760 hours) of 1995 and 89.9 per cent (7898.1 out of a possible total of 8784 hours) of 1996. Submergence on KM6G was 83.0 and 85.4 per cent (7268.1 and 7498.3 hours) of 1995 and 1996 respectively. However not all seaward bolt sites were inundated for such long periods. KM5G, which was located on a raised rampart at 0.88m above mean sea level, was submerged for only 14.0 per cent (1222.8 hours) of 1995 and 16.3 per cent (1428 hours) of 1996. Figure 6.24 illustrates submergence curves for each MEM profile at Kaikoura. This is included to illustrate that there is little difference between platforms types. Slight differences between plotted lines are a result of the varying numbers of bolt site elevations used on each profile.

Calculated tidal cycles presented in Tables 6.10 to 6.16 ranged from the maximum possible of 704 in 1995 and 707 in 1996 (1996 was a leap year) on most bolt sites to 0 on KM3A. Bolt sites on the inner margins of platforms were inundated less often: 559 times in 1995 and 595 times in 1996 on both KM1A and KM2A, 188 times in 1995 on KM5 and 279 times in 1996, and 21 times in 1995 and 37 times in 1996 on KM7. Bolt sites on the seaward margins also had fewer than the maximum tidal cycles due to low tide levels often occurring above the bolt level. On KM1G there were 424 tidal cycles in 1995 and 399 in 1996. On KM5G there were 458 tidal cycles in 1995 and 658 in 1996, and on KM6G there were 563 tidal cycles in 1995 and 440 in 1996. Although both higher landward bolt sites and lower seaward bolt sites had fewer tidal cycles, the duration of submergence was higher on the lower sites.

Given that wave data showed waves cannot cause erosion and these tidal data, it is difficult to argue that marine processes can be effective erosive agents on the inner margins of platforms at Kaikoura. Sunamura (1992) and Trenhaile (1978, 1983a, 1987) argued that cliff recession occurs because of waves undercutting the cliff base and removing the resulting debris. Profiles with actively eroding landward cliff (KM3, KM5 and KM7) had very low submergence times at the cliff foot. In view of this and the low erosive power of waves calculated in Section 6.2, it would appear unlikely that waves are able to cause cliff recession in the way proposed by Sunamura (1992) and Trenhaile (1978, 1987).

Table 6.10 Duration of submergence (hrs/yr), percentage of each year submerged and number of tidal cycles per year calculated for each bolt site on KM1 for the years 1995 and 1996.

		1995			1996		
KM1	Elevation M.S.L. (m)	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles
A	0.872	1470.1	16.8	559	1490.7	17.0	595
B	0.528	3168.1	36.2	704	3406.8	38.8	707
C	0.626	2780.9	31.7	704	2947.9	33.6	707
D	0.511	3276.2	37.4	704	3480.4	39.6	707
E	1.04	385.0	4.4	200	507.3	5.8	282
F	0.375	3863.8	44.1	704	4048.3	46.1	707
G	-0.389	7620.7	87.0	424	7898.1	89.9	399

Table 6.11 Duration of submergence (hrs/yr), percentage of each year submerged and number of tidal cycles per year calculated for each bolt site on KM2 for the years 1995 and 1996.

		1995			1996		
KM2	Elevation M.S.L. (m)	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles
A	0.872	1470.1	16.8	559	1490.7	17.0	595
B	0.712	2400.3	27.4	704	2505.4	28.5	707
C	0.493	3472.0	39.6	704	3557.5	40.5	707
D	0.279	4362.7	49.8	704	4450.6	50.7	707
E	0.076	5156.6	58.9	704	5295.8	60.3	707
F	-0.001	5459.1	62.3	704	5632.4	64.1	707
G	-0.027	5581.9	63.7	704	5759.6	65.6	707
H	0.055	5214.0	59.5	704	5381.3	61.3	707
I	0.192	4646.0	53.0	704	4737.3	53.9	707
J	0.115	4968.3	56.7	704	5128.3	58.4	707

Table 6.12 Duration of submergence (hrs/yr), percentage of each year submerged and number of tidal cycles per year calculated for each bolt site on KM3 for the years 1995 and 1996.

		1995			1996		
KM3	Elevation M.S.L. (m)	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles
A	1.748	0	0	0	0	0	0
B	0.854	1396.9	15.9	522	1606.2	18.3	599
C	0.483	3463.2	39.5	704	3599.5	41.0	707
D	0.423	3917.1	44.7	704	4048.3	46.1	707
E	0.438	3649.6	41.7	704	3784.4	43.1	707
F	0.51	3342.1	38.2	704	3480.4	39.6	707
G	0.052	5261.0	60.1	704	5403.1	61.5	707
H	0.265	4367.6	49.9	704	4499.0	51.2	707
I	-0.059	5748.8	65.6	704	5913.9	67.3	707
J	-0.043	5673.5	64.8	704	5829.6	66.4	707

Table 6.13 Duration of submergence (hrs/yr), percentage of each year submerged and number of tidal cycles per year calculated for each bolt site on KM4 for the years 1995 and 1996.

		1995			1996		
KM4	Elevation M.S.L. (m)	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles
A	-0.096	5932.0	67.7	704	6101.0	69.5	707
B	0.318	4161.3	47.5	704	4290.3	48.8	707
C	0.435	3671.8	41.9	704	3806.8	43.3	707
D	-0.013	5540.8	63.3	704	5689.3	64.8	707
E	-0.154	6236.8	71.2	697	6432.8	73.2	703
F	-0.249	6803.6	77.7	644	7038.8	80.1	621
G	0.092	5102.4	58.2	704	5220.3	59.4	707

Table 6.14 Duration of submergence (hrs/yr), percentage of each year submerged and number of tidal cycles per year calculated for each bolt site on KM5 for the years 1995 and 1996.

		1995			1996		
KM5	Elevation M.S.L. (m)	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles
A	1.053	391.8	4.5	188	458.2	5.2	279
B	0.492	3417.8	39.0	704	3557.5	40.5	707
C	0.307	4200.3	47.9	704	4329.9	49.3	707
D	0.538	3220.9	36.8	704	3364.3	38.3	707
E	0.113	4999.9	57.1	704	5139.0	58.5	707
F	0.53	3254.1	37.1	704	3396.5	38.7	707
G	0.88	1222.8	14.0	458	1428.0	16.3	658

Table 6.15 Duration of submergence (hrs/yr), percentage of each year submerged and number of tidal cycles per year calculated for each bolt site on KM6 for the years 1995 and 1996.

		1995			1996		
KM6	Elevation M.S.L. (m)	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles	Duration of Submergence (hrs/yr)	% of Year Site Submerged	Number of Tidal Cycles
A	0.633	2757.6	31.5	704	2923.3	33.3	707
B	0.145	4860.3	55.5	704	4995.1	56.9	707
C	0.249	4437.4	50.7	704	4568.3	52.0	707
D	0.179	4726.7	54.0	704	4861.4	55.3	707
E	-0.156	6252.0	71.4	699	6447.8	73.4	707
F	-0.195	6476.5	73.9	655	6689.1	76.2	656
G	-0.320	7268.1	83.0	563	7498.3	85.4	440

Table 6.16 Duration of submergence (hrs/yr), percentage of each year submerged and number of tidal cycles per year calculated for each bolt site on KM7 for the years 1995 and 1996.

KM7	Elevation M.S.L. (m)	1995 Duration of Submergence (hrs/yr)	1995 % of Year Site Submerged	1995 Number of Tidal Cycles	1996 Duration of Submergence (hrs/yr)	1996 % of Year Site Submerged	1996 Number of Tidal Cycles
A	1.327	13.0	0.10	21	12.75	0.15	37
B	0.757	2049.8	23.5	704	2249.50	25.61	707
C	0.482	3173.0	36.3	704	3599.50	40.98	707
D	0.502	3373.7	38.6	704	3515.83	40.03	707
E	-0.074	5822.7	66.6	698	5990.50	68.20	705
F	0.170	4758.3	54.4	704	4891.50	55.69	707
G	0.074	5166.4	59.1	704	5306.25	60.41	707
H	0.116	4980.4	57.5	704	5116.83	58.25	707

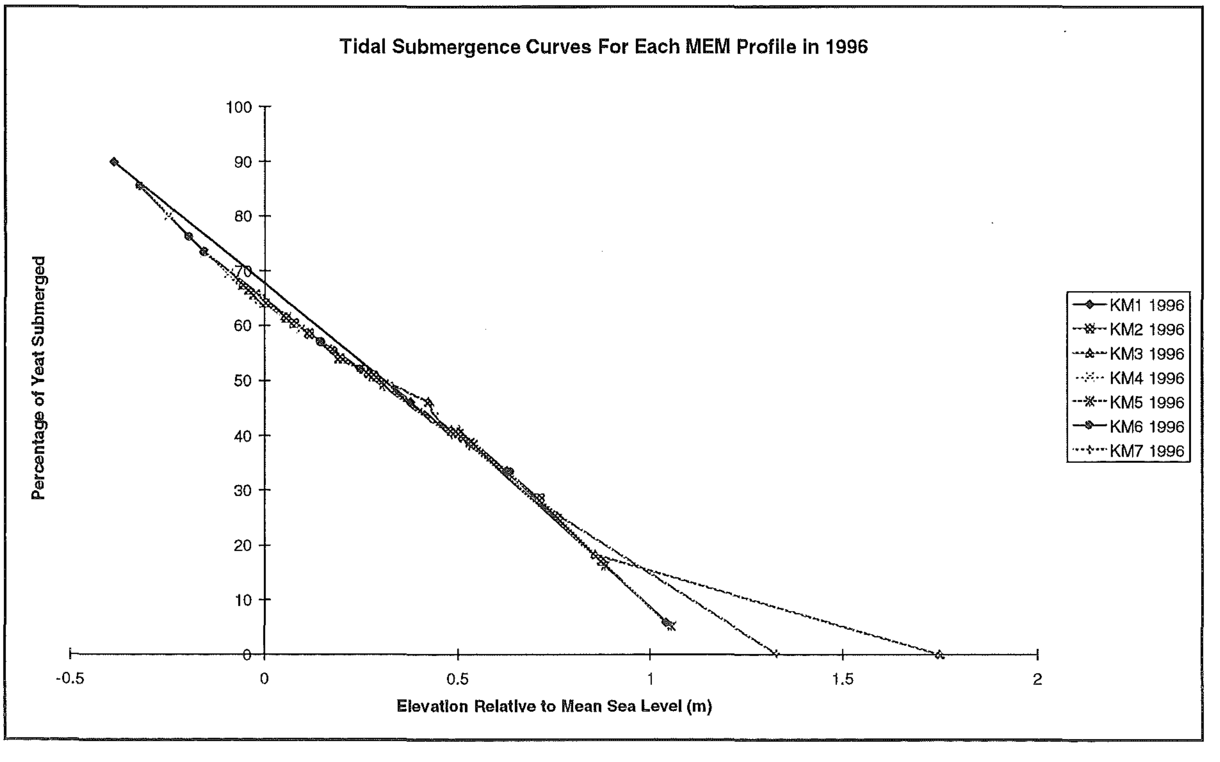

Figure 6.24 Tidal submergence curves for MEM profiles at Kaikoura in 1996. Submergence is as percentage of the year.

6.4 WEATHERING

The intention to investigate whether or not weathering occurs on shore platforms was stated in Chapter Two. Also identified in Chapter Two was the need to assess the proposition that weathering is the dominant erosive process on shore platforms. Erosion data presented in Chapter Five led to the proposition that weathering did have a role in platform development. A more direct investigation of weathering is needed to substantiate this claim. In this chapter evidence is presented for the occurrence, the degree, and zonation of weathering based on morphological and proxy weathering data.

6.4.1 MORPHOLOGICAL EVIDENCE FOR WEATHERING

During field work a number of morphologies that are indicative of weathering processes were observed on shore platforms at Kaikoura. These are presented as supporting evidence for the occurrence of weathering processes and erosion on platforms at Kaikoura.

6.4.1.1 HONEYCOMB WEATHERING

Honeycomb morphology (Fig 6.25) was observed at Kaikoura but was limited in extent, being found at only one location adjacent to KM1. The extent of this morphology is small and localised, covering 3.4m^2. It occurs on a raised part of the horizontal platform, which means it is not submerged at high tide, but it is subjected to spray from wave action. According to Trenhaile (1987) the best developed honeycombs occur under these conditions. The precise mechanism that causes the development of honeycombs is unknown. It has been proposed that mechanical salt weathering has a role (Bartrum 1936; Matsukura and Matsuoka 1991) while Gill et al. (1981) argued that chemical weathering was a formative process. Regardless of the uncertainties surrounding the precise mechanisms of development of honeycombs, the distinctive morphology is taken to be the result of weathering. The occurrence of honeycombs provides evidence of weathering processes operating on shore platforms at Kaikoura.

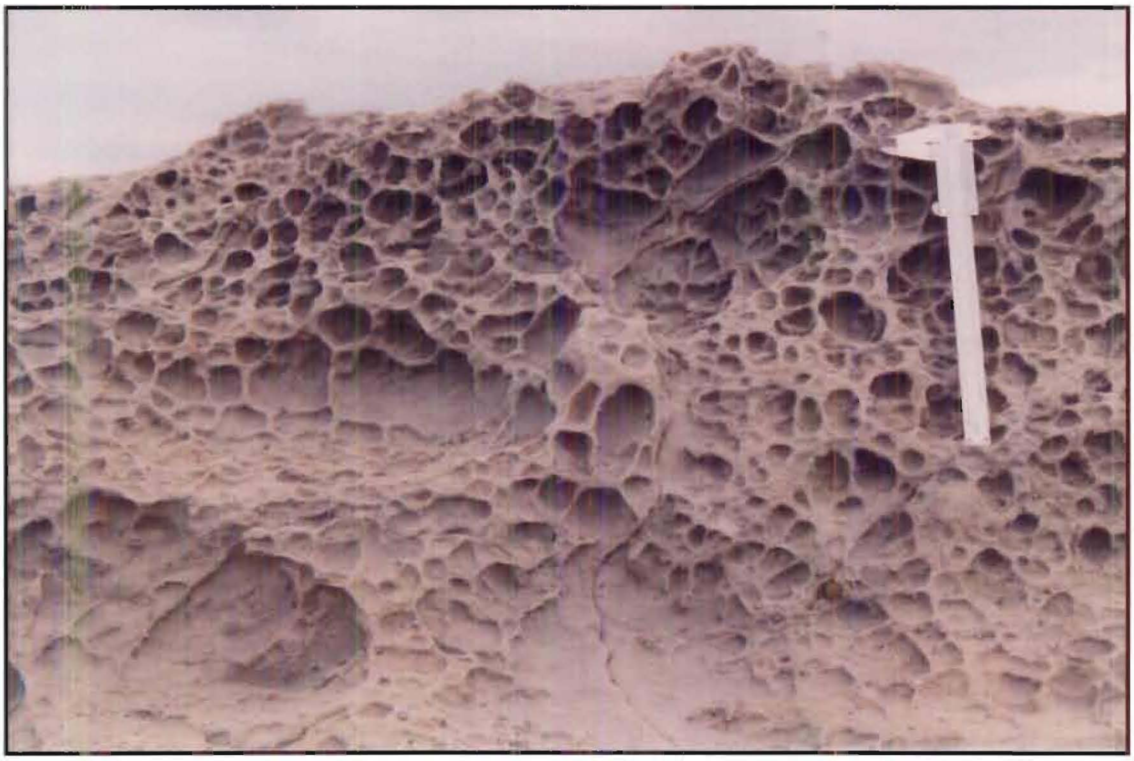

Figure 6.25 Honeycomb weathering on KM1 December 1994. Vernier callipers are 230mm long.

6.4.1.2 SALT WEATHERING

Salt weathering was readily observable on Type B mudstone shore platforms at Kaikoura but only during summer months. There was a noticeable absence of salt weathering on Type A platforms. Salt crystals could be observed around the edge of pools of water left after the tide had receded (Figs 6.26 and 6.27). After sea water had evaporated from pools a "bath tub ring" of salt crystals was left (Fig 6.28). The surface of platforms where salt crystal growth was observed was flaking and pitted (Figs 6.29), small flakes could easily be dislodged with a finger nail. It is proposed that the surface textures shown in Figures 6.29 and 6.30 are the result of mechanical salt weathering as opposed to chemical weathering. However, chemical salt weathering cannot be excluded as a process operating on platforms at Kaikoura.

Figure 6.26 A pool of salt water drying and development of salt crystals around the edge of the pool. Viewable part of pen is 105mm long.

Figure 6.27 Salt crystal growth left after the pool of water has dried. Viewable part of pen is 120mm long.

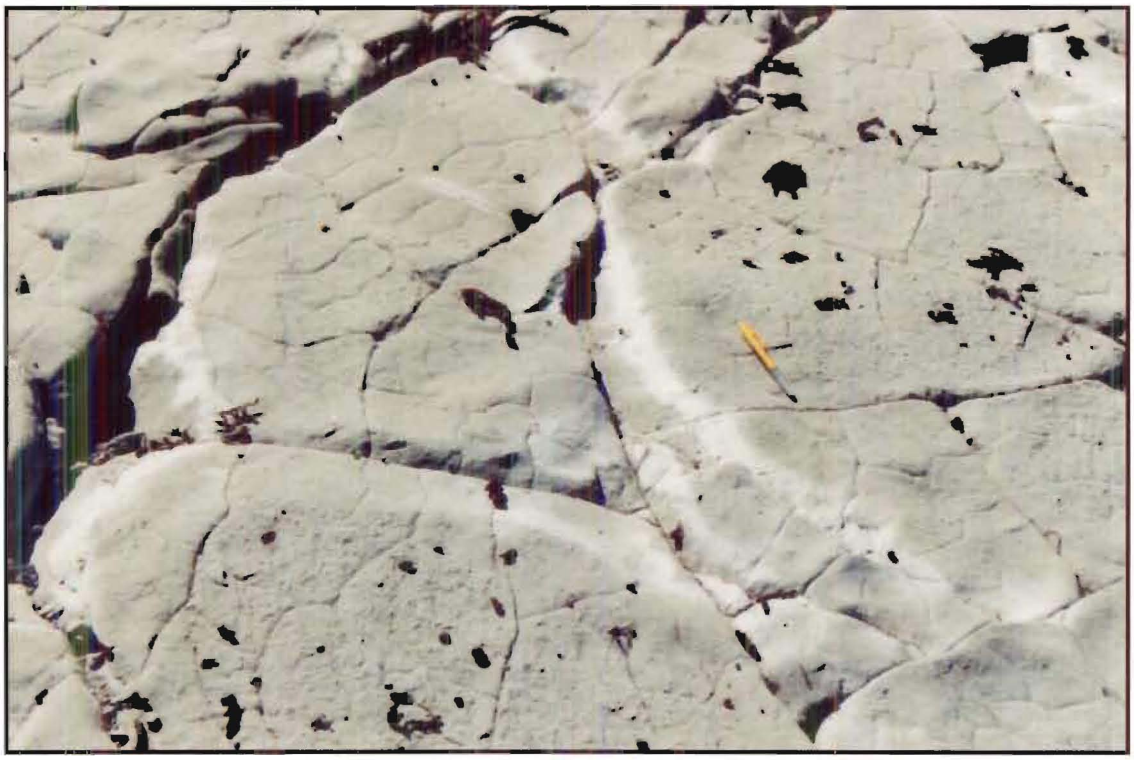

Figure 6.28 Salt crystals ringing a dried pool. Pen is 130mm long.

Figure 6.29 Pitted surface resulting from salt weathering. Viewable part of pen is 85mm long.

6.4.1.3 WATER LAYER WEATHERING

The water layered morphology described by Bartrum (1935) was found at a number of locations on shore platforms at Kaikoura, but only on Type A mudstone platforms. Extensive water layered morphology was found in Mudstone Bay surrounding KM6 (Fig 6.30 and 6.31), although it was restricted to the inner margins. It was also evident on the inner margins of KM2. Bartrum (1935) and Wentworth (1938) proposed salt crystals may play a role in the disintegration of surface depressions but salt crystal growth was noticeably absent on water layered morphologies at Kaikoura. Wetting and drying was identified as a necessary precursor to weathering in Chapter Two. Figure 6.31 shows partially dried pools of water on KM6. Expansion and contraction results when wetting and drying occurs. The clay content of mudstone makes it particularly susceptible to erosion from wetting and drying (Yatsu 1988). The lack of observable crystal growth like that found on Type B platforms is difficult to explain. It is speculated that the softer rock that KM6 is formed in may be too soft to support the high pressures exerted during crystal growth. Clearly the precise contribution of individual processes cannot be explained from the observations but it is clear that weathering in the form of water layer weathering does occur on Type A mudstone platforms on the Kaikoura Peninsula.

Figure 6.30 Water layering morphology with raised rims surrounding shallow pools of water at KM6 profile. Pen is 150mm long.

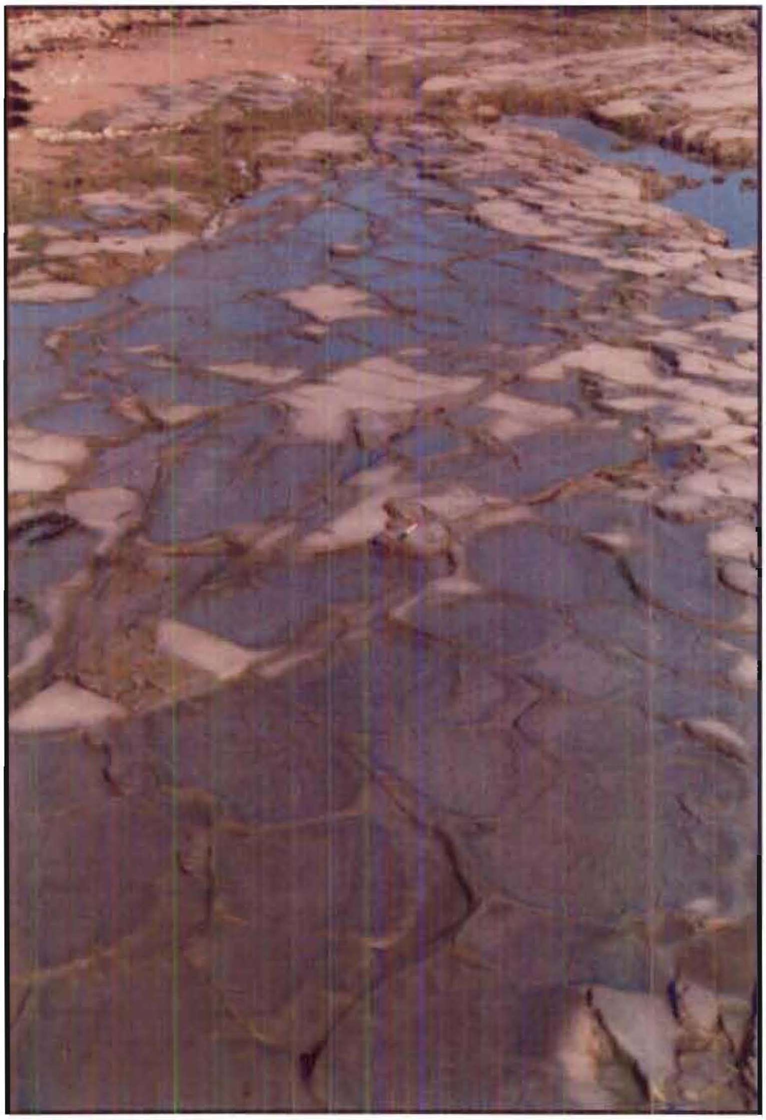

Figure 6.31 Partial dried water layer morphology adjacent to KM6. Note pen centre of photograph.

6.4.1.4 SLAKING

Slaking is a weathering process that results from repeated wetting and drying but it produces a different morphology from water layer weathering. It appears as platy or conchoidal fragments (Figures 6.32 and 6.33). Water attached to clay particles exerts pressures and repeated wetting and drying causes expansion and contractions, resulting in tensional fatigue and fracturing (Ollier 1975). The occurrence of slaking at Kaikoura was confined to landward cliffs on profiles and KM3, KM5 and KM6 (Fig 6.34 and 6.35). Based on visual observations slaking appears to be an important process causing erosion of mudstone cliffs at Kaikoura.

Figure 6.32 Slaking morphology on cliffs adjacent to KM6. Lens cap is 52mm wide.

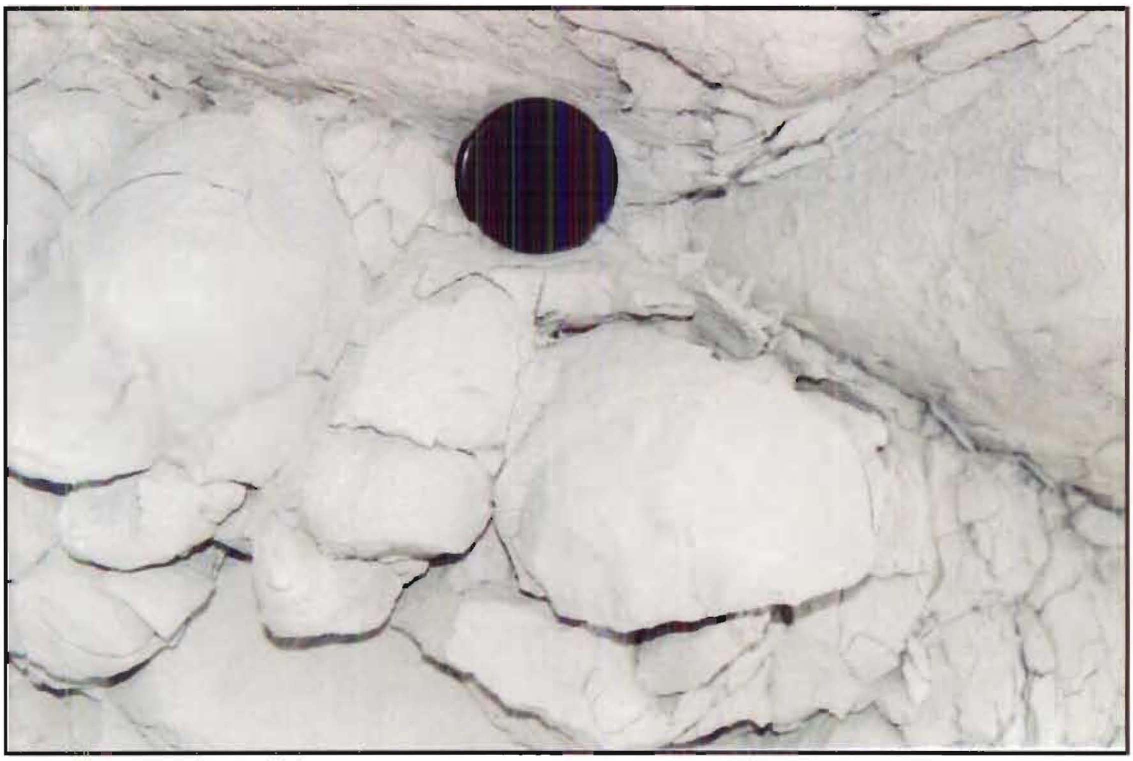

Figure 6.33 Slaking morphology on cliffs adjacent to KM6 note conchoidal shape of rock surface. Lens cap is 52mm wide.

Figure 6.34 Landward cliff face adjacent to KM6 weathered due to slaking. Backpack in centre of photograph is 1m long.

Figure 6.35 Weathered cliff backing KM3 November 1995. Note person right of cliff for scale.

Morphological evidence indicates that four weathering processes occur on shore platforms at Kaikoura. Salt weathering and water layer weathering appear to be significant on horizontal platforms, while honeycomb weathering was restricted to a single location. Salt weathering occurred on Type B platforms and was absent from Type A. Conversely, water layer weathering was found on Type A platforms and was absent from Type B platforms. This suggests that there is some lithological control over the processes. It was speculated that the weaker mudstone that forms Type A platforms is unable to support crystal growth in the rock lattice. This does not explain why water layer weathering was not observed on Type B platforms. On Type A platforms water layer weathering was restricted to the inner landward margins of platforms. The occurrence of salt weathering on Type B platforms did not have a readily observable spatial pattern. It is likely that salt weathering occurs wherever pools of water are left after the tide has ebbed. Slaking was noted to occur on cliffs backing platforms. This analysis has shown an absence of the occurrence of weathering morphologies on limestone platforms. Such an absence does not exclude the possibility of weathering occurring. A different means of assessing the occurrence of weathering is needed. Such a means is the Schmidt Hammer test, which provides a quantitative assessment of the occurrence of weathering.

6.4.2 WEATHERING ASSESSED USING THE SCHMIDT HAMMER TEST

Quantitative assessment of weathering has proven difficult in geomorphology in general but the assessment of relative degrees of weathering between locations is possible using the Schmidt Hammer test. The Schmidt Hammer was originally designed by E. Schmidt in 1948 as a non-destructive test of hardness for *in-situ* concrete. This instrument is a cylindrical device weighing approximately 2kg that contains a spring loaded plunger. The distance this plunger rebounds after it is fired against a surface is related to the hardness of the surface. The rebound number (R) can then be converted into the compressive strength (N/mm^2 or MPa) using calibration curves supplied with the instrument, although this is not necessary for purely comparative studies. The Schmidt Hammer was first used by geomorphologists to assess the compressive strength of rock (Hucka 1965; Yaalon and Singer 1974; Day and Goudie 1977; Day 1980) and later to determine the degree of weathering of rock (McCarroll 1989, 1991; Ballantyne et al. 1989; Sjöberg and Broadbent 1991). Whether or not weathering has occurred is determined by comparing the difference between rebound values for exposed weathered rock surfaces, with values from freshly exposed unweathered surfaces.

Day and Goudie (1977:24) provide five guidelines for use of the Schmidt Hammer in the field.

1) The test site should not be too near the edge of a rock mass or near a void or joint. Readings should be taken 6cm from edges and joints.
2) Surfaces should be flat and free from flakes and dirt. Readings will be lower on rough surfaces than smooth ones. This is important for assessing rock strength. However, weathering processes may cause surfaces to become pitted or flaked and therefore testing of these surfaces is important for assessing weathering.
3) Each test must be performed on a new spot. Repeated testing on or near the same point yields increased R-values due to crushing and compression of the rock surface.
4) The number of impacts made at a site should be 10 to 15. A greater number should be taken if there is a high degree of variability in readings.
5) R-values will vary depending on the angle at which the instrument is held during testing. All tests should be performed either with the hammer held horizontally or vertically.

Day (1980) added that regular testing, service, and calibration of the instrument are required as results vary with the age and extended use of the instrument.

A new, Type L Schmidt Hammer was used at Kaikoura. This hammer had an impact energy of 0.735Nm. Schmidt Hammer tests were performed along each MEM profile where 50 readings were taken as close as possible to, but not on, each bolt site. On KM1, KM4, KM5, and KM6; each with six bolt sites, 300 separate readings were taken. On KM7 with eight bolt sites, 400 separate readings were made. At KM2 there were ten bolt sites, but two were so close together that separate testing was deemed unnecessary so that nine sites produced 450 separate readings. On KM3 ten bolts sites yielded 500 separate readings. In total 2750 individual Schmidt Hammer readings were recorded. In addition to these, three sites were found where limestone and Type A and B mudstone could be exposed using a masonry hammer and tested to establish R-values on unweathered rock.

Table 6.17 show the results of the Schmidt Hammer tests. Rebound numbers ranged from 19 on KM7B to 35 on KM1A respectively. The low values measured on KM7A and B, 20 and 19 respectively are less likely to be as a result of weathering and more likely are due to lithology. In the vicinity of both bolt sites, thin and steeply dipping beds are shattered by tight folding. This made it difficult to comply with Day and Goudie's (1977) first guideline that the test site could not be too near the edge of a rock mass or near a void or joint. While both these rebound numbers may not accurately reflect the degree of weathering, they do give some indication of the strength of the platform surface and its likely resistance to erosion. A rebound value of 19 was also recorded on KM4B where structural factors were not an influence. Rebound values varied widely on individual platform profiles and between profiles. As a comparison, Williams and Robinson (1983) using an Type L hammer, reported R-values of 23.7 and 42.4 for weathered and unweathered sandstone respectively. Day and Goudie (1977) using a Type N hammer reported unweathered R-values from quartzite of 67 from granite 59 and 60, and from limestone 36. Yaalon and Singer (1974) reported an R-value in chalk of 14.

Table 6.17 Schmidt Hammer Test results at each bolt site.

	Profile and Rebound Numbers						
Bolt Site	KM1	KM2	KM3	KM4	KM5	KM6	KM7
A	35	28	27	27	22	23	20
B	31	32	28	19	25	24	19
C	31	27	30	22	29	28	35
D	30	27	28	30	31	24	36
E	28	25	31	32	29	23	34
F	29	28	31	26	32	25	36
G	31	28	29	31	33	24	38
H		28	27				33
I		28	30				
J		28	30				

Table 6.18 contains the average rebound number for each profile, lithology, and platform type. The average rebound value from 50 tests on unweathered limestone and mudstone on both Type A and B platforms is also presented in Table 6.18. There is a clear separation between Type A and B platforms in mudstone based on rebound numbers. This is not surprising given the compressive strength values presented in Chapter Four. The most important result is that average rebound values are lower than those for unweathered rock. The conclusion that can be made is that weathering has occurred on platforms at Kaikoura. Further, weathering clearly did degrade rock strength on platforms. In Table 6.18 the mean rebound value from each profile was converted to a percentage of the rebound values for unweathered rock. This represents the percentage of strength remaining after weathering, since rebound is a proxy measure of compressive strength. For example, at the surface of KM1 compressive strength was 88.5 per

cent of the unweathered rock value, and on KM4 compressive strength was only 48.1 per cent of the unweathered strength. Weathering has reduced compressive strength on platforms on the Kaikoura Peninsula by between 11.5 and 51.9 per cent. This confirms that limestone platforms also undergo weathering. If compressive strength values from Chapter Four which ranged from 8932 to 57856KN/m^2 are reduced by 50 per cent then rock strengths range 4466 to 28928KN/m^2. These still exceed the erosive forces of waves calculated in this chapter, which ranged from 161 to 1400N/m^2.

Table 6.18 Average rebound value for each profile and platform type and unweathered lithologies.

Profile	Mean Rebound Number	Platform R-value as a % of unweathered rock
KM1	31	88.5
KM2	28	87.5
KM3	29	82.8
KM4	26	48.1
KM5	29	82.8
KM6	24	68.7
KM7	31	57.4
Mudstone Type A	26.0	81.2
Mudstone Type B	29.7	84.8
Limestone	28.5	52.7
Unweathered Limestone	54	
Unweathered Mudstone Type A	32	
Unweathered Mudstone Type B	35	

The Schmidt Hammer data were also used to investigate cross-shore variations in weathering. This enables the testing of the hypothesis that shore platforms develop as a result of the zonation of weathering and marine processes across the platform profile. If shore platforms erode in this way, then it would be expected that the degree of weathering on a platform would be highest on the inner landward margin and decrease across the profile in a seaward direction. Data from Table 6.17 have been plotted in Figures 6.36 to 6.42 to illustrate cross-shore variations in the degree of weathering. A linear trend line has also been fitted to each graph to indicate if there is any change in the degree of weathering across the platform profile. The trend line in Figure 6.36 shows a decrease in rebound numbers in a seaward direction, indicating an increase in the degree of weathering in that direction. This trend does not support the hypothesis presented above. One explanation for this pattern is that a cobble and pebble beach backing the KM1 profile causes abrasive action under wave action and results in a hard unweathered rock surface. Schmidt Hammer test data from KM2 are plotted in Figure 6.37. A trend line fitted to these data shows no cross-shore variations of weathering in any direction. KM3 (Fig 6.38) shows a clear cross-shore variation in the degree of weathering. There is a higher degree of weathering on the landward margin relative to the seaward edge of the platform. This pattern is repeated on KM4 (Fig 6.39) and KM5 (Fig 6.40). On KM6 (Fig 6.41) there is no apparent cross-shore variation in weathering, as the trend line is horizontal. Figure 6.42 shows the plotted data from KM7. Here there appears to be a decrease in the degree of weathering in a seaward direction. However, as already explained, the low rebound values on the landward margin are as a result of lithology rather than the degree of weathering.

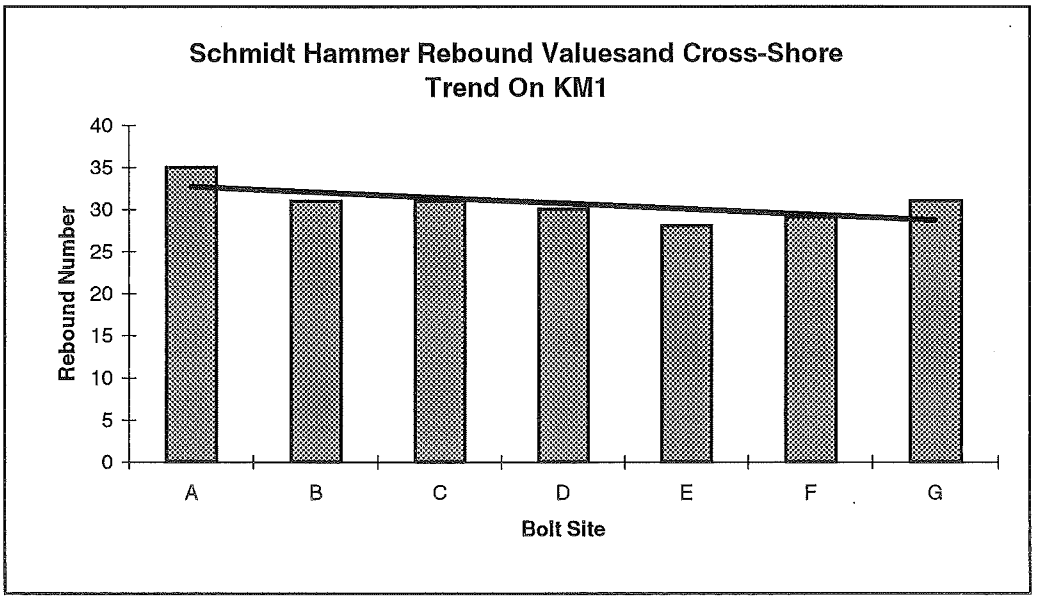

Figure 6.36 Schmidt Hammer rebound numbers from each bolt site on KM1 and a trend line fitted using linear regression.

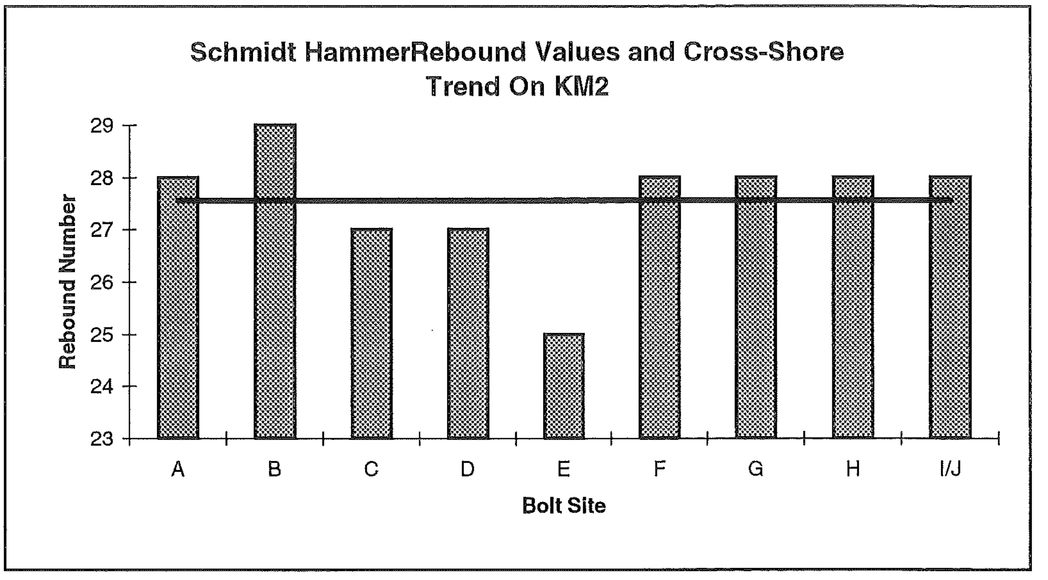

Figure 6.37 Schmidt Hammer rebound numbers from each bolt site on KM2 and a trend line fitted using linear regression.

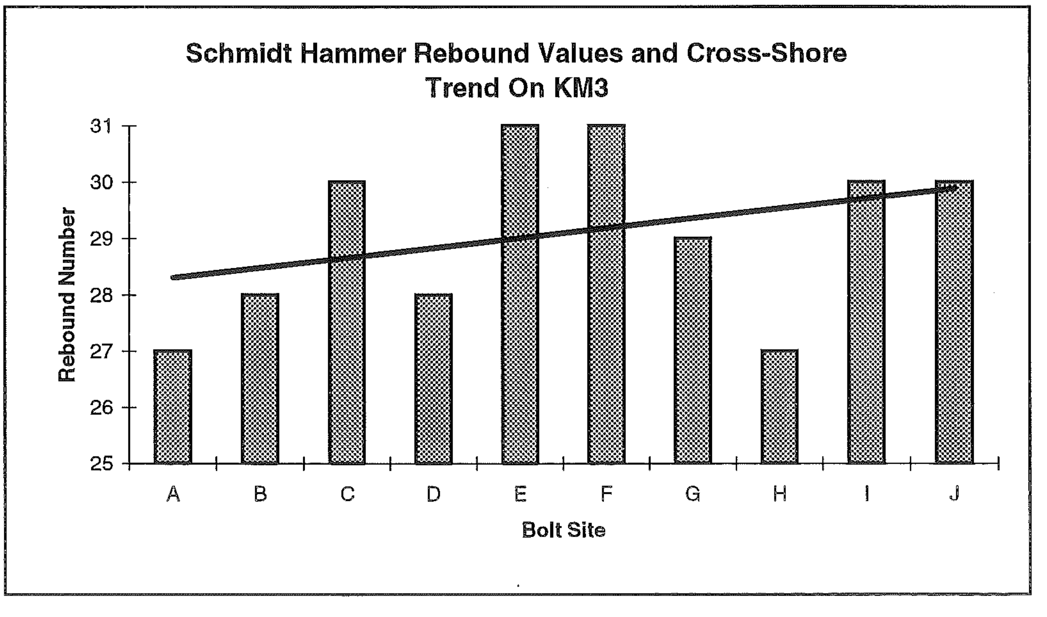

Figure 6.38 Schmidt Hammer rebound numbers for each bolt site on KM3 and a trend line fitted using linear regression.

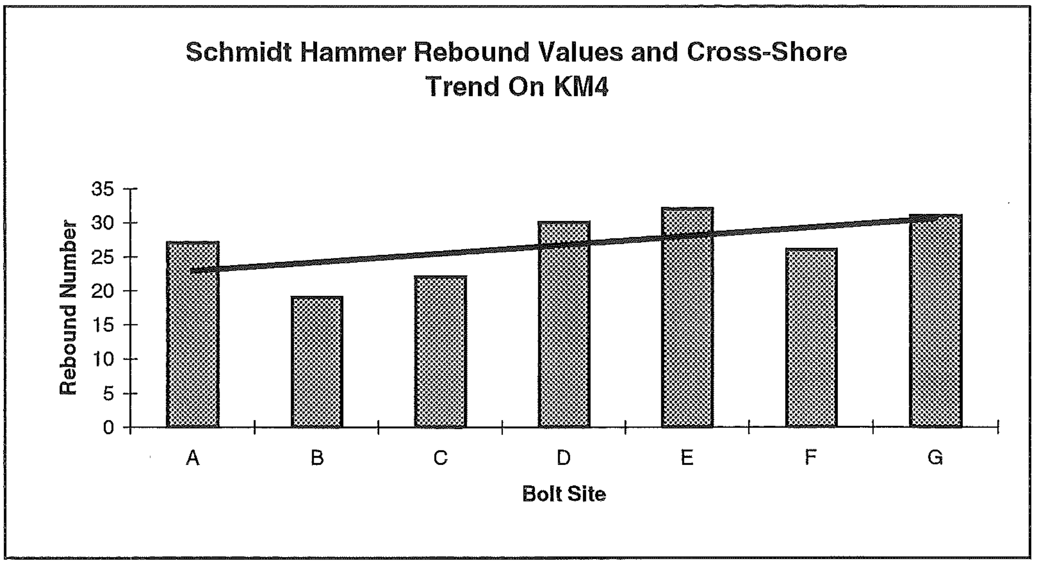

Figure 6.39 Schmidt Hammer rebound numbers from each bolt site on KM4 and a trend line fitted using linear regression.

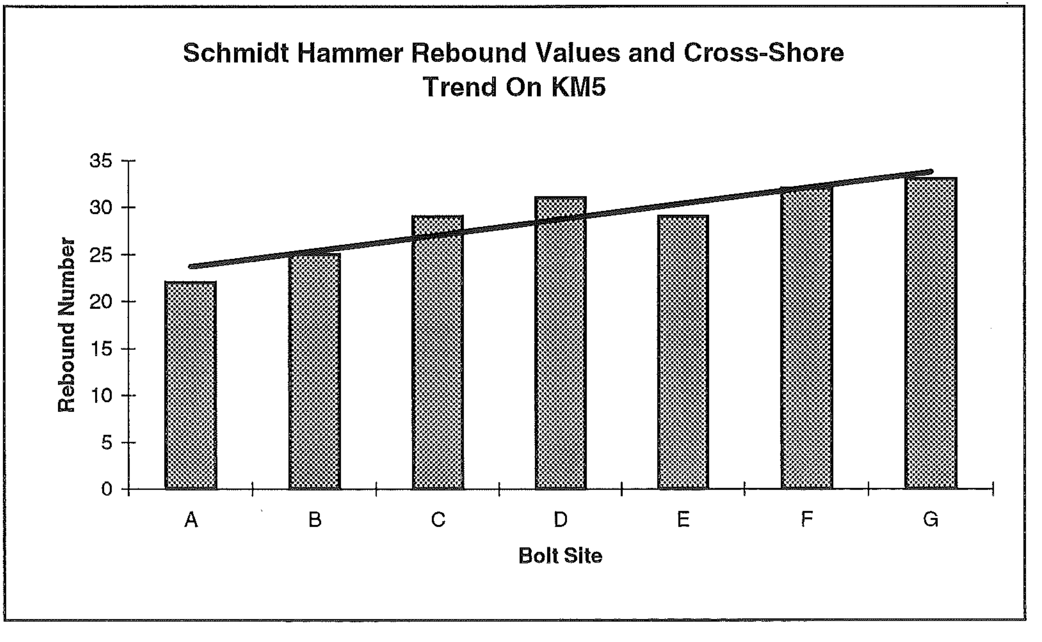

Figure 6.40 Schmidt Hammer rebound numbers from each bolt site on KM5 and a trend line fitted using linear regression.

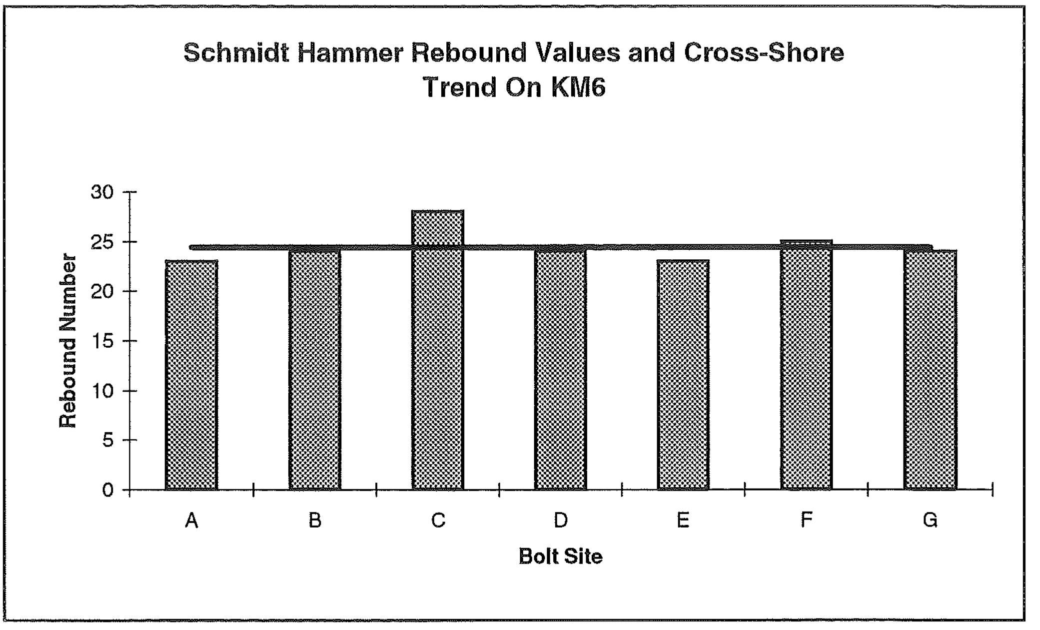

Figure 6.41 Schmidt Hammer rebound numbers from each bolt site on KM6 and a trend line fitted using linear regression.

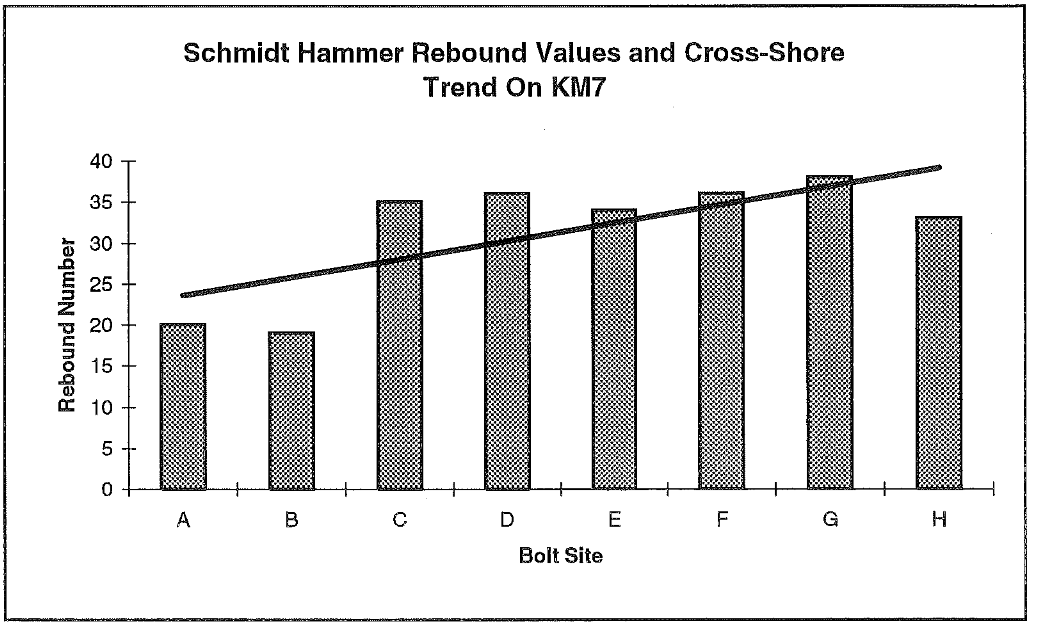

Figure 6.42 Schmidt Hammer rebound numbers from each bolt site on KM7and a trend line fitted using linear regression.

Cross-shore variations in the degree of weathering were found to occur on three of seven profiles. At KM3, KM4 and KM5 there was a trend of lower rebound values on the landward margin of the platforms, increasing to higher values on the outer seaward margin. This result is interpreted as reflecting a higher degree of weathering on the inner portion of the platform than at the outer seaward margin. Based on the results from the other four profiles it is clear that local factors can over-ride the role of weathering. Clearly this is the case on KM1 and KM7. The lack of cross-shore variation in weathering on KM2 and KM6 is more difficult to explain. It is worth noting that both of these are Type A mudstone platforms, which may suggest that the lower compressive strength of the rock material is important. This suggests a difference in response to weathering between Type A and B platforms. One possibility is that because Type A platforms are a softer rock, less weathering is required to reduce rock strength to the point where erosion can occur. There is enough weathering at the more seaward edge of these platforms to reduce rock strength. In contrast, Type B platforms, which are in a more resistant rock, the more seaward parts are subjected to less weathering due to high submergence times, and are not weakened to the same extent as the landward margins. The above results support the hypothesis presented, when it is applied to Type B platforms, but the data do not support it when applied to Type A shore platforms.

6.4.3 WETTING AND DRYING CYCLES

In Chapter Two wetting and drying was shown to be an important factor for salt and water layer weathering and slaking. Matthews (1992) studied the erosion of mudstone shore platforms around the shoreline of Lake Waikaremoana in the North Island of New Zealand. From laboratory experiments, this mudstone was shown to disintegrate to clays and silts after 37 to 107 wetting and drying cycles. From this, one question is how many cycles occur per year on platforms at Kaikoura? Another question is: does this vary across platform profiles? There were no direct means available for this study to record wetting and drying cycles. In order to estimate the number of cycles tidal data, rainfall data and elevation data were used. The number of tidal cycles has already been calculated in Section 6.3. Rainfall data were plotted alongside tidal data in order to identify when rainfall caused a wetting and drying cycle. Clearly rain during high tide did not cause wetting and drying, nor did brief events that occurred immediately before or after the ebb of the tide. Rainfall must be followed by sufficient time to allow drying. However, rainfall could also reduce the number of wetting and drying events if it persisted for longer than a tidal cycle, thus preventing a surface from drying. While it is possible to estimate the number of wetting and drying cycles that result from rainfall it must be recognised that the erosive effect may be different to that caused by tidal cycles since there is an absence of salts. There is the possibility that rainfall will dissolve salts in the lattice of rocks which may re-crystallise upon drying again. A major problem with the method used is that it cannot account for wetting and drying cycles caused by spray or splash from waves.

Elevation is also a factor that was considered when estimating wetting and drying cycles. Tidal data showed that some lower and higher parts of platforms were inundated and exposed less often than elevations around mean sea level. Wetting and drying cycles were estimated at all MEM bolt sites, but were considered in three groups, 1) those that were subjected to the maximum number of tidal cycles, 2) bolt sites on inner margins with higher elevations that reduced the number of tidal cycles and 3) bolt sites that were located at the seaward edge of platforms with lower elevations that reduced the number of tidal cycles. Two assumptions were made during these estimations. First, tidal cycles that occurred at night were deemed not to result in drying of platform surfaces since no data were available to assess evapotranspiration potential at night. This assumption may be unrealistic during summer months but would be more plausible during winter. The second assumption was based on the observation of algae growth during winter months. Algae covered large areas of platforms with the result that the surfaces did not dry during exposure. During summer, algae die thereby re-exposing the surface to wetting and drying. Therefore during winter months no wetting and drying can occur. It has been assumed that algae growth lasts for four months of the year from May to August, based on observations made during attempts to measure erosion on MEM bolt sites. These observations also revealed that higher landward bolt sites were not covered by algae during winter months and some seaward bolt sites were not covered.

Table 6.19 shows estimated wetting and drying cycles for platform elevations that were subjected to the maximum number of tidal cycles. The total number of tidal cycles was 704 in 1995 and 707 in 1996; 352 and 354 respectively, occurred at night; and 199 and 120 respectively were lost during winter due to algae growth. There were a total of 75 and 73 rainfall events in 1995 and 1996 respectively. Only ten (13.3 per cent of the total) rainfall events added cycles in 1995 and nine (12.3 per cent of the total) in 1996. The total number of wetting and drying cycles then is obtained by subtracting the number of tidal cycles at night and day time winter cycles, from the total tidal cycles, and adding the rainfall number. So that in 1995 there were 244 wetting and drying cycles and in 1996 there were 242.

Table 6.19 Estimation of the number of wetting and drying cycles on shore platforms at Kaikoura. Assessed for the central part of platforms.

Bolt Sites with Maximum Number of Tidal Cycles	1995	1996	Percentage of Total Tidal Cycles	
	1995	1996	1995	1996
Number of Tidal Cycles	704	707	100	100
Number of Tidal Cycles During The Night	352	354	50	50
Rainfall Events During Low Tide	10	9	1.4	1.3
Day Cycles Lost During Winter Months	119	120	17	17
Total Number of Wetting And Drying Cycles	244	242	34.6	34.2

On the inner landward margins of shore platforms wetting and drying cycles were estimated for six bolt sites KM1A, KM2A, KM2B, MK3A, KM5A, KM6A, KM7A, and KM7B, for 1995 and 1996. None of these bolt sites were covered by algae during winter months. Table 6.20 shows the results of estimating wetting and drying cycles. There is a large degree of difference between sites, due to elevation differences. On KM3A (the highest bolt site) wetting and drying occur only during rainfall events or when spray or splash wets the site. This site has the lowest number of wetting and drying cycles of any bolt site at Kaikoura with 75 in 1995 and 73 in 1996. Since this bolt site is out of reach of tidal influences and is only wetted during rainfall it also provides an estimate of the number of wetting and drying cycles to which cliffs are subjected each year. At KM7A there were an estimated 96 and 110 wetting and drying cycles in 1995 and 1996 respectively. This site is reached only infrequently by extreme high tides and the majority of wetting and drying cycles result from rainfall. A total of 141 wetting and drying cycles occurred on KM5A in 1995, and 167 in 1996. KM1A and KM2A were wetted and dried an estimated 320 and 332 times in 1995 and 1996, and KM6 an estimated 329 and 337 time in 1995 and 1996. KM2B was wetted and dried an estimated 377 and 372 times in 1995 and 1996, and KM7B an estimated 379 and 376 times in 1995 and 1996. These three sites recorded the highest estimates of wetting and drying cycles.

Table 6.20 Estimation of the number of wetting and drying cycles on bolt sites on the inner margins of shore platforms at Kaikoura. KM1 and 2 are at the same elevation hence in the same column.

	KM1A & KM2A		KM2 B		KM3A		KM5A		KM6A		KM7A		KM7B	
Elevation M.S.L. (m)	0.872		0.715		1.748		1.053		0.633		1.327		0.757	
Year	1995	1996	1995	1996	1995	1996	1995	1996	1995	1996	1995	1996	1995	1996
Number of Tidal Cycles	559	595	704	707	0	0	188	279	704	707	21	37	704	707
Number of Tidal Cycles During The Night	280	298	352	354	0	0	94	138	352	354	0	0	352	354
Rainfall Events During Low Tide	41	35	15	9	75	73	47	26	23	16	75	73	27	23
Cycles Lost During Winter Months	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Number of Wetting and Drying Cycles	320	332	377	372	75	73	141	167	329	337	96	110	379	376

Estimated wetting and drying cycles for the four lowest bolt sites, KM1G and KM6G, KM6F and KM4F are shown in Table 6.21. Four hundred and twenty four tidal cycles were calculated for KM1G in 1995, 399 in 1996; 212 and 199 of these occurred at night. Only four rainfall events caused wetting and drying cycles in 1995 and none in 1996. Observation during visits to this bolt site showed that it was never covered with algae. There were a total of 216 wetting and drying cycles in 1995 and 200 in 1996. A higher number of tidal cycles was noted at KM6G: 563 and 440 in 1995 and 1996 respectively. In these years 282 and 220 cycles took place at night. KM6G was covered during winter months by algae, resulting in the loss of 119 day time cycles in 1995 and 120 in 1996. The net result was a total of 168 wetting and drying cycles in 1995 and 104 in 1995. On KM4F there were 202 cycles in 1995 and 102 in 1996.

Table 6.21 Estimation of the number of wetting and drying cycles on bolt sites on the seaward margins of shore platforms at Kaikoura.

	KM1G		KM6G		KM6F		KM4F	
Elevation M.S.L (m)	-0.389		-0.320		-0.195		-0.249	
Year	1995	1996	1995	1996	1995	1996	1995	1996
Number of Tidal Cycles	424	399	563	440	655	656	644	621
Number of Tidal Cycles During The Night	212	199	282	220	328	328	322	311
Rainfall Events During Low Tide	4	0	4	0	5	3	5	5
Cycles Lost During Winter Months	0	0	119	120	119	120	119	120
Total Number of Wetting and Drying Cycles	216	200	168	104	213	211	202	192

Estimated wetting and drying cycles have been shown to be variable according to the elevation and rainfall. Cross-shore variations are difficult to generalise, but it can be shown that parts of shore platforms between elevations of 0.6 and 0.9m (M.S.L.) are subjected to more wetting and drying cycles than others. Figure 6.43 shows a plot of the number of wetting and drying cycles at all bolt sites for both 1995 and 1996 against the elevation of each bolt site, the largest number occurred between 0.6 and 0.9m above mean sea level. Elevations between 0.6 and 0.9m also occurred most frequently on the inner part of platforms at Kaikoura.

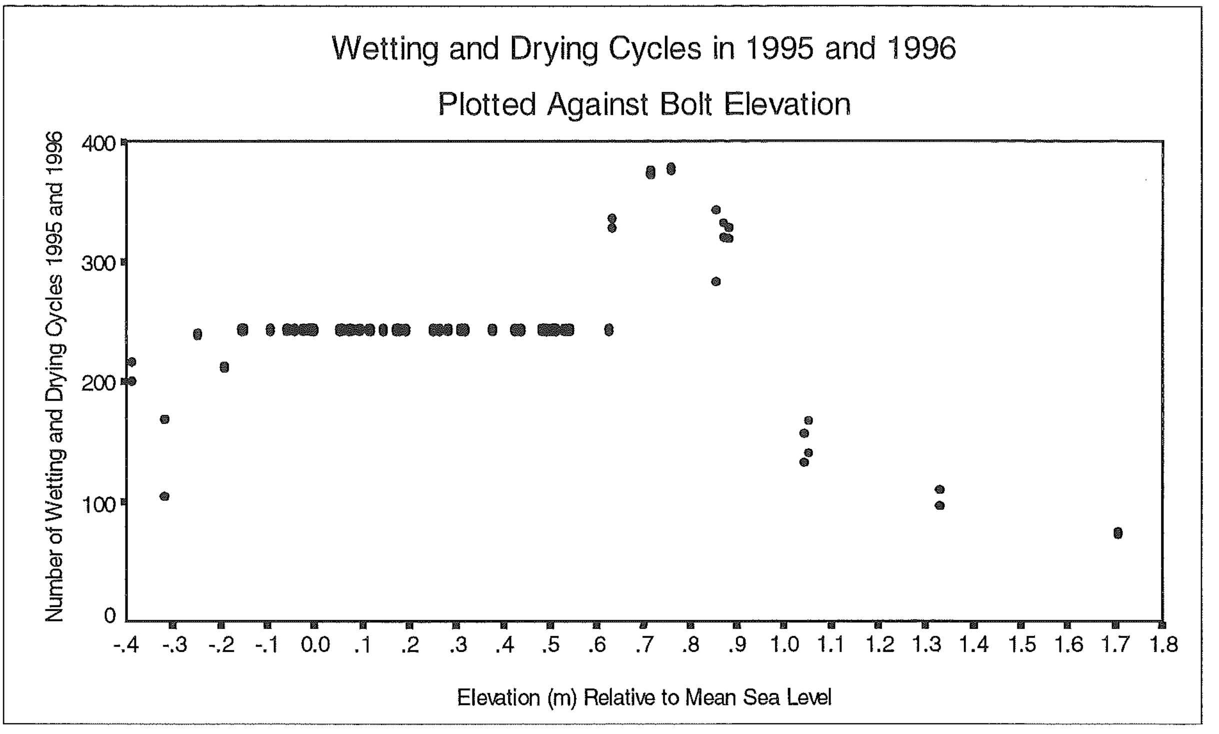

Figure 6.43 Wetting and drying cycles per year plotted against bolt site elevations. The largest number of cycles occurred at elevations between 0.6 and 0.9m above mean sea level.

Wetting and drying has been shown to occur most frequently at elevations of between 0.6 and 0.9m above mean sea level which also coincides with the more landward part of shore platforms at Kaikoura. A linear relationship between elevation and the number of wetting and drying cycles does not exist. This is because of the influence of rainfall and of algae growth during winter months. It is also important to note that where algae are absent the number of cycles is higher irrespective of elevation. This factor is important on the seaward edge of platforms. For example on KM1G, the lowest bolt site, (-0.389) no algae were observed during the field period, but on KM6F (-0.195) and KM6G (-0.320) where algae did grow cycles were fewer. Wetting and drying cycles on these bolt sites were higher than the most landward bolts sites at elevations above 0.9m. This is because tidal extremes inundate these sites less often. The greatest number of wetting and drying cycles is where algae are unable to grow and where tidal cycles are infrequent enough to allow rainfall to contribute a significant proportion of cycles. The most significant factor is the absence of algae. This is demonstrated by the hump in Figure 6.43.

Since salt and water layer weathering are associated with wetting and drying the conclusion that can be drawn from the above analysis is that weathering is more prevalent on the landward parts of platforms than on the seaward edge. Observations of weathering morphology and Schmidt Hammer data support this view. Matthews (1992) found that mudstone at Lake

Waikaremoana disintegrated to clays and silts after 37 to 107 wetting and drying cycles. Significantly, this disintegration experiment was carried out using fresh water. It is plausible that much more rapid breakdown would occur in the presence of salts. Given that between 104 and 337 wetting and drying cycles were estimated to have occurred per year on shore platforms at Kaikoura then very rapid rates of erosion would be expected. The highest rate of erosion (9.914mm/yr) was measured on KM6A. A site with one of the highest incidents of wetting and drying. The ability of weathering processes to cause erosion at Kaikoura can be assessed using a wetting and drying experiment in the same way as Matthews. Such an experiment might also show how many cycles are required for erosion to occur.

6.4.4 A WETTING AND DRYING EXPERIMENT

To investigate the ability of wetting and drying to erode mudstone platforms at Kaikoura, cored samples from Type A and B mudstone platforms were subjected to repeated wetting and drying. A second reason for this experiment was to investigate if there are differences in erosion rates between the two types. It will be recalled from Chapter Five that it was argued that they are, but statistically it was shown there were no differences between mean erosion rates for both rock types. Samples were initially weighed and photographed (Figure 6.44). Both samples were treated with an identical wetting and drying regime. Each sample was soaked in fresh water for periods ranging from 3 to 16 hours and then dried in an oven at 110°C for similar periods. Samples were left to cool to room temperature before being immersed in water again. Wetting and drying times varied because of the impracticality of maintaining a strict time regime in a short period of a few months. While there were variations in wetting and drying times these were identical for both samples.

Figure 6.45 and Table 6.22 illustrate weight changes of the two samples over a total of 20 cycles. The experiment was stopped after 20 cycles because the Type A sample disintegrated into three pieces (Figure 6.46). The sample from the Type A mudstone platform lost weight with each weighing, and had a total loss of 1.508 grams or 1.244 per cent of the initial weight. The Type B sample lost a total of 0.5443 grams or 0.477 per cent of the initial weight, but at two weighings this sample gained weight. This phenomenon is unexplained. Figure 6.47 illustrates the condition of the Type B sample after 20 wetting and drying cycles. It shows that the sample underwent considerably more destruction as a result of wetting and drying, compared with the Type B sample, which showed less dramatic signs of physical disintegration.

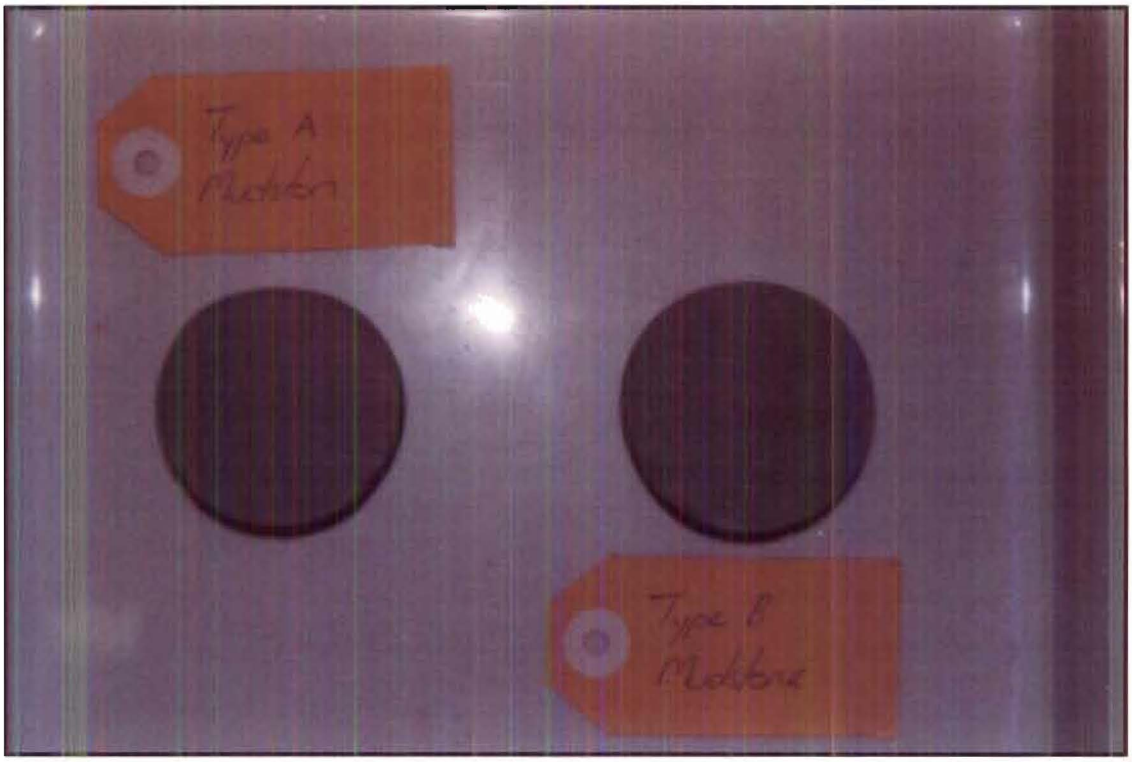

Figure 6.44 Rock samples from Type A and B mudstone shore platforms before being subjected to repeated wetting and drying.

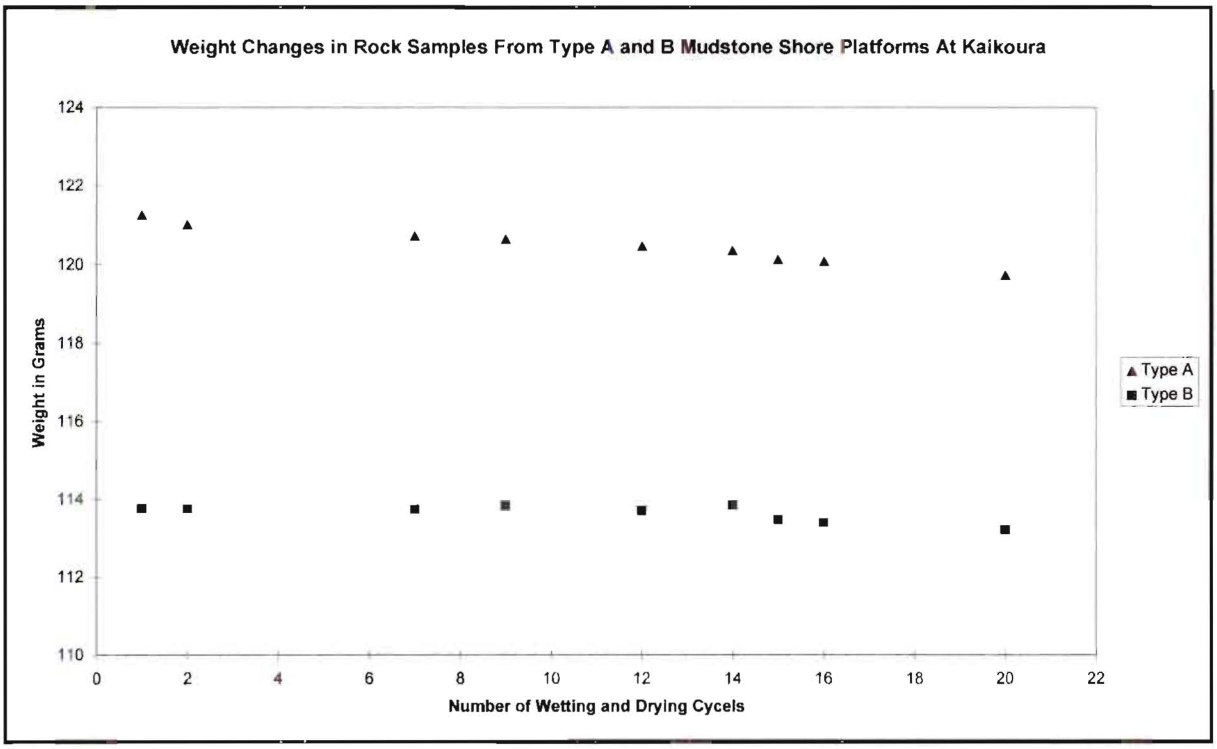

Figure 6.45 Weight changes from two samples taken from a Type A and B mudstoe shore platforms at Kaikoura.

Table 6.22 Weight changes for both samples over 16 wetting and drying cycles.

Number of Wetting and Drying Cycles	Type A Weight (gm)	Type B Weight (gm)
1	121.238	113.763
2	120.989	113.755
3		
4		
5		
6		
7	120.700	113.740
8		
9	120.632	113.835
10		
11		
12	120.462	113.706
13		
14	120.353	113.853
15	120.125	113.471
16	120.08	113.393
17		
18		
19		
20	119.730	113.220
Total Weight Loss	1.508	0.543
Total Loss as a Percentage of Initial Weight	1.244%	0.477%

This experiment has demonstrated that wetting and drying does cause erosion of mudstone platforms on the Kaikoura Peninsula. The Type A sample lost a higher percentage of the initial weight compared with the Type B sample. This loss was also an order of magnitude greater in the same way as erosion rate data in Chapter Five. Significantly, only one wetting and drying cycle was required to cause erosion of both samples.

Figure 6.46 Type A sample after 20 wetting and drying cycles.

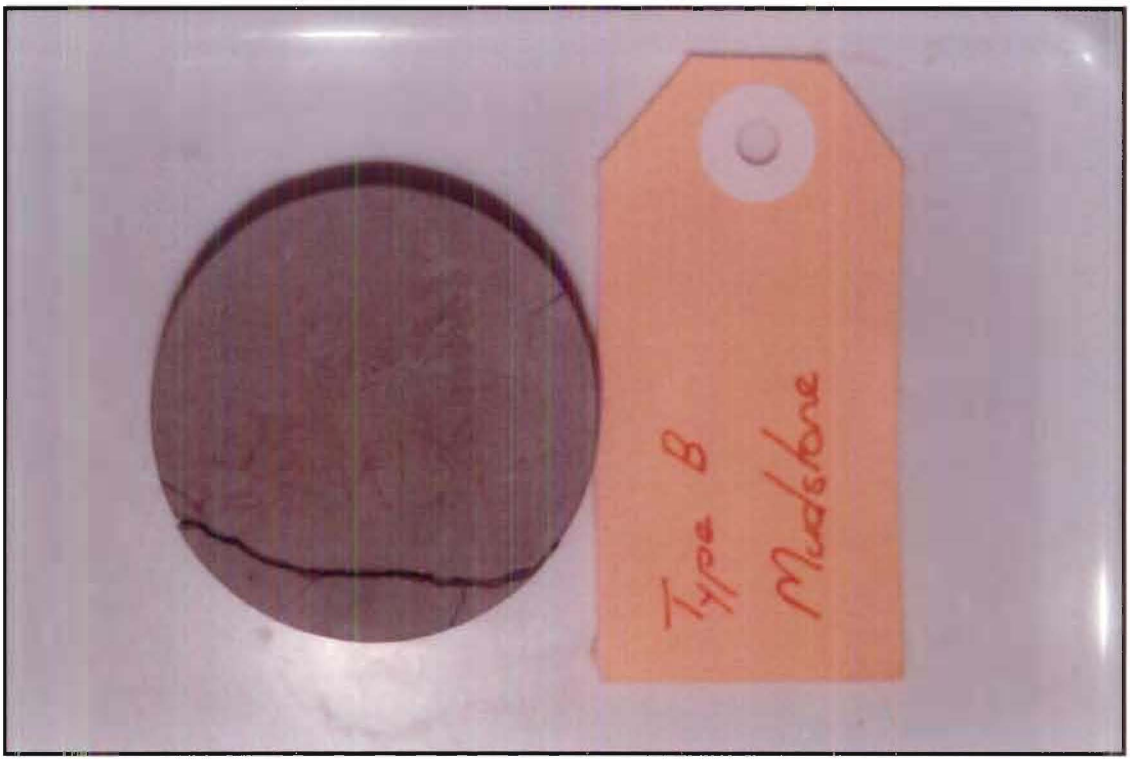

Figure 6.47 Type B sample after 20 wetting and drying cycles.

6.5 CONCLUSIONS

Deep water wave data were used to assess the proposition that breaking waves do not impact directly on shore platforms at Kaikoura. It was demonstrated that only waves with breaking heights of less than 2.0m could break on KM3 and of less than 2.45m on KM5, and only at high tide. The occurrence of breaking waves was also limited to Type B platforms where the depth of water in front of the low tide cliff was sufficient to prevent breaking. Sunamura (1992) proposed that this front depth controls the width of the platform by limiting the height of the breaking wave that can occur, and this has been shown to be the case at Kaikoura. Further, the depth of water in front of Type B platforms also controls the type of wave acting on the platform. Because of the depth of water in front of platforms larger waves always break before arriving at the seaward edge of platforms. Under no conditions did waves break directly on Type A platforms at Kaikoura. Therefore, the only wave type arriving at the landward cliff foot are bores resulting from broken waves.

Wave energy on shore platforms was investigated because it was this that Sunamura (1974, 1983, 1992, 1994) proposed was one of two parameters (the other being nearshore topography) controlling wave induced water motions and ultimately the assailing force of waves. The question posed in Chapter Two was how much energy arrives on shore platforms from deep water? Using deep water wave data and the measurement of waves on shore platforms, the attenuation of wave energy from deep water to the platform edge was assessed. This analysis revealed that a very high proportion of wave energy is lost in shoaling and refraction. As little as 0.3 per cent and no more than 8.8 per cent of wave energy reached the seaward edge of platforms. Attenuation across the platform profile was also considered in order to investigate how much wave energy arrives at the landward cliff foot, where platform extension occurs. Analysis of cross platform attenuation showed that between 4.9 and 6.8 per cent of the energy arriving at the seaward edge of platforms reached the cliff foot. Deep water wave energy had diminished by five to six orders of magnitude by the time waves arrived at the landward cliff foot.

Whether or not waves cause erosion on shore platforms was assessed by calculating wave induced shear stress. Shear stress calculated from wave data ranged from 300 to 1400N/m^2. These values were significantly lower than values of compressive strength of 21800 and 47000KN/m^2 for the study platforms. Wave force at the cliff foot was also found to be much lower than the compressive strength of the rock forming the platforms; dynamic force ranged from 160 to 300N/m^2 at the cliff foot on KM3. Since the amount of wave data was limited further analysis was carried out to determine the largest wave that might reach the cliff foot on

KM3 and KM5 and the landward edge of KM2. This showed that the largest wave on KM3 and KM5 would be 0.74m, and 0.52m on KM2. Predicted shear stresses and dynamic forces under these conditions did not exceed the compressive strength of the rock forming these platforms. It was noted that this analysis had not considered the weakening of the rock material by weathering. Consideration of weathering using the Schmidt Hammer showed a reduction in strength of up to 50 per cent. Even when this was taken into account, wave forces did not exceed the compressive strengths of rocks.

Tidal data were used to calculate inundation times across platforms. This was done by using the elevation of MEM bolt sites as reference points. Inundation times were higher at lower elevations. On the lowest bolt the inundation time was 88 per cent of the year. At the landward cliff foot inundation times were as low as 0.15, 0.5, 4.5, 5.2, 16, and 18 per cent of the year. It was argued that because these times were so low, undercutting of the cliff by wave action was not possible given the dynamic force values calculated from wave data.

Whether or not weathering occurs on shore platforms and causes erosion was a central question for this chapter. It was demonstrated that there is ample morphological evidence to support the view that weathering does occur and that it causes erosion. Honeycomb, salt and water layer weathering morphologies were found on platforms at Kaikoura. Slaking was found on cliffs backing platforms. Significantly, salt weathering did not appear to operate on Type A platforms and water layer weathering did not take place on Type B platforms. With the Schmidt Hammer it was demonstrated quantitatively that weathering occurred and reduced rock strength by up to 50 per cent. The degree of weathering across the platform profile was assessed using the Schmidt Hammer data. It was found that there was a increased degree in weathering across the platform in the landward direction. However, this could be over ridden by localised factors such as the presence of abrasive beach material or bedding. This cross-shore trend was absent on both Type A profiles. Slaking was shown to occur on cliffs and supports the view that weathering causes the retreat of cliffs at Kaikoura.

Wetting and drying cycles were examined as part of the investigation into weathering processes, since these cycles control salt and water layer weathering. Using rainfall data and the number of tidal cycles calculated in Section 6.3, the number of wetting and drying cycles was estimated at each MEM bolt site. It was shown that the greatest number of cycles occurred at elevations between 0.6 and 0.9m above mean sea level. This range was found most often on the landward margins of platforms at Kaikoura. With reference to experimental work carried out by Matthews (1992) it was argued that weathering processes did cause erosion. This was supported by experimental data that showed only one cycle was needed to cause erosion of mudstones from Kaikoura.

The first question posed in this chapter was, what are the erosional processes operating on shore platforms at Kaikoura? Since waves occur on platforms the next question asked was do they cause erosion? Dynamic forces and shear stresses did not exceed compressive strengths but weathering has been shown to reduce rock strength by up to 50 per cent. It was noted that salt weathering reduced the strength of mudstones to the point where they could be broken with a finger nail. This implies that weathering reduces rock strength even further than indicated by the Schmidt Hammer test. If this is the case then the low forces exerted under waves may in fact be able to erode severely weathered rock. Weathering reduces the strength of rock in a very thin layer at the surface, perhaps too thin to assess accurately using the Schmidt Hammer. Waves may be able to erode this thin layer and transport eroded material away. Weathering processes have been shown to operate on shore platforms at Kaikoura and to cause erosion. Investigations of both marine and weathering processes have revealed that there is a zonation of process across the platform profile. This appears to confirm the view of Kirk (1977) who proposed that shore platforms develop because of the zonation of marine and weathering processes across the platform profile. Wave induced shear stresses were higher at the seaward edge of platforms and tidal data showed that this part of the platform is inundated for much longer periods of time, up to 88 per cent of the year. Thus marine processes are afforded more opportunity to cause erosion while such high inundation reduces the opportunity for weathering. Conversely, on the inner landward margins wave induced shear stress and dynamic force are greatly reduced as are the inundation times of tides. Wetting and drying cycles and associated weathering processes are increased. Schmidt Hammer data also supported this to a limited extent by showing that the degree of weathering increased in a landward direction across the platform.

Given that the questions asked in this chapter have been answered, it is now possible to examine modes of platform development, those models reviewed in Chapter Three and the matter of the type of equilibrium platforms attain. They are the subjects of the next chapter.

7. DEVELOPMENT OF SHORE PLATFORMS ON THE KAIKOURA PENINSULA

7.1 INTRODUCTION

This chapter synthesises the results and conclusions presented in Chapters Five and Six by providing a discussion of how shore platforms on the Kaikoura Peninsula are developing. Models of platform development reviewed in Chapter Three are assessed and a new model describing shore platform development is introduced. Evidence is presented for a new demarcation between Type A and B shore platforms based on erosion rates and compressive strengths. Finally, results are used to examine equilibria types that shore platforms at Kaikoura may tend towards.

7.2 PROCESSES OF EROSION ON SHORE PLATFORMS

In Chapter Six it was proposed that erosion of shore platforms at Kaikoura was the result of weathering processes caused by wetting and drying rather than by wave erosion. Wetting and drying cycles were shown to be at a maximum at elevations between 0.6 and 0.9m above mean sea level. Weathering appears to be strongly related to elevation. Erosion and swelling presented in Chapter Five were shown to be statistically grouped by season. The interpretation given to this was that subaerial weathering was the cause of erosion and swelling. Erosion rates were also shown to be higher on the inner margins of platforms than on the seaward edges, suggesting that erosion is related to distance from the seaward edge of platforms. Because of these apparent relationships, further investigation using a number of statistical techniques was undertaken to establish if these are statistically significant.

7.2.1 PRODUCT-MOMENT CORRELATION AND MULTIPLE REGRESSION ANALYSIS

In further examination of the relationships discussed above the erosion rates at each MEM bolt site were plotted against the number of wetting and drying cycles, the elevation of the bolt site and the distance from the seaward edge of the shore platform. The resulting scatter plots are shown in Figures 7.1, 7.2 and 7.3. From an examination of these plots investigations of linear relationships between erosion and the independent variable were deemed worthwhile. If statistically significant relationships are found to occur between erosion and wetting and drying then this finding offers evidence to support the view offered in Chapter Six that erosion results from subaerial weathering. To determine whether or not associations between erosion and wetting and drying cycles, elevation and distance from seaward edge of shore platforms are statistically significant, Product-Moment Correlation Coefficients were calculated and Stepwise Multiple Linear Regression analysis was carried out using SPSS®, a statistical analysis program. Initially analysis was carried out for Type A and B mudstone platforms and limestone platforms. Then analysis was carried out on individual MEM profiles.

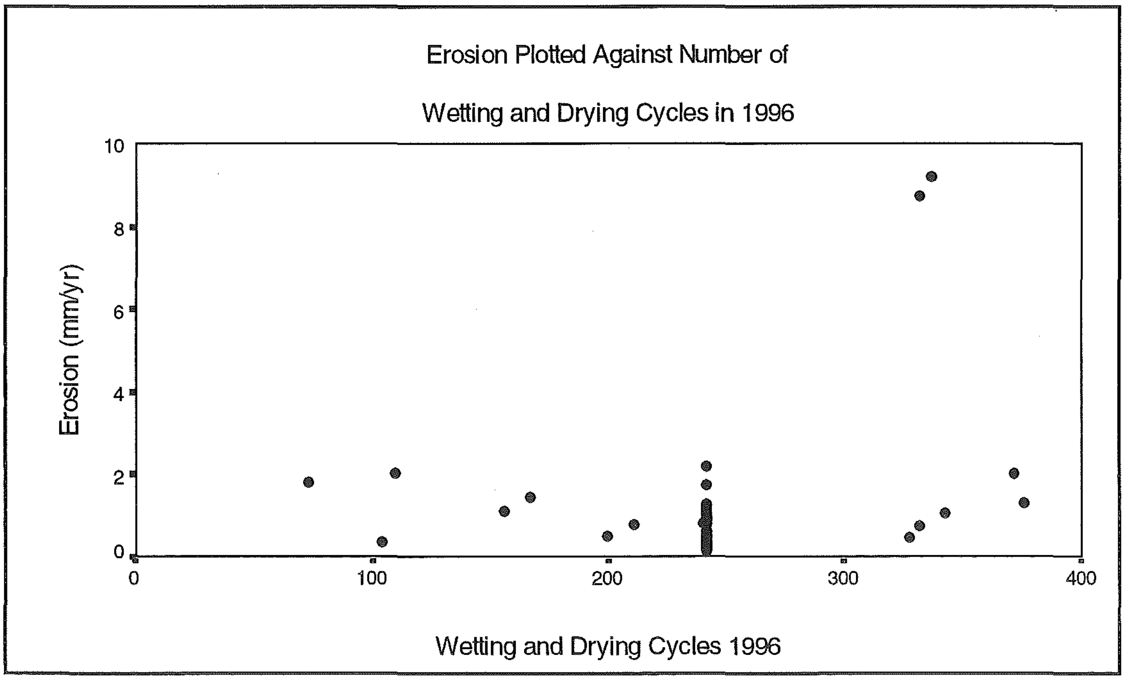

Figure 7.1 Erosion rates at each MEM bolt site plotted against the number of wetting and drying cycles on each site in 1996.

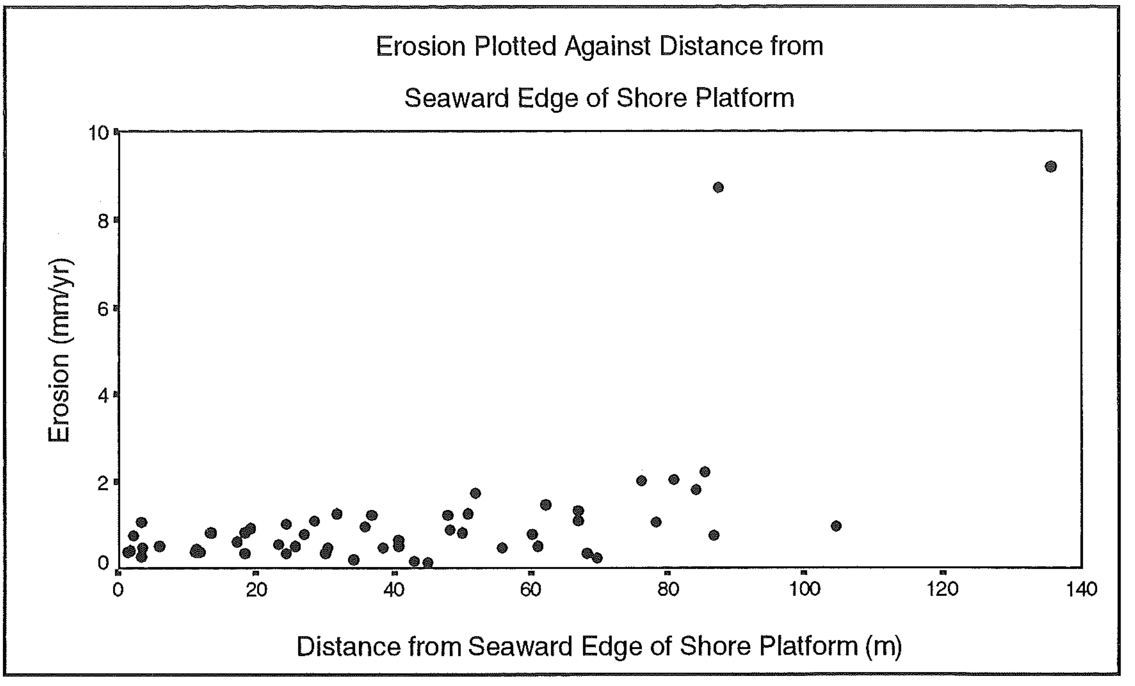

Figure 7.2 Erosion rates at each MEM bolt site plotted against the distance of each bolt site from the seaward edge of shore platforms.

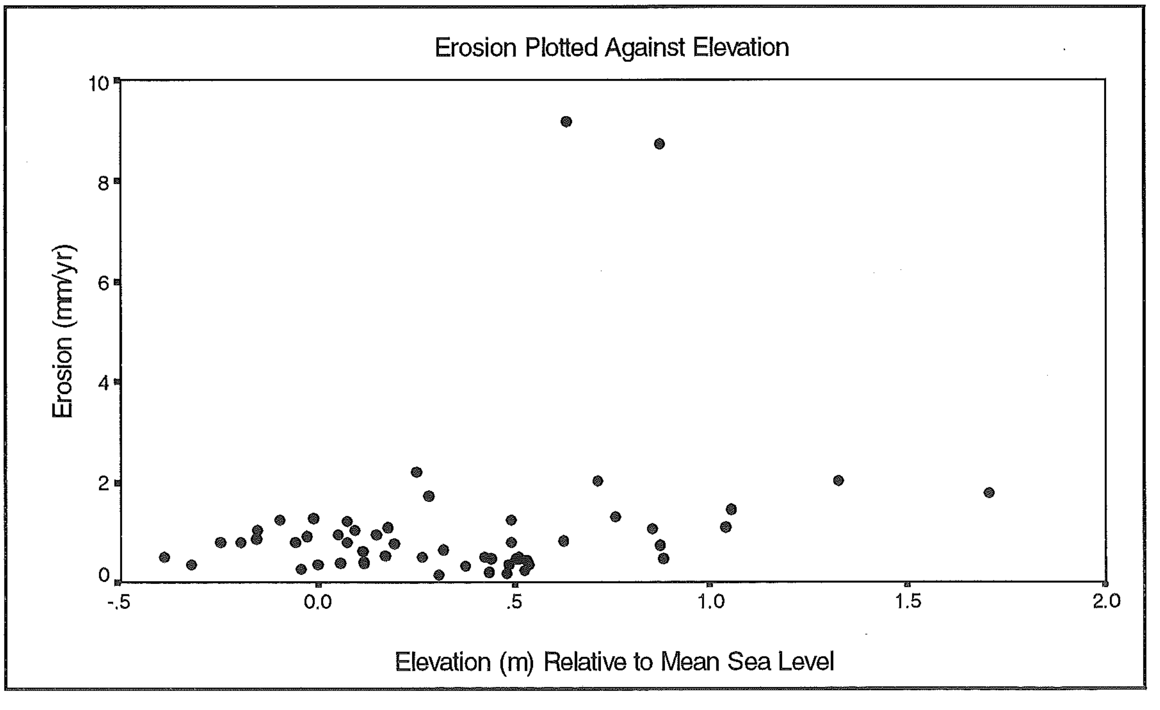

Figure 7.3 Erosion rates at each MEM bolt site plotted against the elevation of the bolt site relative to mean sea level.

Table 7.1 presents the results of Product-Moment Correlation Coefficient calculations carried out using SPSS® on Type A mudstone shore platforms. The correlation coefficient between erosion and the number of wetting and drying cycles was 0.62 and was significant at P = 0.007. Between erosion and elevation the coefficient was 0.72 and this was significant at P = 0.001; and between erosion and distance from seaward edge the coefficient was 0.69 and it was significant at P= 0.002. These high correlations indicate that multiple regression analysis is necessary to establish the relative influence of the variables on erosion rates.

Table 7.1 Correlation Coefficients between erosion rates with the number of wetting and drying cycles, elevation and distance from landward edge of shore platform for Type A mudstone platforms.

Variables	Correlation Coefficients	Significance
Erosion and Wetting/Drying 1996	0.62	P= .007
Erosion and Elevation	0.72	P= .001
Erosion and Distance from Seaward Edge	0.69	P= .002

Table 7.2 shows the output from SPSS® of Stepwise Multiple Regression analysis where erosion rate was the dependent variable and wetting and drying, elevation and distance from the seaward edge of platforms were independent variables. Stepwise regression returned R = 0.72, R^2 = 0.52 and adjusted R^2 = 0.48 with elevation being the only significant control. Adjusted R^2 gives a better indication of "the goodness of fit" between the regression model and the population than R^2. This is because the regression model does not normally fit the population as well as the sample (Norušis 1993). The analysis of variance in Table 7.2 tests the hypothesis that the linear relationship between the dependent and independent variables is significant. In this case the *F* statistic is significant at 0.0006, indicating that there is a significant linear relationship between the variables. The "variables in the equation" part of the table shows which independent variables contribute to the R^2 value in decreasing order of importance. In this case only elevation was used in the equation and the stepwise analysis removed wetting and drying and distance. In this section of the table the column labelled B contains the slope and intercept values, SE B is the standard error of B, and Beta is the standardised regression coefficient. Tolerance indicates if multicollinearity is likely; values close to zero indicate it is and values close to 1 indicate it is not. Multicollinearity occurs when independent variables are highly correlated with each other. This causes the regression coefficients to become unstable (Bryman and Cramer 1997). The *t* statistic is also given and the level at which it is significant. The last section in Table 7.2 shows the

variables not used in the equation, in this case wetting and drying and distance. These variables were not used because they did not satisfy the selection criterion. The selection criterion was based on the probability of the *F* statistic for each variable being significant, minimum values were set at 0.05 and maximum values at 0.10.

Table 7.2 Multiple Regression Analysis of erosion rates with number of wetting and drying cycles, elevation and distance from seaward edge of shore platform for Type A mudstone platforms.

Variable(s) Entered on Step Number 1. Elevation

Multiple R	0.72
R Square	0.52
Adjusted R Square	0.48
Standard Error	1.93

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	1	60.62	60.6
Residual	15	56.08	3.7

F = 16.213 Significant F = 0.001

Variables in the Equation

Variable	B	SE B	Beta	Tolerance	T	Sig T
Elevation	5.993	1.488	0.72	1.0	4.027	0.001
(Constant)	0.775	0.550			1.408	0.179

Variables Not in the Equation

Variable	Beta In	Partial	Tolerance	T	Sig T
Distance	0.394	0.434	0.281	0.132	0.896
Wetting	0.373	0.375	0.580	1.805	0 .092

Table 7.3 contains the results of Product-Moment Correlation Coefficient calculations carried out using SPSS® on Type B shore platforms in mudstone. The correlation coefficient between erosion and wetting and drying cycles was -0.23 and was significant at P = 0.289. Between erosion and elevation the coefficient was 0.60 and significant at P = 0.002 and 0.41 between erosion and distance from landward edge, which was significant at P = 0.044. These correlations are different to those found on Type A platforms. A low negative correlation occurred between erosion and the number of wetting and drying cycles and P was significant at 0.289 indicating an insignificant relationship. Correlations for the other two independent variables were better. Multiple regression analysis was carried out to determine the relative importance of each of the independent variables and the degree of influence on erosion rates.

Multiple regression analysis of erosion with wetting and drying, elevation and distance for Type B platforms is presented in Table 7.4. As with Type A platforms stepwise regression determined that erosion was dependent on elevation rather than distance or wetting and drying. For elevation, multiple R = 0.60, $R^2 = 0.36$ and adjusted $R^2 = 0.34$. The F statistic of 12.63 was significant at 0.0018.

Table 7.3 Correlation Coefficients between erosion rates with wetting and drying cycles, elevation and distance from seaward edge of the shore platform for Type B mudstone platforms.

Variables	Correlation Coefficients	Significance
Erosion and Wetting/Drying 1996	-0.23	P= 0.289
Erosion and Elevation	0.60	P= 0.002
Erosion and Distance from Seaward Edge	0.41	P= 0.044

Table 7.4 Multiple Regression Analysis of erosion rates with number of wetting and drying cycles, elevation and distance from seaward edge of shore platform for Type B mudstone platforms.

Variable(s) Entered on Step Number 1. Elevation

Multiple R	0.60
R Square	0. 36
Adjusted R Square	0. 34
Standard Error	0.34

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	1	1.42	1.42
Residual	22	2.47	0.11

F = 12.63 Significant F = 0.0018

Variables in the Equation

Variable	B	SE B	Beta	Tolerance	T	Sig T
Elevation	0.572	0.161	0.75	1.0	3.555	.0018
(Constant)	0.400	0.106			3.768	.0011

Variables Not in the Equation

Variable	Beta In	Partial	Tolerance	T	Sig T
Distance	0.092	0.092	0.654	1.528	0.654
WD1996	-0.340	-0.410	0.922	-2.066	0. 051

Table 7.5 displays the results of correlation coefficients analysis between erosion and wetting and drying (-0.27 P = 0.034), elevation (0.32 P = 0.26) and distance from the seaward edge of platform (0.54 P = 0.044) on limestone platforms. These correlations are poorer than those for mudstone platforms. Despite these correlation results multiple regression analysis was carried out to determine the relative importance of each of the independent variables and influences on erosion rates.

Table 7.6 presents multiple regression analysis of erosion with wetting and drying, elevation, and distance from the seaward edge, for limestone platforms. Stepwise regression showed that of the three independent variables, distance from the seaward edge of the platform was the most important influence on erosion. For distance, multiple R = 0.57, R^2 = 0.30 and adjusted $R^2 = 0.24$. The *F* statistic of 5.06 was significant at 0.04. Neither elevation nor wetting and drying was entered into the equation.

Table 7.5 Correlation Coefficients between erosion rate with wetting and drying cycles, elevation and distance from seaward edge of limestone platforms.

Variables	Correlation Coefficients	Significance
Erosion and Wetting Drying 1996	-0.27	P= 0.34
Erosion and Elevation	0.32	P= 0.26
Erosion and Distance from Seaward Edge	0.54	P= 0.04

Table 7.6 Multiple Regression Analysis of erosion rates with number of wetting and drying cycles, elevation and distance from seaward edge of shore platform for limestone platforms.

Variable(s) Entered on Step Number 1. Distance

Multiple R	0.57
R Square	0. 30
Adjusted R Square	0. 24
Standard Error	0.44

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	1	0.99	0.99
Residual	12	2.35	0.19

F = 5.06 Significant F = 0.044

Variables in the Equation

Variable	B	SE B	Beta	Tolerance	T	Sig T
Distance	-0.012	0.005	0.54	1.0	2.25	0.044
(Constant)	0.476	0.212			2.23	0.044

Variables Not in the Equation

Variable	Beta In	Partial	Tolerance	T	Sig T
Wetting	-0.193	-0.153	0.443	-0.517	0.615
Elevation	-0.211	-0.250	0.986	-0.857	0. 410

Correlation and Multiple Regression Analysis have shown a variety of significant and insignificant relationships between erosion and wetting and drying, elevation, and distance from the seaward edge of platforms. This variation appears to depends on which platform type and lithology is considered. For this reason further correlation and multiple regression analysis was carried for each MEM profile. Table 7.7 contains the results of correlation coefficients calculated using SPSS®. A number of high and significant correlations stand out: on KM6 a coefficient of 0.74 (P = 0.05) between erosion and wetting and drying occurred. A number of very low and insignificant relationships also occurred. The correlation coefficient between erosion and distance from seaward edge was 0.02 (P=0.95) on KM1 and -0.01 (P= 0.97) on KM4. Erosion and elevation were well correlated on KM7 (0.81 P = 0.02), KM6 (0.83 P = 0.02), KM3, (0.75 P = 0.01), and KM2 (0.76 P = 0.01).

Table 7.7 Correlation Coefficients and significance levels between erosion and wetting and drying, elevation and distance from the seaward edge of platforms for each MEM profile at Kaikoura.

	KM1	KM2	KM3	KM4	KM5	KM6	KM7
Erosion and Wetting and Drying 1996	-0.26 P = 0.56	0.62 P = 0.05	-0.55 P =0.09	0.10 P = 0.82	-0.56 P = 0.18	0.74 P = 0.05	-0.31 P = 0.49
Erosion and Elevation	0.54 P = 0.20	0.76 P = 0.01	0.75 P = 0.01	-0.70 P = 0.07	0.49 P = 0.26	0.83 P = 0.02	0.81 P = 0.02
Erosion and Distance from Seaward Edge	0.02 P = 0.95	0.70 P = 0.25	0.53 P = 0.11	-0.01 P = 0.97	0.63 P = 0.13	0.75 P = 0.05	0.76 P = 0.04

Stepwise multiple regression results from individual MEM profiles are presented in Table 7.8. For three profiles KM1, KM4 and KM5 the independent variables did not meet the selection criterion of the stepwise analysis. For the remaining profiles elevation was the important variable controlling erosion.

Correlation and Multiple Regression analysis have shown that elevation and distance are related to erosion rates. Distance was important for limestone platforms. Elevation is the most important variable for both individual profiles and Type A and B mudstone platforms. The proposition that wetting and drying controls erosion, put forward at the beginning of this chapter is not supported by the regression analysis, although correlation coefficients for Type A mudstone platforms did indicate some influence.

Table 7.8 Multiple Regression Analysis of erosion with wetting and drying, elevation and distance for each MEM profile at Kaikoura. N/A, indicates that stepwise regression did not show any variable as having a significant influence on erosion. N.I.E. indicates that the variable was not entered into the equation.

		KM1	KM2	KM3	KM4	KM5	KM6	KM7
Erosion and Wetting Drying 1996	Ad R^2 F Sig F Step No	N/A	-	N.I.E.	N/A	N/A	N.I.E.	N.I.E.
Erosion and Elevation	Ad R^2	N/A	0.52	0.50	N/A	N/A	0.63	0.59
	F		11.04	10.32			11.42	9.460
	Sig F		0.015	0.012			0.019	.027
	Step No		1	1			1	1
Erosion and Distance from Seaward Edge	Ad R^2 F Sig F Step No	N/A	-	N.I.E.	N/A	N/A	N.I.E.	N.I.E.

Note: Ad R^2 = adjusted coefficient.

7.2.2 CURVILINEAR REGRESSION ANALYSIS

While linear relationships were not well established between erosion and wetting and drying and elevation in the last section, some evidence exists to support the view that curvilinear relationships exist instead. In Chapter Six, Figure 6.32 indicated that there was a non-linear relationship between wetting and drying and elevation. For this reason curvilinear regression analysis was carried out to determine if there was some degree of influence by elevation on wetting and drying. Data from Figure 6.32 were plotted in Figure 7.4. Using the SPSS® software, a cubic curve gave the best improvement on the linear regression model. For the cubic curve R^2 = 0.38 (F = 16.34 significant F = 0.0000). The R^2 value is not high but the relationship is significant. Given that wetting and drying have been shown to be related to elevation, and that erosion was related to elevation, further analysis was carried out to explore curvilinear relationships between erosion and wetting and drying. Figure 7.5 shows a quadratic curve fitted to the erosion data plotted against wetting and drying. For the quadratic curve R^2 = 0.21 (F = 6.85 Significant F = 0.0023). Again the R^2 value is not high but the relationship is significant.

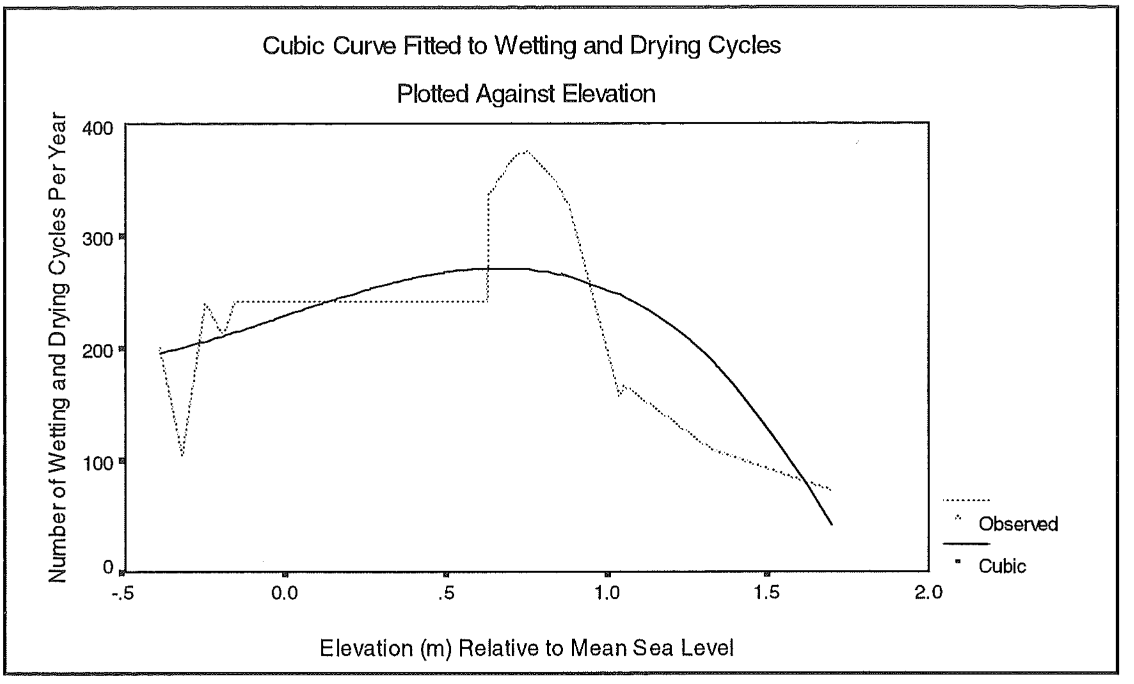

Figure 7.4 Quadratic curve fitted to the number of wetting and drying cycles on each MEM bolt site plotted against the elevation of each bolt site.

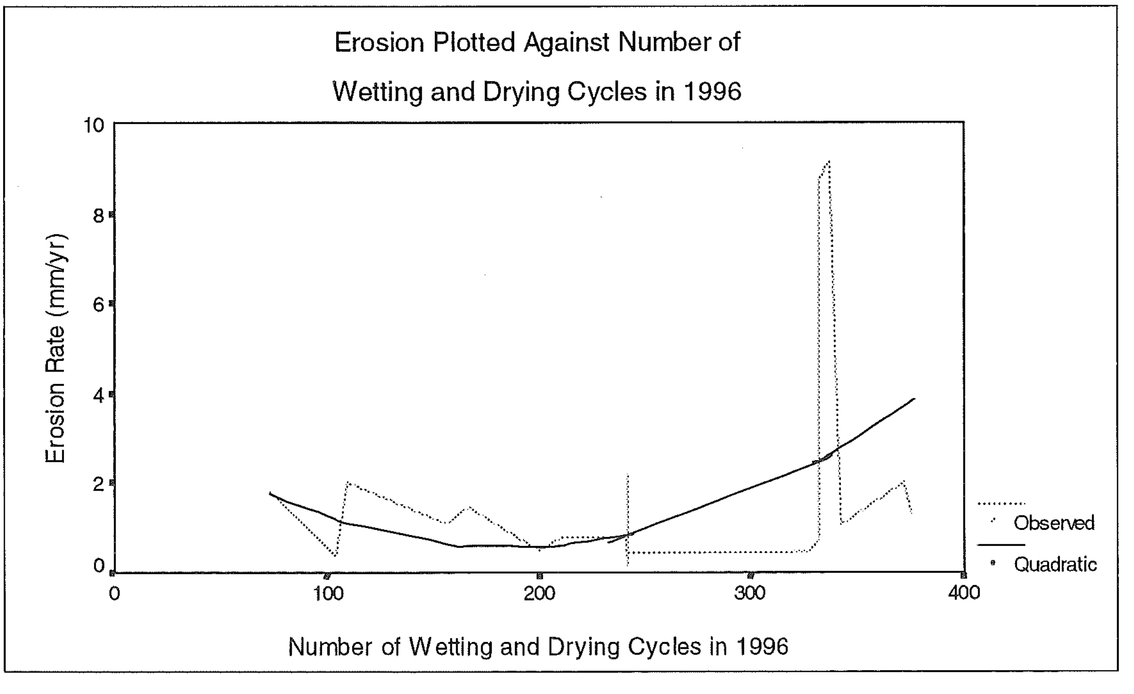

Figure 7.5 Cubic curve fitted to erosion rates at each bolt site plotted against the number of wetting and drying cycles on each bolt site.

7.2.3 CONCLUSIONS

Wetting and drying has been shown to be an important factor influencing erosion, and this relationship can be described as curvilinear. Thus it can be concluded that weathering processes cause erosion on shore platforms at Kaikoura. The degree of explanation is dependent on platform type and lithology. Clearly elevation is the most important factor controlling erosion but this is not a simple relationship. Elevation has also been shown to influence wetting and drying and this is why elevation exerts a significant effect on erosion. Wetting and drying is the process causing erosion but elevation controls the number of wetting and drying cycles. The relationship between erosion and elevation is not linear since wetting and drying cycles decline when the elevation is above or below the tide level, although erosion rates do not. On KM7A, a site with the fewest numbers of tidal cycles, the erosion rate was 2.046mm/yr; and on KM3A a site not covered by the tide at all, the erosion rate was 1.810mm/yr. This suggests that subaerial processes are not entirely dependent on the type of wetting and drying described in this study. High erosion rates above the tide level also suggests that spray and splash (which causes wetting and drying) may also be important.

7.3 DEVELOPMENT OF SHORE PLATFORMS AT KAIKOURA

This section presents an explanation of how shore platforms are thought to develop on the Kaikoura Peninsula based on evidence presented in Chapters Five and Six and in the statistical analysis presented in Section 7.2. Clearly this study has no way of establishing how shore platform development began on the Kaikoura Peninsula. Sanders (1968b) and Sunamura (1991) have both shown how breaking and broken waves initiated a notch in sand and plaster blocks in laboratory wave tanks. Considering this, Sunamura (1992) speculated that shore platform initiation was caused by breaking and broken waves following sea level rise during the Holocene. Wave data presented in Chapter Six for Kaikoura showed only the smallest breaking waves impact directly on the seaward edge of platforms. This breaking was controlled by the depth of water in front of platforms. If the seaward edge of shore platforms does not retreat as proposed by Sunamura (1990, 1991, 1992), then depths of water observed today are the same as at the time platform development began. Therefore breaking and broken waves have had little effect given the high compressive strengths of the rocks and the low shear stresses and dynamic forces under waves. In this case it would be difficult to see how breaking waves could have initiated the development of platforms at Kaikoura. Weathering has been shown to reduce the compressive strength of the rocks at Kaikoura by up to 50 per cent and to cause erosion. There is no reason why weathering processes, especially wetting and drying, could not initiate platform development. Today cliff retreat at Kaikoura results from weathering, and erosion occurs well above the reach of waves. Consequent to cliff erosion by weathering, waves at Kaikoura would then be able to remove the resulting debris and platform extension would proceed.

Marine processes, particularly wave induced shear stresses and impact forces have been shown to be very small at the base of the landward cliff. Landward cliffs at Kaikoura were shown to be eroding while at the same time it was demonstrated that wave action was ineffective and had little opportunity to cause erosion. Trenhaile (1983a) and Sunamura (1992) have both proposed that notches are wave cut features and cliff retreat is caused by undercutting which is followed by the collapse of the cliff and then the removal of debris by waves. At Kaikoura notches are not present at the base of cliffs. Instead, at the foot of cliffs there are either benches or ramps. Neither feature is indicative of the process described by Trenhaile and Sunamura. However, platform extension does occur at the cliff base and face as demonstrated by very high erosion rates. At the same time wave forces are low here and never reached KM3A, a MEM bolt site on the top of a bench at the base of a cliff where the erosion rate was 1.810mm/yr. Thus at Kaikoura, waves do not appear to cause platform lowering at the landward cliff base or the retreat of the cliff itself.

Weathering is the only process that can reduce rock strength enough to allow waves to erode or transport material away. The view proposed here is that shore platforms at Kaikoura result from subaerial weathering. A number of lines of evidence have been presented to support this:

1) In Chapter Five it was demonstrated using Chi Square tests that there is seasonal variation in erosion and swelling. The largest magnitude and frequency of swelling and the highest erosion rates were measured during summer months when wetting and drying were most frequent.
2) Wetting and drying has been shown to be linked statistically with erosion on the platforms.
3) Erosion rates on the shore platforms were highest where the maximum number of wetting and drying cycles occurred.
4) Wave forces were ineffectual as erosion agents.

However, marine processes are necessary for the development of shore platforms. They serve two functions: first waves are needed to remove the debris formed by weathering; and second, tides are necessary to cause repeated wetting and drying, which in turn causes weathering.

Marine processes, particularly tides, should be viewed as the "wetting" half of the weathering process known as wetting and drying. Waves can also be viewed as a weathering agent when spray and splash causes wetting and drying.

Some consideration of the view that waves erode rock weakened by weathering is required. That is, the notion that weathering reduces the compressive strength to the point where waves can cause erosion. This view has been argued by Sunamura (1992). It was reported in Chapter Six that rock surfaces where salt weathering was observed were easily disturbed with the author's finger nails, which supports Sunamura's view. However, waves are not able to reduce compressive strength of rock. Weathering in contrast, has been shown to reduce compressive strength and to cause erosion. Because the development of shore platforms is dependent on the reduction of rock compressive strength, then it can be concluded that subaerial weathering is the cause of shore platform development.

7.3.1 ARE PROCESSES ZONALLY DISTINCT?

A number of lines of evidence support the view that weathering and marine processes operate zonally across platform profiles. Weathering has been shown to be the dominant process operating on the inner landward margin of Kaikoura shore platforms where wave erosive processes were also shown to be the weakest. Conversely wave processes are strongest on the seaward edge of platforms. Tidal duration data showed that the waves are afforded more opportunity to erode the seaward margins of platforms and less opportunity to erode the landward margins. High rates of erosion on the inner margins of platforms were also shown to be statistically related to weathering indices.

There are three points of evidence that show that shore platforms do not develop as a result of the zonation of marine and subaerial processes. First, waves do have more time to cause erosion on the seaward edge of platforms but it was shown in Chapter Six that the erosive force is not enough to cause erosion. Second, erosion rates are fastest at the cliff face and base. It has just been argued that this is where platform extension occurs. Weathering is the principal agent of erosion here but it cannot operate without tides or waves assisting in wetting and drying. Third, both marine (in the form of tides) and weathering processes are required to cause erosion at the cliff base. In this scenario processes are not zonally distinct. From this it is concluded that the development of shore platforms is not dependent on the zonation of marine and subaerial processes as proposed by Kirk (1977), but there is a pattern to the way erosional processes operate on platforms at Kaikoura. The low erosion rates measured on the seaward edge of platform suggest that weathering does not operate as fast as on the landward inner margins so that platform development is dependent on the localisation of subaerial weathering at the landward cliff face and base. It is on this part of platforms where elevations are in the range best suited to maximising the number of wetting and drying cycles and preventing the growth of algae.

7.4 MODELS OF PLATFORM DEVELOPMENT

In Chapter Three a number of models were reviewed. It was noted that three issues needed to be addressed in relation to modelling:

1) the contradiction between the types of equilibria shore platforms have been argued to attain;
2) assessment of the assumptions that these models were based on; and
3) testing of the validity of numerical models with data gathered at Kaikoura.

The question of equilibrium will be addressed in the Section 7.5. Given the mode of platform development at Kaikoura detailed above, then the five models presented in Chapter Three (Trenhaile and Layzell 1980, 1981; Trenhaile 1983a; and Sunamura 1977, 1978b, 1992) cannot be applied to shore platforms at Kaikoura. This is because the underlying assumption that wave erosion causes platform development has been shown not to apply at Kaikoura. It was stated above that platform development is dependent on weathering as the formative process. First it will be recalled that the model presented by Trenhaile and Layzell (1980, 1981) and Trenhaile (1983a) has the form:

$$R_{n,t} = tAF_n \tan\alpha_{n-1} \qquad 3.2$$

where:

R = erosion (cm/yr)
n = platform level 1,2,3...
t = time (years)
A = erodibility factor (cm/hr).
F_n = tidal duration factor

$tan\ \alpha_{n-1}$ = submarine slope at each time interval.

The erodibility factor is derived by:

$$A = FW \tan\alpha / V \qquad 3.3$$

where:

F = still water level

W = deep water wave energy delivered per hour

V = amount of energy required to erode 1cm of rock.

$tan\ \alpha$ = submarine slope

determines the rate of erosion at time t and level n using, among other variables the amount of wave energy delivered per hour W. Wave energy has been shown at Kaikoura to be too low to cause erosion.

Secondly, another model by Trenhaile (1983a) is:

$$T_{n,x} = \left(T_r \cot\beta + nx - E\sum_{T_0}^{T_{n-1}} T \right)(C_1 + C_2 nx)x \qquad 3.7$$

where:

$T_{n,x}$ = total time taken to undercut cliff and remove debris

T_r = tidal range

β = gradient of the inherited slope

n = number of times the cliff has collapsed and debris removed

x = depth of notch at point of collapse

$E\sum_{T_0}^{T_{n-1}} T$ = total erosion that has occurred at the low tide level

C_1 = tan α/UT

where: U = amount of cliff undercutting in a year

α = gradient of the platform

C_2 = tan α/ST

where: S = amount of debris removed in a year.

This model cannot be applied at Kaikoura either, since cliff recession does not occur by waves cutting a notch and undermining the cliff to the point of collapse. In Chapter Four it was shown that at the base of cliffs at Kaikoura ramps and benches occur. These morphologies do not support the mechanism of cliff retreat this model describes.

Thirdly, Sunamura (1977) proposed that the rate of cliff retreat was proportional to the erosive force of waves and could be empirically described by:

$$\frac{dX}{dt} = \kappa\left[\Gamma + \ln\left(\frac{\rho g H}{Sc}\right)\right] \tag{3.11}$$

where:

$\Gamma = \ln(A/B)$ a nondimensional constant

Sunamura (1977) noted that $dX/dt = 0$ when $F_W \leq F_R$. At Kaikoura F_W is less than F_R yet shore platforms are present. Its application to cliffs at Kaikoura would seem inappropriate given that weathering has been proposed as the cause of cliff retreat.

Fourth, it is useful to restate Sunamura's (1978b) model to explain the development of Type A platforms:

$$x = (K_*/\beta_*)\left(1 - e^{-\beta_* \kappa t}\right) \tag{3.12}$$

where:

$$K_* = \Gamma - \beta_* W_o + \ln(\rho g H_b / S_c) \tag{3.13}$$

$$\beta_* = \alpha_* \sqrt{h_b} \,/\, (\sqrt{g}) h_a L_b^2 \tag{3.14}$$

This was designed on the premise that waves cause erosion of the platform.

Fifthly, Sunamura's (1992) model to predict the width of Type B platforms is:

$$x_{t=t_1} = G\left[\Gamma + \ln\left(\frac{\rho g H_b}{S_c}\right)\right] \tag{3.22}$$

where:

$$G = \left(1 - e^{-\alpha'_* xt}\right) / \alpha'_* = \text{ constant} \quad 3.23$$

This model was designed to incorporate the attenuation (G) of waves across platforms which was thought to be the agent causing erosion. Neither equation 3.12 or 3.22 can be applied to shore platforms at Kaikoura.

Given that weathering has been shown to be a formative process in the development of platforms at Kaikoura then these models cannot be used to describe that development. In Chapters One and Three, the issue was raised that models that are designed on the view that waves are the formative process are inherently flawed. This is because of the uncertainties surrounding the roles of waves and weathering in platform development. This view has been supported by the evidence from Kaikoura. Clearly any model developed to explain the evolution of platforms at Kaikoura must incorporate weathering.

The third aim related to modelling was to test each model with data from Kaikoura. For the five models above this cannot be done since the data do not fit the assumptions underlying them. It can be concluded that each of the above models is invalid when applied to Kaikoura. Only one model can be assessed with data from Kaikoura and this is the parallel retreat model. This is the purpose of the next section.

7.4.1 THE PARALLEL RETREAT MODEL

The parallel retreat model does not rest on the assumption that waves cause erosion. Nor does it require assumptions about any means of erosion since it is concerned only with changes to the geometry of a platform. Using erosion data from Chapter Five it is possible to test the validity of the parallel retreat model presented by Trenhaile (1974a), where:

$$dD = dW \tan\alpha \quad 3.1$$

where:

dD = increment of platform down cutting in time

dW = increment of cliff retreat in time

α = platform slope.

Because both rates of cliff recession and platform lowering were measured at Kaikoura, it is possible to test predicted erosion rates against those actually measured. The model as presented by Trenhaile (1974a) showed that down cutting occurs at the seaward edge of the platform (Fig 3.6). However, Trenhaile (1974a) used estimated surface lowering rates at the cliff foot and Kirk (1977) used a mean surface lowering rate calculated from measured erosion rates across shore platforms at Kaikoura. This averaging is important because it has been shown at Kaikoura that erosion rates vary greatly across platform profiles. Clearly failure to adhere to the conditions of the model may undermine conclusions that were reached concerning its validity. Because of this concern three different surface lowering rates were used to test the parallel retreat model:

1) The mean erosion rate for the whole profile;
2) the erosion rate measured at the seaward edge of each platform; and
3) the erosion rate measured at the cliff foot.

Kirk (1977) used 2 years of data from six profiles across shore platforms at Kaikoura including some backed by beaches and lagoons as well as cliffs. Trenhaile (1974a) designed the model for platforms that are backed by eroding cliffs. For this reason the model was tested using data from KM3, KM5 and KM7, which are backed eroding cliffs and hill slopes. The view taken in this study is that only profiles backed by eroding cliffs are valid for testing the model.

Table 7.9 presents the results of testing the parallel retreat model. The estimated rates of platform lowering from the model are within the same order of magnitude as mean profile erosion rates on KM5 and KM7. At KM7 the erosion rate for the profile is estimated to be 0.800mm/yr from the model and the mean annual rate measured for the profile was 0.839mm/yr. On KM3 the estimated lowering rate was an order of magnitude higher than the mean profile erosion rate. Estimated surface lowering compares less well with measured lowering at the seaward edge of shore platforms, although KM5 and KM7 are still within the same order of magnitude. Again estimated surface lowering on KM3 was an order of magnitude higher than that measured at the seaward edge. When compared with measured surface lowering at the cliff base estimated rates were lower by an order of magnitude for all three profiles.

Predicted rates of cliff retreat are also given in Table 7.9. Actual rates of retreat measured from air photographs were 0.11, 0.23 and 0.05m/yr on KM3, KM5 and KM7 respectively. Estimated cliff retreat rates calculated using mean surface lowering rates were in close agreement with measured rates. The estimated values were 0.045, 0.288 and 0.520m/yr on

KM3, KM5 and KM7 respectively. Predicted rates of cliff retreat using surface lowering rates at the cliff foot and the seaward edge provided poor results.

Table 7.9 Estimated rates of platform down cutting and cliff retreat using the parallel retreat model. Cliff retreat (dW) has been estimated using mean platform lowering rates, platform lowering at the cliff foot and lowering rates at the seaward edge of shore platforms.

Profile	dW m/yr	Mean Profile dD mm/yr	Seaward Edge dD mm/yr	Cliff Foot dD mm/yr	Platform Slope tan α	Estimated mm/yr dW*tan α	Estimated m/yr dD/tan α Mean	Estimated m/yr dD/tan α Cliff	Estimated m/yr dD/tan α Sea
KM3	0.11	0.747	0.283	1.810	0.01658	1.824	0.045	0.992	0.006
KM5	0.23	0.839	0.487	1.482	0.00290	0.669	0.288	2.215	0.001
KM7	0.05	0.839	0.433	2.046	0.01599	0.800	0.052	2.557	0.008

The parallel retreat model has provided satisfactory results when tested with erosion data from Kaikoura. The best results were achieved using a mean surface lowering rate for the whole platform in the same way as Kirk (1977), rather than using data from either the seaward edge or at the cliff foot. Kirk (1977) found that a logarithmic or power relationship exists between downwasting and cliff recession. Testing of the model here does not support either type of relationship. One reason for this may be that in this study, the model was only tested using cliff retreat rates, unlike Kirk (1977) who applied the model to sites where there were rapidly eroding lagoon deposits and beaches as well as cliffs. Trenhaile found values for lowering rates in chalk of about two per cent of widening rates and in Lias limestone and shale values of about 0.05 widening rates. In mudstone at Kaikoura lowering is 0.0036 to 0.0067 (0.36 to 0.76 per cent) of widening rate and is 0.017 times (1.7 per cent) the widening rate in limestone.

The agreement between estimated and measured erosion does not prove that shore platforms retreat in a parallel way. In Chapter Three, three points were raised concerning the validation of the parallel retreat model. First, the model shows that surface lowering occurs evenly across the platform profile; second, offshore morphology should indicate parallel retreat has occurred; and third, it was necessary to establish if the low tide cliff retreated. Concerning the first point, surface lowering rates have been shown to vary greatly across platform profiles, with erosion rates being higher on the landward margins of platforms than at the seaward edge. Higher erosion rates on the inner parts of platforms have the effect of reducing the gradient of the profiles. Offshore profile data presented in Chapter Four did not show submarine topography consistent with Challinor's (1949) diagram (Fig 3.2). In Chapter Five evidence was provided indicating that the seaward edge of platforms at Kaikoura did not retreat at the rates the model indicates they should. These three lines of evidence indicate that shore platforms at Kaikoura do not retreat in a parallel fashion, despite the good agreement of modelled with measured surface lowering rates at Kaikoura. The question was asked in Chapter Three: is a parallel retreat model appropriate? The answer is no it is not.

7.4.2 A MODEL OF SHORE PLATFORM DEVELOPMENT AT KAIKOURA

Figure 7.6 presents an empirical model that incorporates those factors found at Kaikoura to affect shore platforms development. There are three primary factors:

1) *Climate*, which determines the efficiency of weathering by controlling the number of wetting and drying cycles. This control is exerted in both directions by causing drying through solar radiation and wetting from rainfall. Rainfall can increase or decrease the number of wetting and drying cycles.
2) *Geology* of the rock material making up the coast is a primary control in two ways. First the structure and lithology of rock determines the resistance of the rock to weathering and second the compressive strength determines the type of platform that will develop. The resistance of rock to weathering ultimately determines whether or not erosion will occur.
3) *Marine processes* contribute to platform development by affecting the number of wetting and drying cycles. Depending on platform elevation tides can increase or decrease the number of cycles. Tides also afford some protection to platforms from weathering through submergence, thus preventing drying. Waves contribute to platform development in two ways: first, by increasing the number of wetting and drying cycles through spray and splash; and second, as a transporting agent of material eroded by weathering is removed from platforms by wave induced currents. Waves also cause erosion when sediment is available to act as an abrasive.

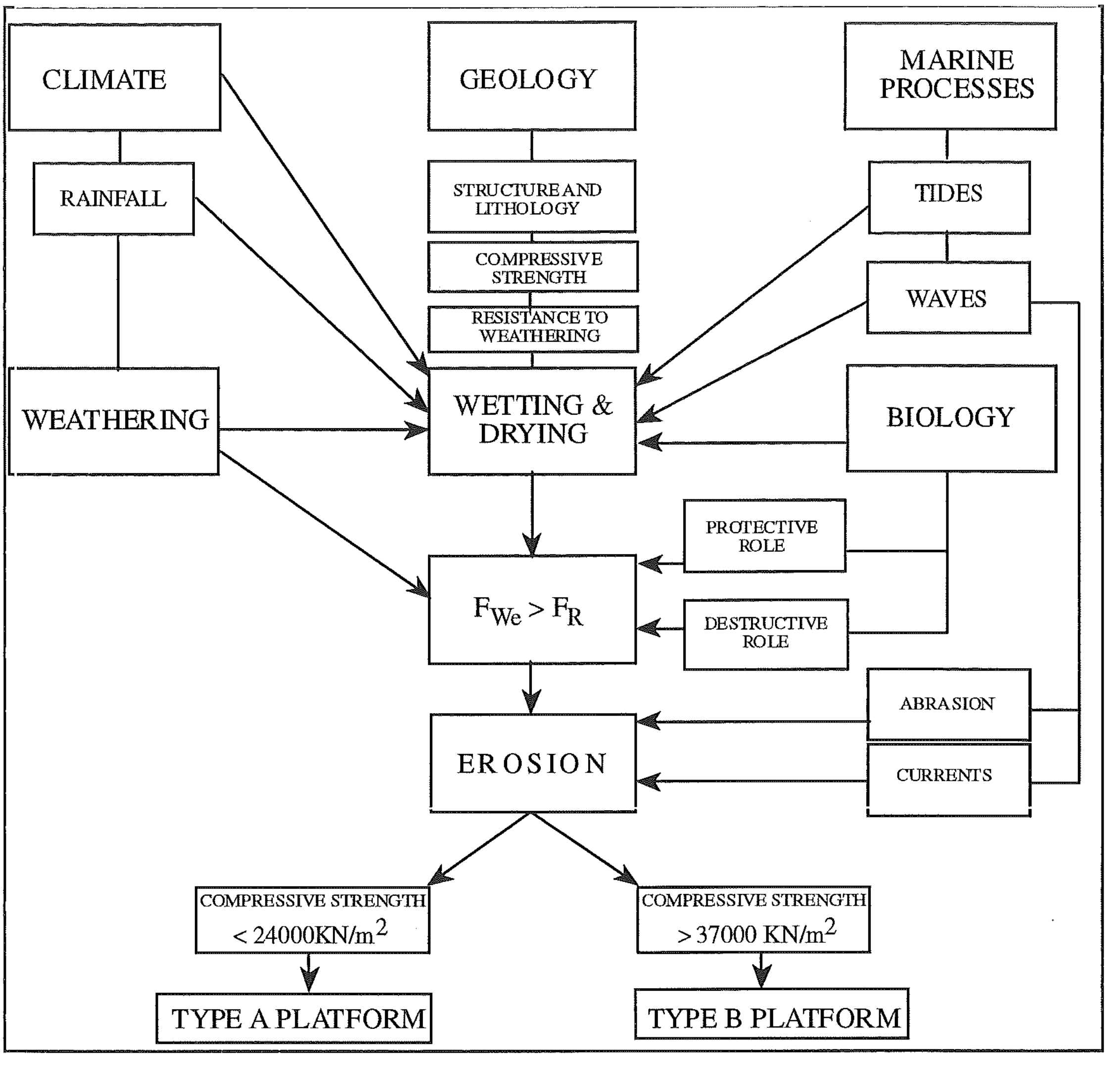

Figure 7.6 Factors affecting the erosion and development of shore platforms on the Kaikoura Peninsula. Platforms develop when the erosive force of weathering F_{We} exceeds the resisting force of the rock F_R. The relative strength of F_{We} and F_R is determined by the three primary controls: climate, geology, and marine processes. Which type of platform results is dependent on the compressive strength of the rock forming the platform.

Weathering not only includes wetting and drying but also other forms such as mechanical weathering resulting from thermal expansion; although wetting and drying is the principal erosional process. Erosion occurs only if the erosive force of weathering exceeds the resisting force of the rock. The same equation presented by Sunamura (1992) $F_W = F_R$ can be applied at Kaikoura except in this case F_W represents the erosive force of weathering and is written F_{We}, when $F_{We} > F_R$ erosion begins. Biology is included in this model although it is not a primary factor. Animals can cause erosion through grazing and boring which is a destructive role. Conversely the growth of algae can inhibit erosion by reducing the number of wetting and drying cycles and providing physical protection. Once erosion has begun, the compressive strength of the material forming the rock controls which type of platform that evolves. At Kaikoura Type A platforms develop when rock compressive strength is less than $24000 KN/m^2$, and Type B platforms develop when compressive strengths are above $37000 KN/m^2$.

Figure 7.6 indicates that there is a demarcation between the occurrence of Type A and B platforms based on compressive strength and the erosive force of weathering. Following the same argument as Tsujimoto (1987), platform development begins when:

$$F_{We} > F_R$$

where F_{We} = the erosive force of weathering

F_R = the resisting force of rock.

Both these variables need to be quantified at Kaikoura. F_R can be represented at Kaikoura using Schmidt Hammer Rebound values. This has an advantage over compressive strength measurements made from cores because it represents the resisting force at the rock surface where erosion occurs. The representation of F_{We} is more difficult. This is because it is not possible to quantify the force exerted by weathering in the same way wave force was by Tsujimoto (1987). It is possible to quantify the response to the weathering force using measured rates of erosion resulting from wetting and drying. It is not possible to represent the force of weathering simply with the number of wetting and drying cycles. To attribute an erosive force to wetting and drying the following expression was used:

$$F_{We} = E/WD$$

where E = erosion rate in mm/yr

WD = the number of wetting and drying cycles per year

In Tsujimoto's view the difference between a Type A and B platform is that no surface lowering occurs on a Type B platform. If surface lowering did occur then a Type A platform resulted, but it was demonstrated in Chapter Five that surface lowering does occur on Type B platforms. The difference between Type A and B is the rate of surface lowering, with average rates on Type A being an order of magnitude faster than on Type B. Therefore a demarcation between Type A and B platforms might be based on the difference in erosion rates and Schmidt Hammer rebound values.

To investigate this, F_{We} and F_R have been calculated for each MEM bolt site on mudstone platforms at Kaikoura. These were then plotted on logarithmic paper in the same ways as Tsujimoto (1987). Figure 7.7a shows the result of this method. A line at 45° separates Type A and B platforms (Fig 7.7b), although the separation is not as good as that found by Tsujimoto (1987). From the line in Figure 7.7 it can be concluded that Type A platforms at Kaikoura develop when:

$$F_{We} > 0.009$$

and Type B platforms develop when

$$F_{We} < 0.009$$

That is, when there is less than 0.009mm of erosion per wetting and drying cycle a Type B platform develops and when there is more than 0.009mm per cycles a Type A platform will result.

In Figure 7.7, Type A and B data points overlap. Some consideration of this is necessary. At sites KM3A and KM5A (two circled points in Figure 7.7b) on Type B platforms, rebound values were low indicating that the degree of weathering was high. Both sites are more that 1m above mean sea level. KM3A is above the reach of the tide and KM5 was wetted and dried 141 and 167 times in 1995 and 1996. This suggests that these sites are subjected to subaerial weathering driven by processes other than wetting and drying. This highlights that elevation is an important control of erosion rate as was demonstrated in Section 7.2 using multiple regression analysis.

It has been shown that it is possible to separate Type A and B platforms based on the erosive force of weathering and the compressive strength represented by Schmidt Hammer rebound numbers. The review in Chapter Two noted that Tsujimoto's (1987) demarcation based on wave force and compressive strength offered compelling evidence to support the view that shore platforms were wave cut. The demarcation based on weathering offered here contradicts this evidence and supports the alternative argument that Kaikoura platforms result from weathering; although the analysis does not provide a perfectly clear demarcation. This may be improved on by expanding the data set using additional sites to those from the Kaikoura Peninsula, and by considering an average value for F_{We} for each platform rather than a number of values from the same platform as done here. This point is highlighted when a plot is constructed using a mean value for each profile at Kaikoura (Figure 7.8). To further substantiate the demarcation presented above more data points are required.

A.

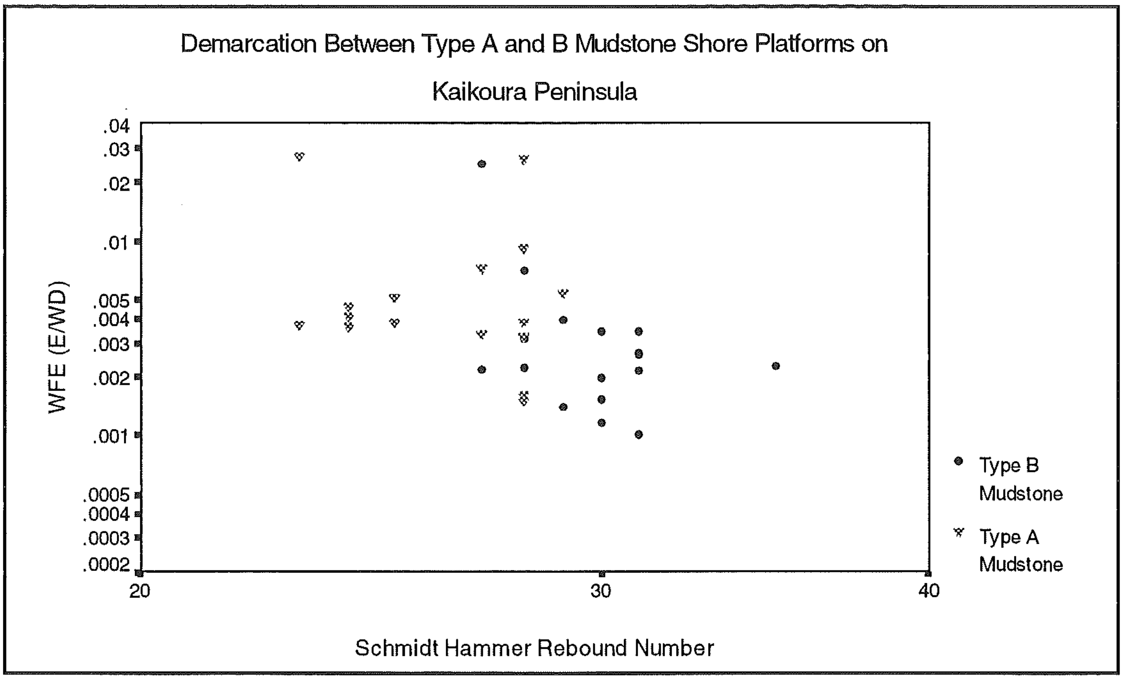

Figure 7.7 Demarcation between Type A and B shore platforms based on compressive strength represented using Schmidt Hammer R-values and the amount of erosion per wetting and drying cycle.

B.

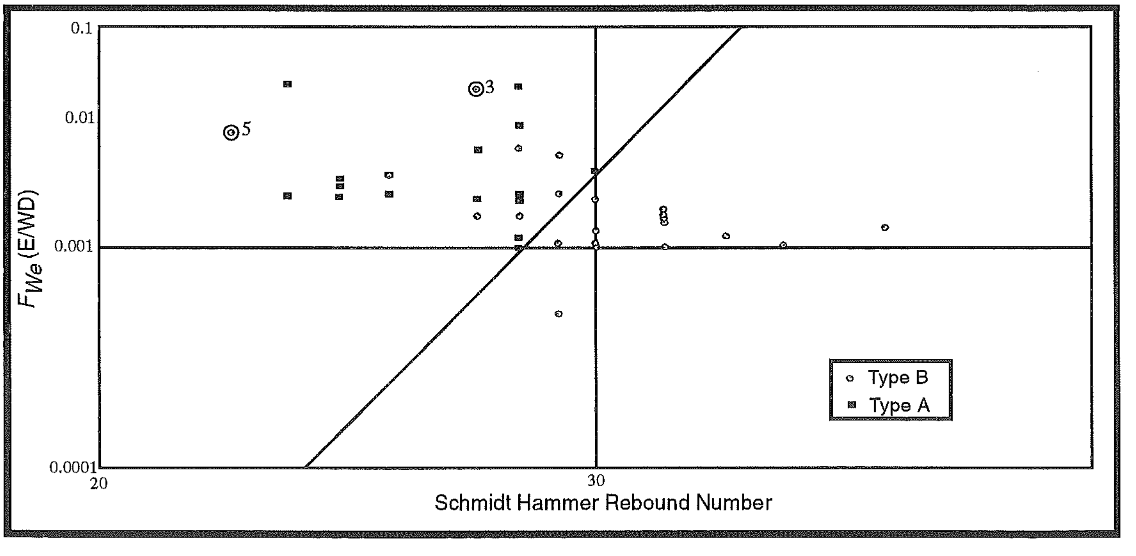

Figure 7.7 continued. Demarcation between platform types separated by a line at 45. Circled letters indicate KM3A and KM5A and are discussed in text.

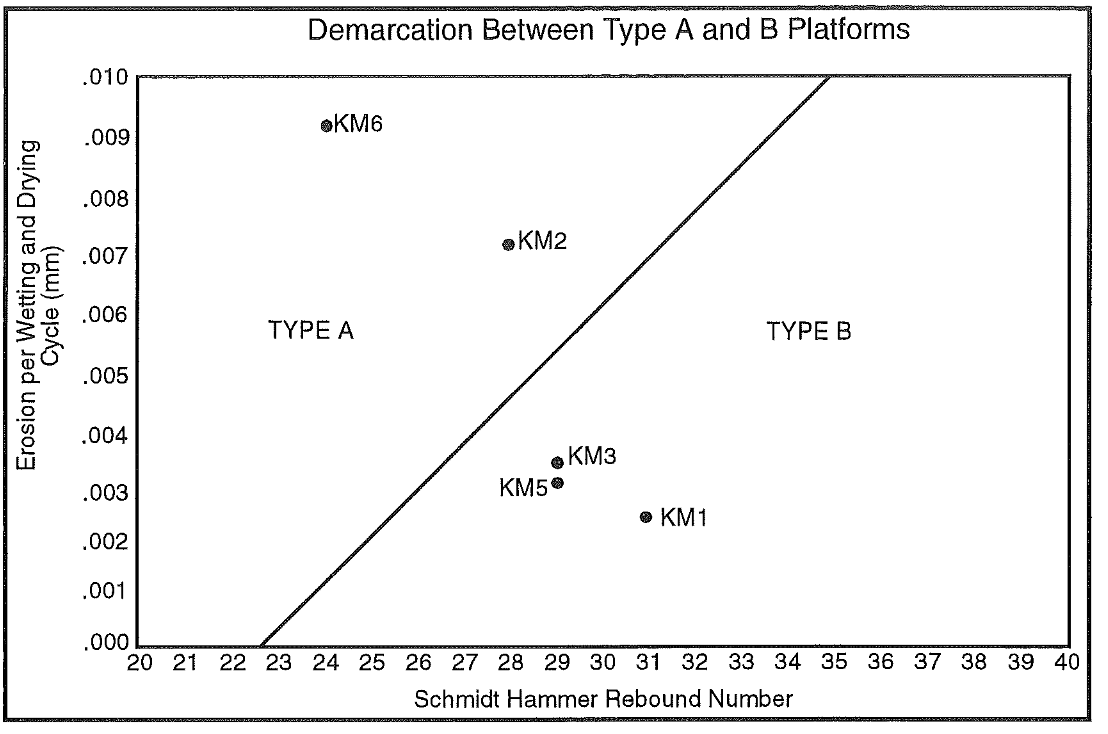

Figure 7.8 Demarcation between Type A and B mudstone profiles at Kaikoura based on mean rebound values and mean erosion per wetting and drying cycle for each profile.

7.5 EQUILIBRIUM FORM OF SHORE PLATFORMS AT KAIKOURA

One of the main questions this thesis sought to answer was, do shore platforms take equilibrium forms? If equilibrium forms exist, a second question was, what forms do equilibria take? These questions originated from the apparent contradictions found in models of shore platform development. Some models indicated platforms tend towards a static state while other showed platforms are in a dynamic state of equilibrium. These models were shown in Section 7.4 to be invalid when applied to shore platforms on the Kaikoura Peninsula. It can be argued then that inferences concerning equilibrium may also be invalid.

A central matter in any discussion of the equilibrium forms, is the question of low tide cliff retreat. Evidence presented in Chapter Five indicated that the seaward edges of shore platforms had not retreated, or at least not at rates detectable by the measurement technique. This supported the view that no erosion of the seaward edge of platform has occurred and demonstrated that parallel retreat does not occur at Kaikoura. Parallel retreat in Trenhaile's (1983a) view was an indicator that shore platforms are in a state of dynamic equilibrium. The conclusion that might be drawn is that platforms are in a static state of equilibrium. If the seaward edge of a shore platform does not retreat then this can be seen as evidence supporting static equilibrium and against the possibility of dynamic equilibrium. Static equilibrium has been argued to result when the erosive force of waves declined due to attenuation across a widening platform. Wave attenuation was shown to be very high at Kaikoura to the point where waves could not cause erosion or retreat of the landward cliff. This also suggests that platforms at Kaikoura may be in a state of static equilibrium, but evidence against this notion comes from measured rates of cliff retreat gained from aerial photographs. That is, cliffs at Kaikoura continue to retreat when wave forces are not competent to cause erosion. Therefore the notion of a static equilibrium state for shore platforms at Kaikoura can be rejected. This leaves the question: what equilibrium form?

It is proposed that shore platform equilibrium must be considered for two separate attributes of the platform. The first is the elevation of platforms and the second is the width of platforms. The reason for this is now discussed. The rate of surface lowering of shore platforms at Kaikoura does not equal the rate of widening. This was demonstrated during testing of the parallel retreat model. Platform erosion rates were shown to correlate with elevation such that the lower the elevation the lower the erosion rate. This relationship suggests that platforms tend down to an equilibrium elevation. The elevation is probably determined by either sea level or the range of the tide. At the same time it is unlikely that shore platforms have an equilibrium width where weathering is the process causing cliff recession. The reason for this is that the continued role of weathering in platform extension is not dependent on the width of a shore platform. So long as waves have enough energy to remove weathered debris then platform extension can continue beyond the widths predicted by Sunamura (1991). Width may be eventually controlled by the ability of waves to remove the debris formed from weathering, rather than by the ability to cause erosion. So long as weathering lowers the platform then waves will continue to reach the cliff base and there is no need for the seaward edge of platforms to retreat. It is proposed that the equilibrium elevation ensures that waves always reach the cliff base to remove debris; in which case there is no equilibrium width for shore platforms at Kaikoura.

A discussion of shore platform equilibrium must identify the time scale at which equilibrium is being considered. The above discussion has dealt with the long time scales of thousands of years. At a time scale of hundreds of years it is proposed that platforms may be in a state of dynamic equilibrium. The reason for this is that platforms at Kaikoura have been shown to respond quickly to tectonic events. Dynamic equilibrium in this sense is not the same as that discussed by Trenhaile (1987). Rather, it refers to adjustments made in response to events in the environment in the same way a beach erodes during a storm event and subsequently accretes during calm periods. Shore platforms do respond to changes in the environmental conditions in which they develop. For example, platforms at Kaikoura have adjusted rapidly to tectonic uplift. The 2m uplift event identified by Duckmanton (1974) ca. 1000 years ago has easily been accounted for by the rapid rates of subsequent erosion. Erosion rates on the inner margins of platforms were measured at between 1.27 and 9.19mm/yr. Such high erosion rates can cause 2m of platform lowering in less than 1000 years. Once adjustment has occurred then platform extension continues in the way described above, suggesting that over times scales of thousands of years platform surfaces tend down towards a static state of equilibrium while widening, without tending to any equilibrium width.

7.6 CONCLUSIONS

Correlation and multiple regression analysis has shown that erosion of shore platforms is related first to elevation. Elevation influences the number of wetting and drying cycles which in turn influences erosion. The conclusion reached from this is that shore platform development at Kaikoura is caused by weathering processes induced by wetting and drying. Marine processes, both waves and tides, aid development by contributing to the number of wetting and drying cycles. Wave induced currents remove the debris formed by weathering. This argument of platform development is contrary to recent views of Sunamura (1992, 1994); Trenhaile (1987); and Griggs and Trenhaile (1994); that platforms develop as a result of marine erosive processes, and is similar to that of Bartrum (1916). Models reviewed in Chapter Three are not valid when applied to Kaikoura because the assumption that waves erode platforms has been shown not to be correct. Widening of shore platforms is significantly correlated with lowering rates in the manner suggested by the parallel retreat model but this does not establish the validity of the parallel retreat model. A demarcation was made between Type A and B platforms based on erosion per tidal cycle and compressive strength represented using Schmidt Hammer Rebound values. Thus Type A and B platforms can be distinguished in at least two ways and not simply on a distinction between wave force and rock compressive strength as proposed by Tsujimoto (1987). The type of equilibrium platforms attain depends on the time scale considered. At short period of hundreds of years dynamic equilibrium may occur. At a scale of thousands of years, platform surfaces tend down to a static state but widths do not have an equilibrium form. This is because widening is an ongoing process independent of platform width.

8. CONCLUSIONS

8.1 OBJECTIVES RECALLED

This thesis set out five objectives in Chapter One:

1) To extend the small body of literature relating to measured rates of erosion, and to allow data from shore platforms on the Kaikoura Peninsula to be compared with those from other studies, thus addressing the problem of a lack of comparison between studies as identified by Kirk (1977). Erosion data were also to be used to interpret processes operating on platforms.
2) To measure directly wave and weathering processes to allow the assessment of the role of each in the development of shore platforms.
3) To answer the following questions: How do shore platforms develop? Are they wave-cut or weathered or some combination of both? Do shore platforms develop as a result of a process gradient across the platform profile as proposed by Kirk (1977)? Answers to the questions were to allow testing of the underlying assumption of models that shore platforms are wave-cut features.
4) To test the validity of models of shore platforms development with data from the Kaikoura Peninsula.
5) To identify the type of equilibrium shore platforms attain. In regard to equilibrium two questions are asked: Do shore platforms have an equilibrium form? If they do what is it?

8.2 SUMMARY OF MAJOR FINDINGS

8.2.1 OBJECTIVE ONE — RATES OF EROSION

Objective one was achieved through the measurement of micro-erosion rates over a two year period. Micro-erosion rates varied at individual bolt sites from an equivalent annual rate of 0.154 to 9.194mm/yr. Differences were found in the rates of erosion between Type A and B mudstone platforms and limestone platforms. Type A mudstone platforms eroded faster than Type B mudstone platforms. The grand mean for all bolt sites was 1.130mm/yr. This compared with 1.48mm/yr reported by Stephenson and Kirk (1996) and 1.53mm/yr reported by Kirk (1977), both for the Kaikoura Peninsula. Compared with studies elsewhere in the world the value of 1.130mm/yr fell in the middle of the range of published values. Viles and Trudgill (1984) reported rates of 1.97mm/yr and Robinson (1977a, 1977b, 1977c) reported rates between 0.0 and 0.9mm/yr. Erosion rates were found to be higher during summer months than winter, contrary to reports by Robinson (1977a, 1977b, 1977c) who found rates were higher in winter. It was found that surface lowering occurred on Type B platforms, contrary to the assertion made by Tsujimoto (1987) that surface lowering does not occur, although surface lowering on Type B platforms was slower by an order of magnitude compared with Type A platforms.

Micro-erosion data also showed that surfaces undergo swelling. Swelling is thought to result from the growth of salt crystals and expansion from wetting and drying. Significant swelling was observed, up to 8.9mm on one occasion. Information concerning the duration of swelling events was also obtained, but it was noted that the period between successive readings negated a detailed examination of duration. The magnitudes of swelling events were found to be greater on Type B mudstone and limestone platforms than on Type A mudstone platforms. As with erosion, swelling was greater during summer months than winter.

Swelling and erosion data showed a marked seasonal trend; both rates being higher in summer than in winter. Chi square tests were used to establish if there was a statistically significant relationship between season, and erosion and swelling. Erosion and swelling at 74 per cent of all bolt sites were shown to be statistically related to season. The conclusion reached was that weathering was the erosional process operating on platforms at Kaikoura, based on the seasonal character of erosion and swelling. Summer provides better conditions for weathering processes, such as salt weathering and wetting and drying because higher temperatures in summer aid drying. In support of this it was noted that the occurrences of storm waves along the Kaikoura coast can happen at any time of year and do not show a seasonal trend.

Analysis of traversing micro-erosion data was extended beyond previous published studies by entering the data into a 3-dimensional surface plotting programme, thus allowing the visualisation of bolt site surfaces and changes in those surfaces over time. This helped illustrate the nature of surface erosion and swelling. The software was also used to calculate the volume of material eroded, so that erosion rates could also be expressed in volumes per unit time. The volume of material yield from bolt sites ranged from 0.644 to 42.8cm^3/yr. Volume data were extrapolated to calculate the total volume of micro-scale erosion from the inter-tidal surface of the Kaikoura Peninsula. This calculation showed that $1010m^3$ was eroded annually from an area of $0.74km^2$.

Erosion rates were also assessed at larger scales to address the issue that micro-erosion meter data do not represent the full range of scales at which erosion can occur. Erosion in the range of centimetres and metres was measured or observed, and the relative contribution to total rock volume at these scales, when compared with micro scale erosion was simialr.

Cliff erosion was investigated using aerial photographs taken 52 years apart. Backshore cliff recession rates were in the range of 0.05 to 0.23m/yr. An attempt was also made to investigate low tide cliff retreat. The first result was that no erosion of the seaward edge of any platforms had occurred in the 52 years elapsed. The parallel retreat model showed that the seaward edge of platforms should have retreated at a similar rate to the backshore cliff, and since the landward cliff retreat was detectable, then it should have been possible to detect low tide cliff recession. This was not the case, and it was concluded that the seaward cliffs do not retreat. However, an alternative conclusion was arrived at, after consideration of Edwards' (1941) proposition that the seaward edge retreats at a rate much slower than the landward cliff. This raised the possibility that recession occurred too slowly to be detected with the technique employed. The alternative conclusion was that cliff retreat may proceed at a rate of an order of magnitude slower than the landward cliff. This left unanswered questions as to the role as well as the rate of seaward cliff recession.

8.2.2 OBJECTIVE TWO — MEASUREMENT AND ASSESSMENT OF EROSIVE PROCESSES

The point was made in Chapter One that platform morphology is an ambiguous indicator of process and previous studies had suffered from trying to interpret process from it. Morphology can assist in process interpretation, but it was noted that direct investigation of process might provide a less ambiguous understanding of how shore platforms develop. A review of the literature relating to the development of shore platforms showed that wave erosion and subaerial weathering had been identified as the erosive processes on shore platforms. The questions that were asked in Chapter Six were: Given that waves can be observed on shore platforms, do they cause erosion? Does weathering occur on shore platforms and if so does this result in erosion?

8.2.2.1 Waves

Marine erosive processes were considered through an examination of deep water wave data and from the measurement of waves on shore platforms at high tide. Two issues relating to deep water wave data were considered. First, the amount of deep water wave energy that arrived on the seaward edge of platforms was investigated. This showed that a very large proportion of energy was lost in refraction and shoaling only 0.3 to 9.0 per cent of deep water wave energy arrived on platforms. The second aspect of wave processes examined was the occurrence of breaking waves. It was shown how only small waves could impact directly on the seaward edge of platforms. The height of breaking waves was determined by the depth of water in front of the platform. For this reason the only time breaking waves were able to break on platforms was at high tide. This analysis showed that the role of breaking waves in platform development was questionable, when previous workers had attributed significance to it.

Wave measurements on shore platforms showed that attenuation of waves across platforms reduced the energy in them by as much as 95 per cent, between the seaward edge and the landward cliff. Calculations of wave induced shear stresses and dynamic forces showed that these never exceeded the compressive strength of the material forming the platforms. Shear and dynamic forces ranged from 311 to 1400N/m^2 and compressive strengths were in the range of 21755 to 47198KN/m^2. Theoretical consideration was given to the highest wave that could occur at the landward cliff foot. It was found that a wave could not be more than 0.74m in height on platforms because tides limited the depth of water on the platform. A wave of 0.74m could not generate shear stresses or dynamic forces to erode the rock. This showed the importance of the depth of water in front of the landward cliff as a control on the amount of wave energy reaching it. In answer to the question of whether waves cause erosion, the conclusion reached was that at Kaikoura they do not.

8.2.2.2 Subaerial Weathering

Morphological data indicated that at least four forms of subaerial weathering were operating on shore platforms at Kaikoura: honeycomb, salt, water layer weathering and slaking. Slaking was thought to be responsible for cliff weathering and the other three for platform lowering, although honeycomb weathering played only a minor role. Salt weathering appeared to be restricted to Type B mudstone platforms, and water layer weathering to Type A mudstone platforms. No morphological evidence of weathering was found on limestone platforms. A quantitative method was used to determine if weathering did operate on shore platforms. The chosen method was the Schmidt Hammer test, which showed that weathering did occur. Rebound numbers were higher on freshly exposed rocks than those exposed to the atmosphere for some time. Rebound numbers reduced by as much as 52 per cent when weathered rocks were compared with unweathered. The Schmidt Hammer test showed that weathering did occur on limestone platforms. Empirical evidence suggested that weathering reduced the strength of rocks even further. It was noted that micro-scale surface morphologies associated with salt weathering, such as pitting and flaking, could be removed by scraping with a finger nail.

It was not possible to directly measure subaerial weathering, so a number of proxy data were used to calculate the number of wetting and drying cycles on shore platforms. Wetting and drying was identified in Chapter Two as an important control for water layer and salt weathering. The numbers of wetting and drying cycles were estimated using tidal and rainfall data for the years 1995 and 1996. The most significant result from this analysis was that there was a range of elevations where the numbers of cycles was at a maximum. Between 0.6 and 0.9m above mean sea level, approximately 330 to 370 cycles per year were estimated, and below this, the number dropped to 240, until at -0.195m around 200 cycles were estimated. At -0.389m, the lowest elevation considered, on the seaward edge of a platform, the number of cycles was between 200 (1996) and 216 (1995). The number of cycles also declined above 0.9m with between 140 and 160 at an elevation of 1.053m above mean seal level, and 96 to 110 at 1.327m. At one site, 1.748m above mean sea level, only 75 cycles occurred. This site is above the tide level and wetting and drying resulted only from rainfall. It was not possible to account for cycles resulting from spray or splash. The growth of algae was shown to exert an important control over the number of wetting and drying cycles on shore platforms by preventing drying during winter months.

Correlation coefficient and stepwise regression analysis were undertaken to establish whether statistically significant relationships existed between erosion rates and other variables: platform elevation, distances from the seaward edge of shore platforms, and the number of wetting and drying cycles. This analysis showed that the best linear relationship was between erosion and elevation. Distance was also important on two individual profiles (KM6 and KM7). A quadratic curve regression model showed a significant relationship ($R^2 = 0.38$ F = significant at 0.000) between elevation and erosion. It was necessary to verify that erosion and wetting and drying were related to establish the role of weathering as an erosive agent. Because wetting and drying varied with elevation, and elevation was related to erosion, curvilinear regression models were used to investigate relationships between elevation and wetting and drying. Elevation was not concluded to cause erosion but wetting and drying might have. Curve regression models were tested against the data and a quadratic curve was found to provide the best fit (R^2 = 0.21 F = 6.82 significant at 0.002) between the two variables. The conclusion reached was that erosion was related to wetting and drying and this was strong evidence to support weathering as an important erosional agent on platforms.

8.2.3 OBJECTIVE THREE — SHORE PLATFORM DEVELOPMENT

A major objective of this study has been to answer the question: how do shore platforms develop? This was directed at the difference in published views that platforms are wave cut, or weathered, or that they result from some combination of both. Considering that waves were shown not to have enough energy to erode rock material and given that statistically significant relationships were found between weathering variables and erosion at Kaikoura, then the conclusion that can be drawn is that platforms at Kaikoura result from weathering, as opposed to being wave cut. However, it is necessary to have waves to induce currents that transport eroded material away. If this did not occur then scree slopes would develop and fossilise the cliffs. This conclusion is similar to the mode of formation proposed by Bartrum (1916) and Bell and Clare (1909). The presence of marine processes is necessary for shore platform development, but only after weathering has caused erosion. However, it does not propose an elevation limit controlled by saturation, as argued by Bartrum (1916).

One part of objective three was to test the proposition put forward by Kirk (1977) that shore platforms develop as a result of marine and subaerial processes being zonally distinct across the platform profiles. Kirk (1977) proposed that subaerial weathering was the dominant process on the landward margins of platforms and marine processes were dominant on the seaward edge, and both were graded towards the middle of the platform. Some data support this proposition. Tidal distribution data showed how the seaward edges of platforms are submerged for up to 80 per cent of the year. This prevents subaerial weathering and supposedly gives more opportunity for marine processes to erode the outer margins of platforms. Conversely, the landward margins are exposed to the atmosphere for up 80 per cent of the year, giving opportunity to weathering to cause erosion. Schmidt Hammer data supported this view of process zonation, showing that the landward margins were more weathered that the seaward edges of platforms. Weathering was shown to be more severe on the inner margins of some platforms than on the seaward edges, although this was not always the case. Investigations of wave forces showed that these were greater at the seaward edge than at the cliff foot on the landward part of platforms. Erosion data also indicated that processes might be zonally distinct. Rates of erosion (and swelling) were higher on the inner margins of most platforms and these were statistically associated with season. The proposition advance by Kirk, was based on erosion data that showed rates of erosion were higher on the inner and outer margins than in the middle. This pattern was not replicated at Kaikoura. While much of the evidence above supports Kirk's (1977) view, the lack of replication of the cross shore pattern in erosion rates suggests otherwise. The proposition that processes are zonally distinct across the platform profile would appear to hold based on the evidence above. However, the idea that this is how shore platforms develop is rejected. Instead it is argued that platform development occurs because of weathering, which is more prevalent on the inner margins of platforms, and marine processes do not cause erosion on the seaward edges of shore platforms at Kaikoura.

8.2.4 OBJECTIVE FOUR — VALIDITY OF MODELS

Existing models describing or predicting shore platform development have been shown not to apply to shore platforms at Kaikoura. This is because the underlying assumption that shore platforms develop as a result of wave erosion is incorrect when applied there. It was intended to address the contradictions between models identified in Chapters One and Three. These models were shown to be invalid when applied to Kaikoura and such an exercise was deemed unnecessary.

The parallel retreat model was tested with data from Kaikoura. Considering morphological evidence the validity of the model was rejected. First, it is doubtful that the seaward edge of shore platforms retreated as the model requires. Second, erosion data showed a cross shore variation in the rates of erosion, where the model requires it to be constant. Thirdly, surveys of offshore topography did not show the type of morphology that would be expected if parallel retreat was occurring. In spite of these three points, erosion data were used to test the predictive capabilities of the model. Good agreement was found between predicted and measured rates for both surface lowering and cliff retreat, but this agreement did not support the notion that platforms retreat in a parallel fashion.

Given that previous models were found to be invalid when applied to platforms at Kaikoura, a conceptual model was presented to illustrate the explanation of how shore platforms at Kaikoura are developing. This incorporated three primary controls; climate, geology, and marine processes. Wetting and drying was identified as the primary erosive process. The number of wetting and drying cycles was controlled by rainfall, solar radiation, tides, waves and biology. Platforms develop when the erosive force of weathering exceeds the resisting force of the rock. Resisting force is represented as a compressive strength, and is controlled by structure and lithology. The model showed that Type A platforms develop when the compressive strength of the rock is less than $24000KN/m^2$ and Type B platforms develop when it exceeds $37000KN/m^2$. Waves were important as a transporting agent of the debris formed by weathering. This difference between platform types was extended to show that a demarcation existed based on erosion rates (resulting from wetting and drying), and compressive strength. The significance of this is that it illustrates a demarcation related to weathering in the same way as Tsujimoto (1987) has done using wave energy. Thus platform character is not uniquely related to wave energy.

8.2.5 OBJECTIVE FIVE — STATES OF EQUILIBRIA

The aim of objective five was to identify what, if any, are the equilibrium forms of shore platforms. This aim was set because one of the contradictions identified between models of platform development is in the different equilibrium forms that models have identified. The question was asked: do platforms tend towards a static, a dynamic or some other equilibrium form? Given the inadequacies of the models, and that the models could not be tested, the issue of equilibrium form was decided based on an explanation of how shore platforms develop, as presented in Chapter Seven. It was argued that without a definitive answer to the question of seaward edge retreat, a clear understanding of the equilibrium form cannot be gained. The weight of evidence indicated that the seaward edge of a platform does not retreat. This being the case, and given that platform extension results from weathering, then it is proposed that there is no limit to the width a platform will attain. This is because weathering is not limited by platform width in the same way as wave erosion. So long as surface lowering of platforms always allows waves to cross the platform and remove the material formed by weathering, platform extension can continue.

Based on statistically significant correlations between erosion rates and platform elevations, which showed erosion decreases with decreasing elevation, it was argued that platforms tend down towards a level determined either by sea level or tide range. The view taken here is that this can be called a static state of equilibrium. This led to the argument that platform equilibrium must be viewed in two parts. First, platforms can be seen not to have an equilibrium width; and second, platforms do have an equilibrium elevation. It was noted that these states occur over time periods of thousands of years. At shorter time periods of hundreds of years, it was argued that platforms can be viewed as being in dynamic equilibrium with their environment, because they respond rapidly to environmental change. The example given from Kaikoura was tectonic events that caused 2m of uplift. Platforms have responded to this and are now almost fully readjusted to it; the evidence for this response comes from rates of erosion than can cause 2m of surface lowering in the time elapsed since the uplift event.

8.3 THESIS EVALUATION AND SUGGESTIONS FOR FURTHER RESEARCH

Overall this thesis has successfully met the five aims set out in Chapter One. Measured rates of shore platform erosion are now better known and the presentation of TMEM data has been advanced. Results from the TMEM were cautiously used to interpret process, bearing in mind that erosion rates do not discriminate between individual processes. For this reason, direct investigation of processes causing erosion was undertaken. To the knowledge of the author, waves have been measured on shore platforms for the first time, although the data set collected was small and a larger one would have been desirable. The role of subaerial weathering processes has been successfully assessed at a broad level. More detailed study of specific processes would have added to the proposition that different subaerial processes operate on different platform types. Questions of how shore platforms at Kaikoura develop have been answered in light of results from the investigation of processes. An attempt was made to apply models of platform development at Kaikoura and were shown to be invalid. The question of platform equilibrium has been addressed, but a conclusive decision as to the type of equilibrium remains elusive. This is because the question of retreat of the seaward edge of platforms has not been definitively answered. While this thesis has succeeded in meeting the aims set out for it a number of avenues for further research can be identified.

It has been argued that platforms develop at Kaikoura because of weathering and that waves serve only to remove the debris that results. This proposition clearly requires testing on shore platforms in different geographical locations, under different conditions of climate, marine environments and geology. A conceptual model was introduced to explain the development of shore platforms at Kaikoura. The wider application of this needs to be tested. The development of predictive models that incorporate weathering would be a useful avenue for further research. An unanswered question in this thesis has been: do the low tide cliffs or seaward edges of shore platforms erode? A definitive answer to this question would provide important clues to platform equilibrium and the validity of models predicting platform widths and gradients. There is still the possibility that waves erode material from surfaces that have been severely weakened by weathering. For this reason a better assessment of the degree of reduction in compressive strength is required, focusing on the first few millimetres in depth of rock surfaces. Attempts were made to directly measure processes operating on shore platforms but this was not always possible, particularly with weathering. This reflects the complicated nature of weathering processes. Wetting and drying cycles were estimated from proxy data. It should be possible to develop instrumentation that would not only record wetting and drying events but also show to what degree a surface is dried or wetted. This would provide a more accurate measurement of the number of cycles occurring on shore platforms. It has been shown in this study that biology plays an important role in controlling the number of wetting and drying cycles, and ultimately the amount of erosion. No attempt was made to directly investigate biological factors influencing shore platform development. Detailed investigations of the role of biology affecting platform erosion are required.

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APPENDIX ONE

A reprint of:

Stephenson, W.J. and Kirk, R.M. (1996). Measuring Erosion Rates Using the Micro Erosion Meter: 20 Years of Data From Shore Platforms, Kaikoura Peninsula, South Island New Zealand. *Marine Geology*. **131**:209-218.

Reprinted from

MARINE GEOLOGY

INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

Marine Geology 131 (1996) 209–218

Measuring erosion rates using the micro-erosion meter: 20 years of data from shore platforms, Kaikoura Peninsula, South Island, New Zealand

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Received 16 March 1995; revision accepted 17 January 1996

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Marine Geology 131 (1996) 209–218

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

Measuring erosion rates using the micro-erosion meter: 20 years of data from shore platforms, Kaikoura Peninsula, South Island, New Zealand

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Received 16 March 1995; revision accepted 17 January 1996

Abstract

Fifteen micro-erosion meter sites, giving 42 individual readings of erosion were remeasured twenty years after installation on mudstone and limestone shore platforms on the Kaikoura Peninsula, South Island, New Zealand. The mean annual surface lowering rate was calculated to be 1.43 mm/yr. Longer term data were compared to shorter term data collected over a two-year period between 1973 and 1975 to test the validity of extrapolating average erosion rates from shorter term data. It was found that the average lowering rate for the shorter term data were in statistically acceptable agreement with those for the longer term data. Extrapolation of short term micro-erosion meter data is therefore acceptable in this particular environment. In previous work it has been suggested that measurements from as few as thirty individual micro-erosion meter positions are required to calculate a mean annual lowering rate on shore platforms. Measurements from 30 MEM positions provided an statistically acceptable mean annual lowering rate for shore platforms on the Kaikoura Peninsula.

1. Introduction

This paper presents the results from 15 micro-erosion meter (MEM) sites remeasured after twenty years. These are the remaining sites of 31 that were installed in 1973 by Kirk (1977) to investigate rates of surface lowering on intertidal shore platforms cut in limestone and mudstone on the Kaikoura Peninsula, South Island of New Zealand (Fig. 1). The micro-erosion meter (MEM) is an instrument designed to give precise measurements of erosion rates on rock surfaces. The technique is described later in this paper. It has been used extensively to investigate the rates of down cutting on shore platforms (Trudgill, 1976; Kirk, 1977; Robinson, 1977a,b,c; Spencer, 1981, 1985; Trudgill et al., 1981; Gill and Lang, 1983). The need to gain such data arises from a lack of quantitative data in shore platform studies and to determine the age and rate of development of shore platforms. However, while platforms are thought to require hundreds or thousands of years to form, most techniques that measure erosion rates are applied only for one or two years. For example, Kirk (1977) calculated cliff retreat rates from air photographs over three decades and surface lowering rates from the MEM technique over two years.

Viles and Trudgill (1984) question extrapolating shorter term MEM data to longer time scales. They believe that the accuracy of such extrapolations are unknown. Thus longer term data is useful

SSDI 0025-3227(96)00008-4

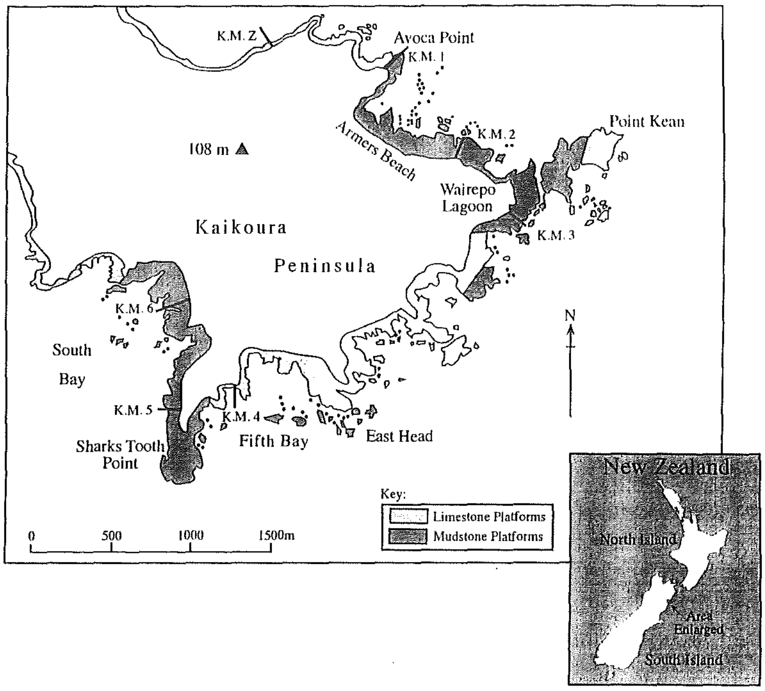

Fig. 1. Kaikoura Peninsula showing the location of MEM profile locations.

as a check on extrapolations made with shorter term data.

As yet, no longer term erosion rates on intertidal shore platforms in temperate environments have been published. The longest record to date is eleven years as reported by Viles and Trudgill (1984). The data presented here enable an average erosion rate to be calculated on a time scale longer than previously published and they allow examination of the validity of extrapolating shorter term average erosion rates to longer time periods.

Previously published MEM erosion rates have most often been calculated from short time periods of about two years (Trudgill, 1976; Kirk, 1977; Robinson, 1977a,b,c; Spencer, 1981, 1985; Trudgill et al., 1981; Gill and Lang, 1983). Only two previous studies have presented MEM results from periods longer than two years: one is Mottershead's (1989) work and the other is Viles and Trudgill (1984). Mottershead (1989) calculated a mean lowering rate of 0.625 mm/yr on supratidal greenschist, on the Start-Prawle Peninsula, on the south Devon coast of the UK based on a seven-year time period. There the principal agent of erosion was salt spray weathering. Mottershead (1989) concluded that measurements taken from 30 individual positions were sufficient to calculate a representative mean annual lowering rate on the Start-Prawle Peninsula and that year to year variations in total lowering were not statistically significant. The minimum number of MEM sites required is an interesting question, particularly when establishing new studies. How many sites are required for representative results to be gained? Clearly this is dependent on how much area is to be considered and the degree of variability in the morphogenetic environment. Mottershead (1989) used 30 individual positions from ten MEM sites at three locations that were no more than 250 m apart. The opportunity exists to test whether or not 30 readings will provide a valid erosion rate from the shore platforms on the Kaikoura Peninsula. The peninsula has an area of 5.2 km^2 of which 0.77 km^2 is shore platform (Kirk, 1977). The distribution of the MEM sites used on the Kaikoura Peninsula are shown in Figs. 1 and 2.

Viles and Trudgill (1984) present results from Aldabra Atoll in the Indian Ocean, based on an eleven year period. On the intertidal surfaces of a raised coral reef the mean lowering rate was reported to be 1.97 mm/yr. Viles and Trudgill (1984) also attempted to test the validity of extrapolating short term data to longer periods by comparing predicted erosion for an eleven year period derived from a two year data set. The shorter term measurements were within an order of magnitude of the long term rates with a 10% difference in mean rates. Viles and Trudgill (1984) concluded

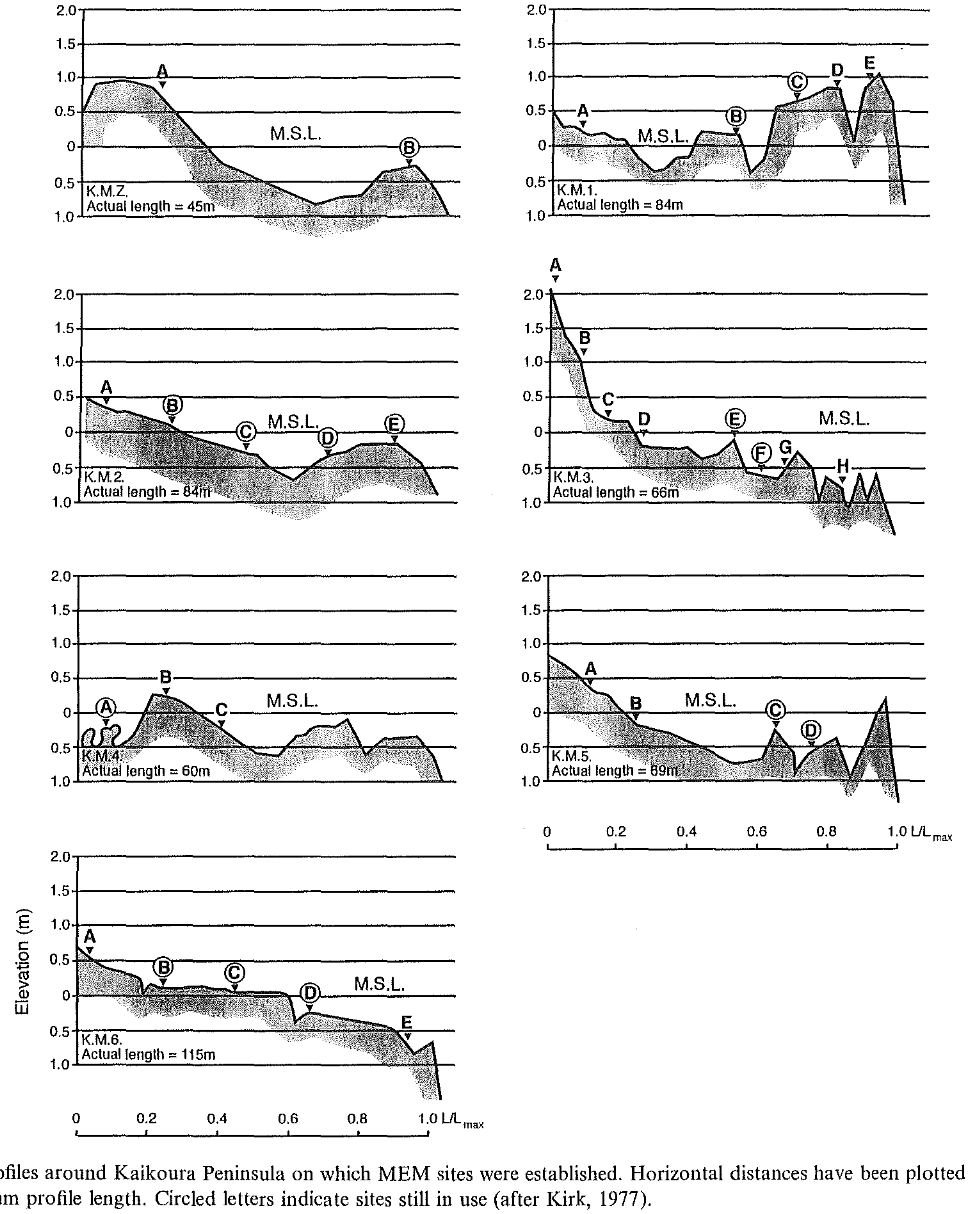

Fig. 2. Profiles around Kaikoura Peninsula on which MEM sites were established. Horizontal distances have been plotted as a ratio of maximum profile length. Circled letters indicate sites still in use (after Kirk, 1977).

that the use of a "small" number of sites was suspect and that a "larger" number of MEM sites were needed to gain acceptable data. They did not suggest the number of data. Attempts to extrapolate shorter term data were thought to be invalid, except to establish an order of magnitude, and extrapolation should be done with a degree of caution.

Some concern is expressed by the present authors about the data used by Viles and Trudgill (1984). Viles and Trudgill (1984) reported problems with disruption to MEM sites. In some cases the ball bearings on which the MEM rests had been lost. In such cases the studs were replaced or new ball bearings were put in place. This has the result of interrupting the continuity of the record as the original reference point was lost. Added to this was the problem that surface lowering was such that the probe of the MEM no longer reached the surface. Where this occurred a ruler was used to take a measurement alongside the exposed bolt. The integration of results from this form of measurement and readings taken solely by the MEM is questionable. Since Viles and Trudgill (1984) do not report depths to which bolts were countersunk into the rock surface at the time of installation the total amount of erosion over the eleven year period could not be calculated. The matters of longer term erosion rates and their estimations from shorter term data are thus still open questions for research.

2. Study area

The Kaikoura Peninsula is located on the east coast of the South Island of New Zealand at 42°25′S and 173°42′E (Fig. 1). The highest elevation of the peninsula is 108 m. Geologically the peninsula consists of an asymmetrical anticline bounded on either side by two synclines, the axis of which strikes NE–SW (Chandra, 1968). Two sedimentary rock types make up the peninsula, Palaeocene Amuri limestone and Oligocene grey marls (mudstone). Intense folding and minor faulting occur, particularly in the limestone area. Shore platforms are cut into both lithological units, those in limestone displaying wider variability in morphology.

Development of shore platforms has dominated the Quaternary history of the peninsula shoreline. Four erosional surfaces have been identified resulting from still stands during tectonic uplift. Suggate (1965) and Chandra (1968) propose that these surfaces are most likely to be former shore platforms. The elevation of the erosional surfaces occur at 108 to 94 m, 80 to 76 m, 68 to 58 m and 40 to 50 m (Duckmanton, 1974). Chandra (1968) proposed that the surface between 40 and 50 m correlated with the last interglacial. There is a strong possibility that shore platforms on the peninsula are polygenetic in origin

The climate of the Kaikoura Peninsula is temperate with an average rainfall of 865 mm/yr and average monthly temperatures of 7.2°C in July and 16.7°C in January, with frost frequent in winter (Kirk, 1977). The Kaikoura Peninsula receives oceanic swell and storm waves from the south, southeast and northeast. Significant wave height ranges from 0.5 to 2.44 m with periods between 7.5 and 10 s and storms can occur at any time of the year (Kirk, 1975). Tides at Kaikoura are dominantly semi-diurnal containing some diurnal inequality, and the mean range is 1.36 m and the maximum 2.57 m (Kirk, 1976).

3. Methodology

The MEM used at Kaikoura was constructed according to the specifications outlined by High and Hanna (1970). It consists of an equilateral triangular base with legs located at each corner and an engineering dial gauge located on a central pillar. The spindle of the gauge extends through the base plate. Readings are taken by placing the triangular base on three bolts which have been permanently fixed into a rock surface. These bolts are masonry anchor bolts. On the head of these bolts a small depression is machined and a ball bearing is glued to the bolt head. Exact relocation on the fixed bolts is obtained by using the Kelvin Clamp Principle. The end of each leg has been machined differently, one has a cone shaped depression, one a v-notch depression and the third is flat. Each leg end opposes movement in three, two and one direction respectively, thus preventing movement of the plate when placed on a bolt site. The engineering dial gauge is located off centre in the base plate so that three positions are located by rotating the instrument on the bolts 120° (High and Hanna, 1970). Thus a MEM site yields three readings.

A calibration block was constructed at the same time as the MEM. This enables the meter to be checked periodically to ensure that it is still operating accurately. On the 29 October 1994 it was found that readings were different at each of the three positions by no more than 0.001 mm from readings taken on the 15 February 1973. All of the 15 MEM bolt sites were remeasured on the 21 November 1994. The total time period elapsed for each of the bolt sites varied between 19.02 and 20.98 years. This was as a result of bolts having been replaced between 1973 and 1975 due to failure of the original ball bearing bolt design as described by Viles and Trudgill (1984). The first readings taken after the replacement of a bolt were used to ensure continuity in the record. Replacement bolts installed by Kirk (1977) were of a machined, single piece design later described by Trudgill et al (1981). None of the original ball bearing design bolts remain, emphasising the importance of using machined single piece bolts in MEM studies.

An operational problem was that the rate of surface lowering was such that the original spindle of the dial gauge no longer reached the surface when the MEM was placed on a bolt site. This problem was overcome by adding probe extensions to the original. These were purchased from an engineering tool supplier. It was necessary to add either a 25 mm extension or one of two 12.5 mm extensions or a combination of these. The length of whichever probe length was used was added to the recorded measurement.

All 31 MEM bolt sites installed by Kirk (1977) were located on profiles across shore platforms around the Kaikoura Peninsula. The locations of these profiles are shown in Fig. 1 and the location of bolt sites on profiles are shown in Fig. 2. Sites were selected according to their suitability for the MEM technique, which requires a level surface and to give representation to the wide range of exposures, rock types and structures (Kirk, 1977). At least one MEM site remains on each profile and in the case of KM2 only one bolt site has been lost. The 15 remaining sites represent 51.6% of the total number installed. Of the 15 bolt sites 13 are on mudstone platforms and 2 on limestone platforms.

Of the 16 MEM sites no longer in service most have simply disappeared without any trace. Some shallow depressions exist where bolts were installed. In other cases, rusted bolts no longer useable protrude from platform surfaces. Some have become inoperative because of vandalism, or failure of the glue used to fix ball bearings to bolts. The sites remaining are those where glued bolt/ball bearing combinations were later replaced by the specially made one piece, marine grade stainless steel bolts. It was necessary to resurvey the profiles established by Kirk (1977) in order to correctly identify bolt sites because missing bolt sites made this difficult.

4. Results

Table 1 presents the results from readings taken on 21 November 1994. Total erosion for each MEM site is defined as the average of the three readings taken at each position on a bolt site. Based on this, and the time period elapsed a mean annual rate has been calculated for each bolt site. Table 1 also contains the mean annual rate calculated by Kirk (1977) for each MEM site. On three bolt sites it was possible to obtain only two readings; this was because the surface elevation on the third position fell between combinations of extension probes. For example, at KM2E a 12.5 mm extension was not long enough to reach the surface, while a 25 mm extension was too long to allow any travel in the probe of the dial gauge. A total of 42 positions were measured. This is a significantly greater number than the 30 proposed by Mottershead (1989) for "representative" surface lowering to be calculated.

Table 1 illustrates that a wide variation occurred in average lowering rates between MEM sites. Minimum total erosion occurred at KMZB, a limestone platform, with the removal of 13.56 mm

Table 1
Results from the remeasurement of MEM bolt sites after approximately twenty years

Bolt site	Total erosion (mm)	Time period elapsed (years)	Mean annual rate (mm/yr)	Mean annual rate 1973–1975 (mm/yr)
KMZB[b]	13.56	20.61	0.66	0.38
KM1B	29.98	20.56	1.46	2.78
KM1C	34.91	20.42	1.71	0.59
KM2B	25.24	20.73	1.25	1.23
KM2C	51.87	20.54	2.53	1.10
KM2D[a]	25.39	19.94	1.27	1.41
KM2E[a]	19.37	19.02	1.02	2.98
KM3E	21.46	20.73	1.04	0.49
KM3F	38.89	20.19	1.93	0.98
KM4A[a,b]	32.29	20.98	1.54	1.01
KM5B	25.52	20.74	1.23	0.67
KM5C	25.50	20.74	1.23	0.35
KM5D	17.46	20.74	0.84	0.52
KM6C	43.37	20.55	2.11	1.21
KM6D	32.81	19.66	1.67	1.42

[a]Profiles from which only two readings could be obtained.
[b]Limestone platforms.

over 20.61 years giving an annual rate of erosion of 0.66 mm/yr. The greatest amount of erosion occurred at KM2C, a mudstone platform, where a total of 51.87 mm was removed over a period of 20.54 years, an annual rate of loss of 2.53 mm/yr. These rates compare with a minimum annual lowering rate from Kirk (1977) of 0.35 mm/yr and a maximum of 2.98 mm/yr, both these rates occurring on mudstone platforms. Thus, the longer term data show a 3.8 fold range of rates while the shorter term data show a range of 8.5 times.

Table 2 presents mean annual rates of erosion calculated from each bolt site for limestone and mudstone shore platforms as well as a grand mean.

Table 2
Mean annual erosion rates at Kaikoura from Kirk (1977) and 1994 calculated from individual MEM sites

Lithology	Mean erosion rate 1994 (mm/yr)	Mean erosion rate from Kirk (1977) (mm/yr)
Mudstone	1.48	1.63
Limestone	1.10	0.96
Grand Mean	1.43	1.53

Again these results are presented alongside rates calculated from data in Kirk (1977). For mudstone platforms an average annual rate of surface lowering of 1.48 mm/yr occurred over twenty years compared with 1.21 mm/yr for the two-year period from 1973 to 1975. On limestone platforms the longer term rate was 1.10 mm/yr compared with 0.69 mm/yr from the two-year record. Overall surface lowering combined for both lithologies was 1.43 mm/yr over the twenty-year period compared with 1.53 mm/yr between 1973 and 1975.

5. Discussion

A distinctive feature of the MEM data (Table 1) is a large degree of variability between bolt sites and between the same bolt site from the 1973 to 1975 period compared with the 1994 measurements. This reflects the large variability in erosive processes from bolt site to bolt site and between profiles around the Kaikoura Peninsula. Kirk (1977) showed how differences in rates of erosion varied across shore platform profiles. Unfortunately this cannot be examined for the longer period because of the number of bolt sites now missing from profiles. A number of significant differences in the morphodynamic environment also help to explain the variability in surface lowering rates. Such differences occur in exposure to wave energy, lithology and structure, and backshore deposits. Profiles KM3 and KM5 are backed by an eroding cliff and hill slope respectively, while the remaining profiles are being exhumed from beneath lagoon deposits or are backed by beach deposits. Such deposits supply materials that are used either as abrasive tools or provide a protective covering on the shore platform.

One simple test of the validity of extrapolating shorter term data into longer term average erosion rates is to compare predicted amounts of surface lowering obtained by extrapolating from the first two years of data with erosion actually measured over the longer period. This was the technique used by Viles and Trudgill (1984). Table 3 presents the results of this comparison. Extrapolated shorter term rates both over and under-predicted the total amount of surface lowering. Only one site, KM2B, provided a prediction in good agreement, with a 1.01% difference. For three bolt sites shorter term rates over-predicted the amount of longer term erosion by as much as 192%, while predictions for eleven sites were less than the actual erosion that occurred. Thus there is a clear trend for shorter term data to under-predict total surface lowering (Fig. 3). The trend to under-predict is somewhat different from the results of Viles and Trudgill (1984) who found a reasonable evenness.

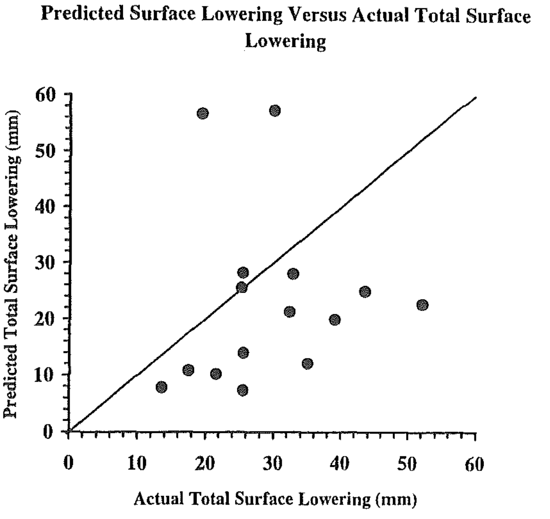

Fig. 3. Predicted surface lowering from 2 years data versus actual total surface lowering over 20 years on shore platforms on the Kaikoura Peninsula.

Table 3
Comparison of predicted surface lowering with measured actual surface lowering

Site	Rate from Kirk (1977) (mm/yr)	Time period (years)	Total predicted erosion (mm)	Actual erosion (mm)	Short term prediction to long term actual measurement (%)
KMZB	0.38	20.61	7.83	13.56	57.74
KM1B	2.78	20.56	57.15	29.98	190.59
KM1C	0.59	20.42	12.05	34.91	34.51
KM2B	1.23	20.73	25.50	25.24	101.01
KM2C	1.10	20.54	22.59	51.87	43.56
KM2D	1.41	19.94	28.11	25.39	110.72
KM2E	2.98	19.02	56.67	19.37	292.54
KM3E	0.49	20.73	10.16	21.46	47.34
KM3F	0.98	20.19	19.79	38.89	50.87
KM4A	1.01	20.98	21.18	32.29	65.61
KM5B	0.67	20.74	13.89	25.52	54.43
KM5C	0.35	20.74	7.26	25.50	28.46
KM5D	0.52	20.74	10.78	17.46	61.77
KM6C	1.21	20.55	24.87	43.37	57.34
KM6D	1.42	19.66	27.92	32.81	85.09

The large degree of variability between bolt sites has been smoothed by averaging data from Table 1 to produce mean annual rates in Table 2. This results in fair agreement between shorter and longer term mean annual rates, certainly to within an order of magnitude as found by Viles and Trudgill (1984). It is proposed that, (while surface lowering rates on shore platforms display a wide variance), it is indeed valid to extrapolate (to an order of magnitude level) mean annual rates of surface lowering calculated from shorter term data, at least to decadal time scales.

In order to further test the hypothesis that shorter term data from Kaikoura are representative of longer term lowering rates Student's t-test for paired data was performed using the data in Table 1. If both sets of data are shown to be derived from the same population then it can be argued that shorter term data are as statistically representative of surface lowering rates as longer term data so that shorter term data can be extrapolated with an acceptable degree of confidence. The results of Student's t-test are displayed in Table 4. The t-statistic is 1.256 with 14 degrees of freedom and t-critical (for a two-tail distribution) is 2.145 at 5% probability. We therefore accept the hypothesis that shorter term data are representative of longer term surface lowering rates on shore platforms at Kaikoura. This result also indicates that there has been no significant change in environmental conditions responsible for surface lowering on the Kaikoura Peninsula since 1973 (for example, no alteration related to sea level change is detectable), even though the longer term erosion rate is more rapid than the shorter term one derived from the earlier time.

Table 4
Student's t-test for paired data for mean annual rates of surface lowering for each bolt site

	1994	1974
Mean	1.431	1.141
Variance	0.247	0.630
Observations	15	15
df	14	
t Stat	1.256	
$P(T \leq t)$ two-tail	0.229	
t Critical two-tail	2.148	

Using the Kaikoura data, it is possible to test Mottershead's (1989) proposition that 30 individual positions are sufficient to calculate a mean annual lowering rate. Initially there was some doubt concerning this when applied to intertidal shore platforms as erosive processes are thought to be more varied temporally and spatially than on supratidal raised platforms where salt spray weathering dominates. To test Mottershead's (1989) conclusion 10 mean annual rates were selected at random from the Kaikoura data and subjected to the Student's t-test for paired data. Random selection proved difficult, but the method adopted here was to place a label for each bolt site in a hat and draw 5 labels. The ten remaining means were used. The number of individual readings were between 27 and 30 depending on whether or not one or more of the three bolt sites with only two readings taken on them were drawn. This was repeated arbitrarily 5 times. The results are presented in Table 5. In all cases the t-statistic was not significant at 5% probability, and we accepted that thirty individual readings are sufficient to represent surface lowering. None of the five tests were based on thirty individual positions, two were based on 29 readings, two on 27 and one on 28. Clearly mean annual rates of surface lowering on intertidal shore platforms (at Kaikoura anyway) can be calculated based on thirty individual MEM positions.

6. Conclusions

This paper has presented rates of surface lowering on intertidal shore platforms on the Kaikoura Peninsula calculated over a twenty-year period. This is the first occasion that erosion rates from the MEM technique have been calculated over a period this long. On mudstone shore platforms the average annual lowering rate was 1.48 mm/yr and on limestone platforms it was 1.10 mm/yr. The grand mean for both lithologies was 1.43 mm/yr. Lowering rates on individual MEM bolt sites ranged from a minimum of 0.66 mm/yr on a limestone platform to a maximum

Table 5
Student's t-test for randomly selected MEM site data

	Run 1	Run 2	Run 3	Run 4	Run 5
Mean 1994	1.466	1.437	1.608	1.257	1.418
Observations	10.000	10.000	10.000	10.000	10.000
Mean 1973–1975	1.288	1.207	1.105	0.961	1.131
Observations	10.000	10.000	10.000	10.000	10.000
df	9.000	9.000	9.000	9.000	9.000
t Stat	0.543	0.669	2.053	1.082	0.992
$P(T \langle = t)$ two-tail	0.600	0.520	0.070	0.307	0.347
t Critical two-tail	2.262	2.262	2.262	2.262	2.262

of 2.53 mm/yr on a mudstone platform. These results are in close agreement with Kirk (1977). The extrapolation of short term data by Kirk (1977) can therefore be accepted as valid at a decadal scale

The use of individual MEM site data for predicting even longer term erosion rates should not be attempted as it has been shown that individual shorter term data under-predict surface lowering when compared to actual longer term lowering rates. It is statistically valid to extrapolate mean data from a number of MEM sites, in this case 15 sites which yielded 42 individual readings. Thirty individual positions were sufficient to gain statistically significant mean annual lowering rates on the 0.77 km^2 of intertidal surface of the Kaikoura Peninsula. The area or length of coast for which the 30 readings are representative remains to be determined. Clearly this question can not be answered with the present data set. Establishment of MEM bolt sites requires careful consideration of the environment in which they are to be located in order to fully represent variation in process and morphology. This is particularly the case at Kaikoura where large variability occurs in the morphogenetic environment. The MEM is still the only method available for obtaining accurate surface lowering rates on shore platforms. The usefulness of the data yielded by this technique for shore platform research is steadily becoming more certain as the time periods it represents lengthen.

Acknowledgments

Work at Kaikoura has been supported by many people since 1973. The authors thank them all. The assistance of Peter Tyree and Jonathan Allan has been crucial. Financial support by University of Canterbury (Grant 1431973) and the Department of Geography is gratefully acknowledged. Thanks to Michelle Rogan University of Canterbury, Department of Geography, Cartographic Services for drafting Figs. 1 and 2. This work was carried out while based at the Edward Percival Marine Field Station, Kaikoura. The assistance of the station manager Mr. Jack van Berkel is gratefully acknowledged.

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APPENDIX TWO

A reprint of:

Stephenson, W.J. (1997). Improving the Traversing Micro-Erosion Meter. *Journal of Coastal Research.* **13**(1):236-241.

Journal of Coastal Research	13	1	236–241	Fort Lauderdale, Florida	Winter 1997

TECHNICAL COMMUNICATIONS

Improving the Traversing Micro-Erosion Meter

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ABSTRACT

STEPHENSON, W.J., 1997. Improving the traversing micro-erosion meter. *Journal of Coastal Research,* 13(1), 236–241. Fort Lauderdale (Florida), ISSN 0749-0208.

A traversing micro-erosion meter has been fitted with an electronic digital dial gauge so readings can be logged to a laptop computer. This facilitates rapid collection and analysis of data of erosion rates on shore platforms. Data analysis is enhanced by using 3-D plotting software to calculate volumes of material being eroded and to investigate processes of erosion.

INTRODUCTION

The micro-erosion meter was first described by HIGH and HANNA (1970) and used to measure relatively slow rates of lowering on rock surfaces caused by a variety of erosion processes. Subsequently, ROBINSON (1976), KIRK (1977), GILL and LANG (1983), VILES and TRUDGILL (1984), SPATE *et al.* (1985), and MOTTERSHEAD (1989) used the technique to investigate processes and rates of erosion on shore platforms. All these investigations utilised manual methods of data collection. This paper describes modifications that were made to allow data to be logged digitally to a laptop computer. This was done as part of an investigation of erosion rates on shore platforms around Kaikoura Peninsula, on the east coast of the South Island, New Zealand. The study utilises 42 micro-erosion meter measuring sites. The traversing micro-erosion meter currently in use allows 120 positions to be located per measuring site, so that 42 micro-erosion meter sites yield a total of 5,040 readings per survey. Manual recording of such a large data set was considered to be too time consuming. Analysis is being undertaken to calculate the volume of material being eroded from each micro-erosion meter site, to derive a mean erosion rate on shore platforms on the Kaikoura Peninsula and to provide an insight into processes of erosion acting on the shore platforms.

THE MICRO-EROSION METER

The micro-erosion meter (Figure 1) consists of an equilateral triangular base with legs located at each corner and an engineering dial gauge located on a central pillar. The spindle of the gauge extends through the base plate. Readings are taken by placing the base on three bolts permanently fixed into a rock surface. Exact relocation on the fixed bolts is obtained by using the Kelvin Clamp Principle. The end of each leg has been machined differently; one has a cone shaped depression, and the other a v-notch depression and the third is flat (HIGH and HANNA, 1970). Each leg end opposes movement in three, two and one direction respectively; thus, preventing movement of the plate when placed on a bolt site. In the original design, the engineering dial gauge was located off centre in the base plate so that three readings could be obtained by rotating the instrument on the bolts (HIGH and HANNA, 1970).

TRUDGILL *et al.* (1981) presented a modified version of the micro-erosion meter, the traversing micro-erosion meter. The traversing micro-erosion meter differs in that the dial gauge is independent of the base and is mounted with three arms separated at 120° intervals (Figure 2). The dial gauge can be moved to a number of different positions by locating each horizontal arm between ball bearings fixed along the sides of the base. The centre of the base plate is cut out to allow the dial gauge to be moved within the area defined by the permanent bolts. As long as each arm is at right angles to a side of the triangular base, a precise location is obtained each time the instrument is placed on a bolt site. The number of locations depends on the size of the base, the number of ball bearings fixed along each edge and on the size and configuration of the dial gauge and arms.

The sides of the base plate are labeled clockwise A, B, and C, and the spaces between ball bearings are numbered clockwise. At present an instrument of the traversing type being used at Kaikoura has 15 positions along each side (16 ball bearings). A labeled position at which a measurement is taken would be in the form A12, B4, C8. The first set of data

95060 received 3 May 1995; accepted in revision 14 July 1995.

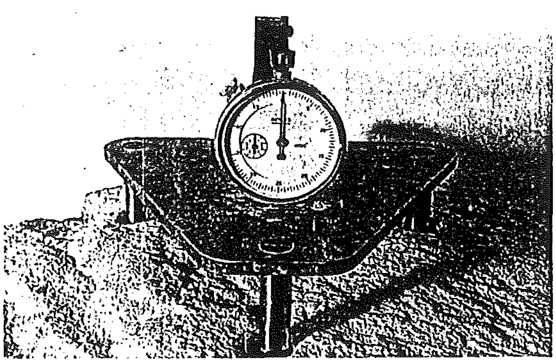

Figure 1. The micro-erosion meter.

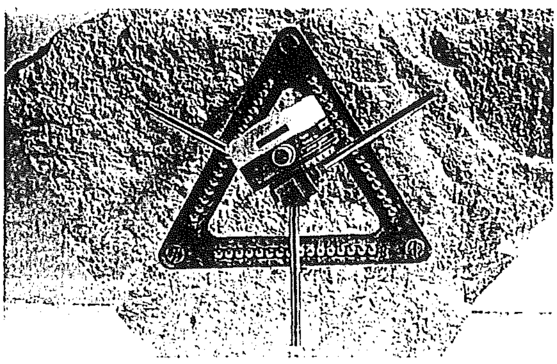

Figure 2. The traversing micro-erosion meter.

Table 1. *Example of a spread sheet template with micro-erosion meter site details, position labels and collected data.*

Profile KM1 Site No A Date 1/4/94

A Reference	Measure	B Reference	Measure	C Reference	Measure
A13/B3/C8	14.628	B13/C3/A8	13.917	C13/A3/B8	10.404
A12/B4/C8	15.108	B12/C4/A8	13.973	C12/A4/B8	8.931
A12/B5/C7	14.889	B12/C5/A7	14.137	C12/A5/B7	13.076
A11/B4/C9	14.658	B11/C4/A9	13.982	C11/A4/B9	8,525
A11/B5/C8	14.883	B11/C5/A8	13.920	C11/A5/B8	13.545
A11/B6/C7	15.231	B11/C6/A7	14.574	C11/B6/A7	14.855
A11/B7/C6	15.139	B11/C7/A6	14.643	C11/A7/B6	15.271
A10/B5/C9	14.730	B10/C5/A9	14.055	C10/A5/B9	13.059
A10/B6/C8	15.263	B10/C6/A8	14.528	C10/A6/B8	15.043
A10/B7/C7	15.557	B10/C7/A7	14.487	C10/A7/B7	15.249
A10/B8/C6	15.046	B10/C8/A6	15.084	C10/A8/B6	14.732
A10/B9/C5	14.979	B10/C9/A5	15.429	C10/A9/B5	14.965
A9/B5/C10	14.493	B9/C5/A10	13.913	C9/A5/B10	11.390
A9/B6/C9	14.909	B9/C6/A9	14.648	C9/A6/B9	15.018
A9/B7/C8	15.212	B9/C7/A8	14.687	C9/A7/B8	15.757
A9/B8/C7	15.355	B9/C8/A7	15.038	C9/A8/B7	15.060
A9/B9/C6	14.930	B9/C9/A6	15.069	C9/A9/B6	14.618
A9/B10/C5	15.269	B9/C10/A5	15.466	C9/A10/B5	14.643
A9/B11/C4	15.605	B9/C11/A4	15.309	C9/A11/B4	14.967
A8/B6/C10	14.499	B8/C6/A10	14.762	C8/A6/B10	13.719
A8/B7/C9	14.548	B8/C7/A9	15.453	C8/A7/B9	15.441
A8/B8/C8	14.284	B8/C8/A8	15.579	C8/A8/B8	15.350
A8/B9/C7	13.522	B8/C9/A7	15.191	C8/A9/B7	14.825
A8/B10/C6	13.828	B8/C10/A6	15.000	C8/A10/B6	14.150
A8/B11/C5	13.785	B8/C11/A5	15.172	C8/A11/B5	14.113
A8/B12/C4	13.570	B8/C12/A4	14.756	C8/A12/B4	14.656
A7/B6/C11	13.070	B7/C6/A11	14.921	C7/A6/B11	13.294
A7/B7/C10	12.816	B7/C7/A10	15.751	C7/A7/B10	14.895
A7/B8/C9	12.150	B7/C8/A9	15.979	C7/A8/B9	14.969
A7/B9/C8	10.749	B7/C9/A8	15.931	C7/A9/B8	14.751
A7/B10/C7	10.748	B7/C10/A7	15.122	C7/A10/B9	14.133
A7/B11/C6	11.019	B7/C11/A6	14.995	C7/A11/B6	13.903
A6/B7/C11	7.931	B6/C7/A11	14.722	C6/A7/B11	14.016
A6/B8/C10	9.442	B6/C8/A10	15.708	C6/A8/B10	14.568
A6/B9/C9	9.373	B6/C9/A9	15.918	C6/A9/B9	14.634
A6/B10/C8	9.286	B6/C10/A8	15.243	C6/A10/B8	14.147
A5/B7/C12	10.657	B5/C7/A12	12.180	C5/A7/B12	12.863
A5/B8/C11	11.465	B5/C8/A11	12.535	C5/A8/B11	13.993
A5/B9/C10	10.745	B5/C9/A10	13.976	C5/A9/B10	14.246
A4/B8/C12	11.607	B4/C8/A12	9.998	C4/A8/B12	12.791

is taken along the "A" side of the base. For this to occur the dial gauge faces the flat leg, or the leg labeled "A". The base plate is always located on a bolt site with leg "A" pointing seaward. In all, forty readings can be taken off each side of the base plate. This is achieved by keeping the arm, in the case of the "A" side of the base plate, in the same position and moving the other two arms away from the "A" side. Thus a series of readings off one position on the "A" side would be, A8/B6/C10; A8/B7/C9; A8/B8/C8; A8/B9/C7; A8/B10/C6; A8/B11/C5 and A8/B12/C4 (Table 1). The gauge is then rotated 120° so that the dial gauge faces the wedge shape leg (Leg B) and then the second set of data is taken off the B side, (for example B12, C4, A8). The third set of data is taken off the B side; the dial gauge is rotated to face the cone shaped leg (Leg C), and all readings are taken off the C side of the base (for example C12, A4, B8). It should be noted that the same sequence of numbers such as B12, C4, A8 and C12, A4, B8 does not represent the same position. This is because the spindle of the dial gauge is off centre from the junction of the three arms.

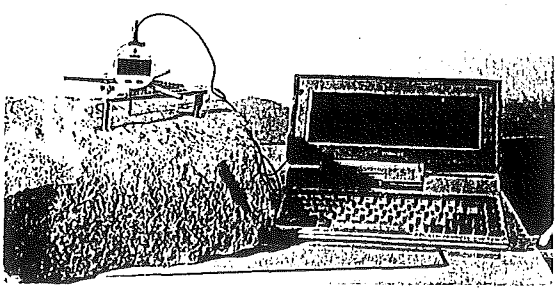

Figure 3. The traversing micro-erosion meter with digital gauge and laptop computer.

Table 2. *Results from successive readings from a micro-erosion meter site at Kaikoura. All readings are in millimeters.*

KM6A 28/12/93	04/04/94	Change	28/12/93	04/04/94	Change	28/12/93	04/04/94	Change
21.678	17.999	3.679	22.26	18.658	3.602	21.726	17.473	4.253
21.856	18.241	3.615	23.069	19.352	3.717	21.232	18.135	3.097
22.157	18.684	3.473	21.686	17.876	3.81	21.262	17.819	3.443
21.645	18.032	3.613	22.477	17.617	4.86	21.383	17.211	4.172
21.932	18.531	3.401	21.393	18.002	3.391	21.949	18.004	3.945
22.469	18.743	3.726	22.056	18.518	3.538	20.898	17.647	3.251
22.603	18.777	3.826	22.506	18.483	4.023	20.849	17.39	3.459
21.749	18.451	3.298	22.6	18.733	3.867	21.184	17.455	3.729
22.233	18.596	3.637	22.606	18.846	3.76	22.377	18.442	3.935
22.176	18.788	3.388	22.55	18.742	3.808	22.639	18.767	3.872
22.115	18.425	3.69	22.465	18.775	3.69	21.41	17.936	3.474
21.623	17.898	3.725	22.117	18.142	3.975	20.724	16.959	3.765
21.642	18.304	3.338	22.631	18.789	3.842	22.307	18.081	4.226
22.013	18.508	3.505	22.682	18.759	3.923	23.938	18.892	5.046
22.328	18.504	3.824	22.66	18.767	3.893	21.729	18.138	3.591
22.047	17.959	4.088	22.825	18.919	3.906	22.61	18.583	4.027
21.906	16.918	4.988	22.538	18.661	3.877	22.935	18.889	4.046
21.202	16.808	4.394	22.44	18.695	3.745	20.517	17.71	2.807
21.517	17.449	4.068	22.205	18.635	3.57	21.258	18.367	2.891
21.684	18.473	3.211	22.37	18.788	3.582	22.018	18.577	3.441
21.08	17.692	3.388	22.533	18.765	3.768	23.312	19.771	3.541
20.2	16.72	3.48	22.482	18.725	3.757	23.124	18.652	4.472
21.485	17.696	3.789	22.368	18.643	3.725	22.516	18.411	4.105
21.602	18.019	3.583	22.347	18.711	3.636	22.849	18.756	4.093
20.862	17.564	3.298	22.244	18.571	3.673	20.473	17.367	3.106
20.71	17.867	2.843	22.412	18.321	4.091	21.189	18.109	3.08
21.301	18.409	2.892	22.481	18.67	3.811	21.21	18.348	2.862
19.837	16.377	3.46	22.294	18.635	3.659	22.718	19.325	3.393
21.179	18.05	3.129	22.403	18.56	3.843	22.886	19.332	3.554
21.658	18.224	3.434	22.238	18.444	3.794	22.519	18.508	4.011
21.298	18.059	3.239	22.037	18.391	3.646	21.37	18.283	3.087
21.086	17.713	3.373	22.466	18.79	3.676	21.576	18.845	2.731
20.484	17.772	2.712	22.465	18.804	3.661	21.783	18.679	3.104
21.457	18.384	3.073	22.226	18.411	3.815	22.481	19.68	2.801
21.519	18.226	3.293	22.106	18.173	3.933	20.923	18.242	2.681
21.126	17.434	3.692	22.876	18.781	4.095	22.062	18.847	3.215
20.486	18.093	2.393	23.355	19.137	4.218	21.802	18.805	2.997
21.237	18.447	2.79	23.192	19.434	3.758	22.49	19.142	3.348
21.316	18.185	3.131	23.504	19.945	3.559	Mean Change		3.598
21.05	18.555	2.495	21.279	17.478	3.801	Minimum Change		2.393
22.236	18.599	3.637	20.942	17.707	3.235	Maximum Change		5.046

TRUDGILL *et al.* (1981) provided a system to check with each of the three arms on the dial gauge that a proper location has been obtained. The sum of the three positions of each arm in a label must (in the case of the instrument used at Kaikoura) be 24 (12 + 4 + 8 = 24). In the example of a traversing micro-erosion meter provided by TRUDGILL *et al.* (1981) which had six positions between ball bearings, the sum was 11. The sum of each position is thus dependent on the size of the traversing micro-erosion meter constructed. For the present study, a square was used to ensure that each arm was perpendicular to a side of the base plate before calculating the sum of the sides.

MODIFICATIONS TO THE TRAVERSING MICRO-EROSION METER

Previous published designs of the micro-erosion meter have used an analogue dial gauge which required the operator to read and physically record results. This is considered to be too restrictive given the time constraints of working on shore platforms in the inter tidal zone where large data sets are desired to improve knowledge of erosion. To overcome this, the micro-erosion meter currently in use was fitted with a digital dial gauge (Figure 3). Such gauges are readily available from suppliers of engineering tools. The gauge in use at Kaikoura is manufactured by SYLVAC, has a range of 25–0.001 mm or 1–0.0005″ and is accurate to 0.001 mm. The digital dial gauge is connected to a laptop computer via an optical RS 232 cable (Figure 3). Each reading is logged directly to a spreadsheet using software supplied with the gauge. At present, a spreadsheet template is used for each micro-erosion meter site. The spreadsheet contains labels for each position of the gauge, a site label and date (Table 1). When readings have been taken, the template is saved as the site location label.

As well as speed of use, there are a number of other advantages resulting from this modification. One source of error is removed from the technique in that the operator is no longer required to read an analogue face. This entails a degree

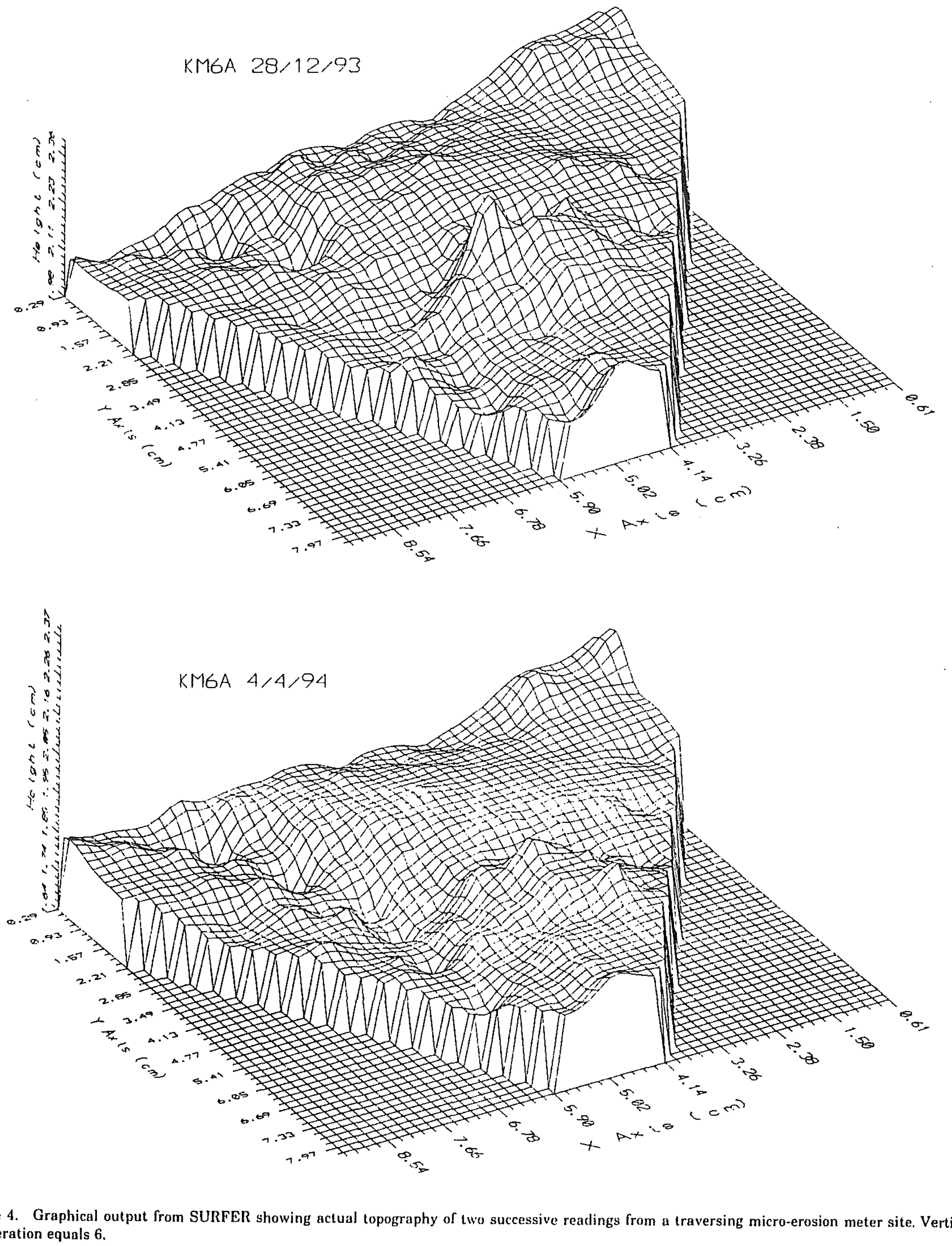

Figure 4. Graphical output from SURFER showing actual topography of two successive readings from a traversing micro-erosion meter site. Vertical exaggeration equals 6.

Table 3. *Surfer output of volume and surface area data.*

```
Volume computations
  Time of logging: Mon May 09 10:11:09 1994
Upper surface
    Grid File: C:\KM6A1.GRD
      Rows: 1 to 32767
      Cols: 1 to 32767
    Grid size as read: 50 cols by 50 rows
      Delta X: 0.176115
      Delta Y: 0.159944
      X-Range: 0.614978 to 9.24462
      Y-Range: 0.288978 to 8.12623
      Z-Range: 1.9848 to 2.37474
Lower surface
    Grid File: C:\KM6A2.GRD
      Rows: 1 to 32767
      Cols: 1 to 32767
    Grid size as read: 50 cols by 50 rows
      Delta X: 0.176115
      Delta Y: 0.159944
      X-Range: 0.614978 to 9.24462
      Y-Range: 0.288978 to 8.12623
      Z-Range: 1.63907 to 1.99396
Volumes
  Approximated Volume by
    Trapezoidal Rule: 16.6361
    Simpson's Rule: 16.6383
    Simpson's 3/8 Rule: 16.6457
Surface computations
  Time of logging: Tue May 10 11:37:08 1994
    Grid file: C:\KM6A1.GRD
      Rows: 1 to 32767
      Cols: 1 to 32767
    Grid size as read: 50 cols by 50 rows
      Delta X: 0.176115
      Delta Y: 0.159944
      X-Range: 0.614978 to 9.24462
      Y-Range: 0.288978 to 8.12623
      Z-Range: 1.9848 to 2.37474
    Constant Level: 0
      Log file: MEM2D.LOG
  Computed surface area above level: 45.7254
  Computed surface area below level: 0
Surface area computations
  Time of logging: Tue May 10 11:37:24 1994
    Grid file: C:\KM6A2.GRD
      Rows: 1 to 32767
      Cols: 1 to 32767
    Grid size as read: 50 cols by 50 rows
      Delta X: 0.176115
      Delta Y: 0.159944
      X-Range: 0.614978 to 9.24462
      Y-Range: 0.288978 to 8.12623
      Z-Range: 1.63907 to 1.99396
    Constant Level: 0
      Log file: MEM3D.LOG
  Computed surface area above level: 45.6836
  Computed surface area below level: 0
```

of interpretation in reading to three decimal places. Reading errors may be larger if more than one operator is involved in collecting data. It is also possible to obtain results immediately in the field by setting up a spreadsheet with the last set of data collected and logging the new set alongside the last set collected. Repeated readings at each label position provides a check on the integrity of the data. This also helps to ensure that the dial gauge is positioned correctly. Positioning is important as the operator has to handle the dial gauge during readings in order to log the result to the laptop computer.

ANALYSIS OF DATA

The collected data already in a spreadsheet, calculating statistics such as the mean erosion rate for a bolt site and all bolt sites, becomes instant by adding the appropriate equation into the spreadsheet. TRUDGILL *et al.* (1981) indicated that data obtained from the traversing micro-erosion meter provide an opportunity to examine the micro relief of a micro-erosion meter site and provide a means of identifying erosion processes. How well this can be done clearly depends on the spatial and temporal sampling densities achievable in the field.

To examine how the surface of a site erodes, the data are displayed as successive 3-D surface plots using a plotting program. The software used is SURFER, from Golden Software, Colorado, USA. The detailed use of SURFER to represent coral reefs was presented by ISDALE (1991). The input variables for this program are x, y, and z co-ordinates. Co-ordinates x and y represent positions of the dial gauge in the horizontal plane. The z axis is the vertical reading given by the gauge which is in reference to the position of the probe when it is at zero, or at rest. Recorded results can be plotted directly into SURFER giving a graphical representation of bolt site surface. Within SURFER, vertical exaggeration can be applied and is often necessary to emphasis detail on "smooth" surfaces.

SURFER allows the volume of a plot to be calculated and also the difference in volume between successive plots. SURFER utilises three methods for calculating volumes and each generates slightly different results. These methods are discussed in the accompanying manual. It is therefore possible to calculate the volume of material eroded from each bolt site, which may provide an insight into the contribution of shore platforms to local sediment budgets around the Kaikoura Peninsula. It is also possible to overlay successive plots and visually interpret changes in a surface over time. This can also be investigated by using SURFER to calculate surface areas of bolt sites. High or low surface areas may give an indication of the morphology of a surface as well as changes in morphology. Marked changes in surface areas may indicate changes in the type of erosion at a bolt site. The geomorphic significance of these types of analyses is at present under consideration.

AN EXAMPLE WITH DATA FROM KAIKOURA

Table 2 presents the results of two successive micro-erosion meter readings from a site located on a rapidly eroding Mudstone shore platform at Kaikoura. The results show the net erosion at each position over 97 days. The mean rate of erosion for the site was 3.598 mm the minimum 2.393 mm and the maximum 5.046 mm. Figure 4 show the surfaces plotted from both sets of data. Table 3 is an example of the output of SURFER and provides the net change in volume between the two plots and respective surface areas. It can be seen that the net erosion of material was 16.6 cm^3. The surface areas were 45.72 cm^2 and 45.68 cm^2, respectively.

CONCLUSIONS

The modifications to the traversing micro-erosion meter described allow rapid collection and analysis of data. This is particularly useful when a large data set is being collected, such as that being generated at Kaikoura, and previous studies have been hampered by low spatial and temporal erosion data sampling rates. Data in digital form provides access to many new forms of manipulation and visualisation. Analysis of erosion data using SURFER provides one new set of insights into erosion rates and processes on shore platforms. The developments reported here help to overcome a scarcity of quantitative data in shore platforms studies generally. The use of the traversing micro-erosion meter is not limited to shore platforms; the analysis described here can be applied in many different environments.

ACKNOWLEDGEMENTS

Purchase of the digital dial gauge and software was made possible by R.M. Kirk through University of Canterbury Research Grant 1431973 and Department of Geography, University of Canterbury funding. Appreciation is extended to R.M. Kirk and A.P. Sturman for commenting on early drafts. Thanks to Peter Tyree, Geomorphological Laboratories, Department of Geography, University of Canterbury for constructing a second traversing micro-erosion meter and helping to install bolt sites at Kaikoura. Thanks also to Jonathan Allan for help in the field.

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APPENDIX THREE

G.P.S locations of micro-erosion meter bolt sites on the Kaikoura Peninsula. Included are the designations for bolt sites from Kirk (1977).

MEM Bolt Site	Latitude and Longitude	NZMS 260 Map Series
KMZA Unused	42°24'59.093"S, 173°41'52.470"E	5865608.40,2567457.50
KMZB Unused	42°24'57.338"S, 173°41'50.618"E,	5865662.89,2567415.61
KM1A	42°25'04.962"S, 173°42'27.131"E	5865420.88,2568248.50
KM1B	42°25'05.091"S, 173°42'28.068"E	5865416.73,2568269.89
KM1C (KM1B Kirk 1977)	42°25'04.769"S, 173°42'28.324"E	5865426.62,2568275.84
KM1D	42°25'04.318"S, 173°42'29.532"E	5865440.31,2568303.55
KM1E (KM1C Kirk 1977)	42°25'03.766"S, 173°42'29.774"E	5865457.30,2568309.23
KM1F	42°25'02.727"S, 173°42'30.786"E	5865489.17,2568332.63
KM1G	42°25'02.498"S, 173°42'31.309"E	5865496.12,2568344.65
KM2A	42°25'23.908"S, 173°42'44.709"E	5864832.99,2568645.58
KM2B	42°25'23.574"S, 173°42'44.685"E	5864843.32,2568645.11
KM2C (KM2B Kirk 1977)	42°25'23.010"S, 173°42'44.701"E	5864860.71,2568645.63
KM2D	42°25'22.658"S, 173°42'44.755"E	5864871.56,2568646.94
KM2E (KM1C Kirk 1977)	42°25'22.270"S, 173°42'44.780"E	5864883.53,2568647.62
KM2F	42°25'22.054"S, 173°42'44.858"E	5864890.17,2568649.46
KM2G (KM1D Kirk 1977)	42°25'21.694"S, 173°42'44.874"E	5864901.27,2568649.92
KM2H	42°25'21.430"S, 173°42'44.837"E	5864909.43,2568649.13
KM2I (KM2E Kirk 1977)	42°25'21.126"S, 173°42'44.802"E	5864918.82,2568648.40
KM2J	42°25'21.126"S, 173°42'44.802"E	5864918.82,2568648.40
KM3A	42°25'33.123"S, 173°42'58.784"E	5864546.00,2568965.01
KM3B	42°25'33.194"S, 173°42'58.917"E	5864543.79,2568968.01
KM3C	42°25'33.427"S, 173°42'59.207"E	5864536.57,2568974.59
KM3D	42°25'33.565"S, 173°42'59.432"E	5864532.26,2568979.70
KM3E (KM3D Kirk 1977)	42°25'33.708"S, 173°42'59.652"E	5864527.79,2568984.7
KM3F	42°25'34.053"S, 173°43'00.099"E	5864517.07,2568994.83
KM3G (KM3E Kirk 1977)	42°25'34.166"S, 173°43'00.293"E	5864513.55,2568999.22

KM3H (KM3F Kirk 1977)	42°25'34.390"S, 173°43'00.620"E	5864506.56,2569006.64
KM3I	42°25'34.529"S, 173°43'00.832"E	5864502.25,2569011.45
KM3J	42°25'34.813"S, 173°43'01.368"E	5864493.38,2569023.63
KM4A (KM4A Kirk 1977)	42°26'03.812"S, 173°41'40.306"E	5863613.68,2567163.40
KM4B	42°26'04.125"S, 173°41'40.398"E	5863604.01,2567165.42
KM4C	42°26'04.328"S, 173°41'40.428"E	5863597.75,2567166.07
KM4D	42°26'04.387"S, 173°41'40.461"E	5863595.92,2567166.80,
KM4E	42°26'04.609"S, 173°41'40.530"E	5863589.05,2567168.32,
KM4F	42°26'04.991"S, 173°41'40.601"E	5863577.25,2567169.84,
KM4G	42°26'05.302"S, 173°41'40.737"E	5863567.65,2567172.88
KM5A	42°26'06.892"S, 173°41'27.570"E	5863520.98,2566871.53,
KM5B (KM5B Kirk 1977)	42°26'06.856"S, 173°41'26.953"E	5863522.21,2566857.45
KM5C	42°26'06.860"S, 173°41'26.476"E	5863522.17,2566846.55
KM5D (KM5C Kirk 1977)	42°26'06.887"S, 173°41'25.915"E	5863521.43,2566833.70
KM5E (KM5D Kirk 1977)	42°26'06.841"S, 173°41'25.604"E	5863522.91,2566826.61
KM5F	42°26'06.917"S, 173°41'25.339"E	5863520.62,2566820.55
KM5G	42°26'06.876"S, 173°41'24.986"E	5863521.96,2566812.49
KM6A	42°25'45.008"S, 173°41'31.308"E	5864195.55, 2566962.38
KM6B	42°25'45.606"S, 173°41'30.253"E	5864177.28, 2566938.11
KM6C (KM6C Kirk 1977)	42°25'45.943"S, 173°41'29.563"E	5864167.01, 2566922.25
KM6D	42°25'46.294"S, 173°41'28.915"E	5864156.29, 2566907.35
KM6E (KM6D Kirk 1977)	42°25'46.633"S, 173°41'28.210"E	5864145.97, 2566891.15
KM6F	42°25'47.043"S, 173°41'27.449"E	5864133.46, 2566873.66
KM6G	42°25'47.340"S, 173°41'26.907"E	5864124.40, 2566861.19
KM7A	42°25'54.995"S, 173°42'16.731"E	5863879.04,2567998.19
KM7B	42°25'53.601"S, 173°42'15.863"E	5863922.19,2567978.69
KM7C	42°25'55.448"S, 173°42'16.224"E	5863865.13,2567986.48
KM7D	42°25'55.965"S, 173°42'16.760"E	5863849.08,2567998.60
KM7E	42°25'54.955"S, 173°42'15.178"E	5863880.54,2567962.69
KM7F	42°25'55.360"S, 173°42'16.005"E	5863867.91,2567981.49
KM7G	42°25'56.691"S, 173°42'18.355"E	5863826.38,2568034.88
KM7H	42°25'57.250"S, 173°42'18.709"E	5863809.08,2568042.82

APPENDIX FOUR

GPS Locations of erosion frame bolt sites.

Bolt Site	Latitude and Longitude	NZMS 260 Map Series
	Adjacent to KM3	
KB1A	42°25'33.432"S, 173°42'58.373"E	5864536.55,2568955.52
KB1B	42°25'34.231"S, 173°42'59.654"E	5864511.65,2568984.59
KB1C	42°25'34.890"S, 173°43'00.392"E	5864491.19,2569001.30
	Adjacent to KM7	
KB2A	42°25'54.995"S, 173°42'16.731"E	5863879.04,2567998.19
KB2B	42°25'55.566"S, 173°42'16.078"	5863861.53,2567983.11
KB2C	42°25'56.768"S, 173°42'17.001"E	5863824.28,2568003.90
	Adjacent to KM4	
KB3A	42°26'04.108"S, 173°41'40.491"E	5863604.52,2567167.55
KB3B	42°26'04.630"S, 173°41'40.370"E	5863588.44,2567164.66
KB3C	42°26'05.302"S, 173°41'40.737"E	5863567.65,2567172.88
	Adjacent to KM5	
KB4A	42°26'06.892"S, 173°41'27.570"E	5863520.98,2566871.53
KB4B	42°26'06.717"S, 173°41'26.477"E	5863526.58,2566846.61
KB4C	42°26'06.797"S, 173°41'25.378"E	5863524.30,2566821.46
	Adjacent to KM6	
KB5A	42°25'45.253"S, 173°41'31.339"E	5864187.99,2566963.02
KB5B	Could not be found during GPS exercise	because of algae.
KB5C	42°25'47.043"S, 173°41'27.449"E	5864133.46, 2566873.66

APPENDIX FIVE

Wave data statistics resulting from the deployment of the S4 on the 21 June 1996 on KM2.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/21/96	19:04	0.2	0.2	0.3	8	8.7	6.6	8.4	0.58
06/21/96	19:13	0.2	0.2	0.3	8.9	9.7	7.1	9.3	0.61
06/21/96	19:21	0.2	0.2	0.4	8.1	8.7	6.7	8.4	0.57
06/21/96	19:30	0.2	0.3	0.4	7.7	8.2	6.6	7.9	0.52
06/21/96	19:38	0.2	0.3	0.4	7.6	8.1	6.4	7.9	0.53
06/21/96	19:47	0.2	0.3	0.4	7.7	8.2	6.5	7.9	0.53
06/21/96	19:55	0.2	0.3	0.4	7.8	8.3	6.7	8.1	0.52
06/21/96	20:04	0.2	0.3	0.4	7.6	8.1	6.5	7.9	0.53
06/21/96	20:12	0.2	0.3	0.4	8	8.6	6.7	8.3	0.55
06/21/96	20:21	0.2	0.3	0.4	7.6	8.1	6.6	7.9	0.51
06/21/96	20:29	0.2	0.3	0.4	7.8	8.4	6.5	8.1	0.56
06/21/96	20:38	0.2	0.3	0.4	7.6	8	6.6	7.8	0.49
06/21/96	20:47	0.2	0.3	0.4	7.4	7.7	6.5	7.6	0.47
06/21/96	20:55	0.2	0.3	0.4	8.1	8.7	6.8	8.4	0.56
06/21/96	21:04	0.2	0.3	0.5	7.5	7.9	6.4	7.7	0.52
06/21/96	21:12	0.2	0.3	0.4	7.4	7.8	6.5	7.6	0.49
06/21/96	21:21	0.2	0.3	0.4	7.8	8.2	6.7	8	0.52
06/21/96	21:29	0.2	0.3	0.4	7.7	8.2	6.4	7.9	0.54
06/21/96	21:38	0.2	0.3	0.4	8.3	8.9	6.9	8.6	0.57
06/21/96	21:46	0.2	0.3	0.4	8	8.5	6.8	8.2	0.52
06/21/96	21:55	0.2	0.3	0.4	7.9	8.5	6.6	8.2	0.54
06/21/96	22:03	0.1	0.2	0.3	7.7	8.3	6.5	8	0.54
06/21/96	22:12	0.2	0.3	0.4	8	8.6	6.7	8.3	0.55
06/21/96	22:20	0.2	0.2	0.4	7.9	8.4	6.7	8.2	0.53
06/21/96	22:29	0.2	0.2	0.3	8.9	9.7	7	9.3	0.62
06/21/96	22:37	0.1	0.2	0.3	8.5	9	7.1	8.7	0.55
06/21/96	22:46	0.1	0.2	0.3	8.5	9.2	7	8.9	0.58
06/21/96	22:55	0.1	0.2	0.3	8.2	8.8	6.9	8.5	0.54
Minimum		0.1	0.2	0.3	7.4	7.7	6.4	7.6	0.47
Maximum		0.2	0.3	0.5	8.9	9.7	7.1	9.3	0.62
Mean		0.2	0.3	0.4	7.9	8.5	6.7	8.2	0.54

Wave data statistics resulting from the deployment of the S4 on the 22 (AM) June 1996 on KM2.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/22/96	07:35	0.1	0.2	0.3	8.2	8.9	6.8	8.6	0.57
06/22/96	07:44	0.1	0.2	0.3	8.3	8.8	7.0	8.5	0.54
06/22/96	07:52	0.1	0.2	0.3	8.4	9.2	6.9	8.8	0.58
06/22/96	08:01	0.1	0.2	0.3	7.7	8.1	6.9	7.9	0.46
06/22/96	08:09	0.1	0.2	0.3	7.6	8	6.8	7.8	0.45
06/22/96	08:18	0.1	0.2	0.3	7.9	8.3	7.0	8.1	0.47
06/22/96	08:26	0.1	0.2	0.3	7.5	7.9	6.7	7.7	0.45
06/22/96	08:35	0.1	0.2	0.3	8.2	8.8	6.8	8.5	0.55
06/22/96	08:43	0.1	0.2	0.3	8.6	9.2	7.1	8.9	0.57
06/22/96	08:52	0.2	0.3	0.4	8.2	8.7	6.9	8.4	0.53
06/22/96	09:00	0.1	0.2	0.3	8.1	8.7	6.9	8.4	0.53
06/22/96	09:09	0.2	0.3	0.4	8	8.6	6.7	8.3	0.54
06/22/96	09:17	0.2	0.3	0.4	7.8	8.3	6.9	8.1	0.49
06/22/96	09:26	0.2	0.2	0.3	8.2	8.9	6.6	8.6	0.59
06/22/96	09:35	0.1	0.2	0.3	7.8	8.2	6.7	8.0	0.52
06/22/96	09:43	0.2	0.3	0.4	7.5	7.9	6.7	7.7	0.46
06/22/96	09:52	0.2	0.2	0.3	7.8	8.2	6.7	8.0	0.51
06/22/96	10:00	0.2	0.2	0.4	8.3	8.9	6.9	8.6	0.56
06/22/96	10:09	0.1	0.2	0.3	8.5	9.1	6.9	8.8	0.58
06/22/96	10:17	0.1	0.2	0.3	8.1	8.6	6.8	8.3	0.54
06/22/96	10:26	0.1	0.2	0.3	8.4	9.0	7.0	8.7	0.55
06/22/96	10:34	0.1	0.2	0.3	8.1	8.7	6.8	8.4	0.55
06/22/96	10:43	0.1	0.2	0.3	8.3	8.9	6.9	8.6	0.56
06/22/96	10:51	0.1	0.2	0.3	8.3	8.9	7.0	8.6	0.55
06/22/96	10:59	0.1	0.2	0.2	8.4	9.2	6.8	8.8	0.58
06/22/96	11:08	0.1	0.2	0.2	8	8.5	6.9	8.3	0.51
06/22/96	11:17	0.1	0.2	0.2	8.3	9	6.9	8.7	0.57
06/22/96	11:25	0.1	0.2	0.2	8.1	8.7	6.8	8.4	0.54
Minimum		0.1	0.2	0.2	7.5	7.9	6.6	7.7	0.45
Maximum		0.2	0.3	0.4	8.6	9.2	7.1	8.9	0.59
Mean		0.1	0.2	0.3	8.1	8.7	6.9	8.4	0.53

Wave data statistics resulting from the deployment of the S4 on the 23 and 24 June 1996 on KM2.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/23/96	20:34	0.2	0.3	0.4	9.2	10.3	6.8	9.7	0.67
06/23/96	20:43	0.2	0.3	0.5	8.9	10	6.7	9.4	0.66
06/23/96	20:51	0.2	0.3	0.5	9.6	10.9	7.0	10.2	0.69
06/23/96	0.875	0.2	0.3	0.4	9.2	10.4	6.8	9.8	0.67
06/23/96	21:08	0.2	0.3	0.5	8.6	9.6	6.5	9.1	0.66
06/23/96	21:17	0.2	0.3	0.5	8.8	9.8	6.8	9.3	0.64
06/23/96	21:25	0.2	0.4	0.5	8.6	9.8	6.5	9.2	0.66
06/23/96	21:34	0.2	0.3	0.5	8.7	9.8	6.5	9.2	0.67
06/23/96	21:42	0.2	0.4	0.5	9.3	10.6	6.6	9.9	0.71
06/23/96	21:51	0.2	0.3	0.5	8.3	9.2	6.5	8.7	0.62
06/23/96	21:59	0.2	0.4	0.5	9.1	10.3	6.8	9.7	0.66
06/23/96	22:08	0.2	0.4	0.5	8.6	9.7	6.4	9.1	0.67
06/23/96	22:17	0.2	0.3	0.5	8.4	9.5	6.4	8.9	0.64
06/23/96	22:25	0.2	0.3	0.5	8.8	9.8	6.7	9.3	0.64
06/23/96	22:34	0.2	0.4	0.6	8.9	10.1	6.7	9.5	0.67
06/23/96	22:42	0.3	0.4	0.6	10.2	11.6	7.3	10.9	0.7
06/23/96	22:51	0.2	0.4	0.5	9.2	10.3	6.9	9.7	0.66
06/23/96	22:59	0.2	0.4	0.6	8.6	9.6	6.6	9.0	0.64
06/23/96	23:08	0.2	0.4	0.5	9.7	11	7.0	10.3	0.69
06/23/96	23:16	0.2	0.4	0.5	8.8	9.7	7.0	9.2	0.61
06/23/96	23:25	0.2	0.4	0.5	9.9	11.6	6.8	10.7	0.73
06/23/96	23:33	0.2	0.3	0.5	8.7	9.7	6.6	9.2	0.65
06/23/96	23:42	0.2	0.3	0.5	10.3	12	7.0	11.1	0.73
06/23/96	23:50	0.2	0.3	0.4	9.3	10.6	6.7	9.9	0.69
06/23/96	23:59	0.2	0.3	0.4	9.3	10.7	6.7	10.0	0.7
06/24/96	00:07	0.2	0.3	0.4	9.4	10.5	7.1	9.9	0.66
06/24/96	00:16	0.1	0.2	0.3	9.3	10.5	6.9	9.9	0.67
06/24/96	00:25	0.1	0.2	0.3	10.1	11.5	7.1	10.7	0.7
Minimum		0.1	0.2	0.3	8.3	9.2	6.4	10.7	0.61
Maximum		0.3	0.4	0.6	10.3	12.0	7.3	8.7	0.73
Mean		0.2	0.3	0.5	9.1	10.3	6.8	9.7	0.67

Wave data statistics resulting from the deployment of the S4 on 24 June 1996 on KM2.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/24/96	09:05	0.1	0.2	0.3	9.6	11.1	6.8	10.3	0.70
06/24/96	09:14	0.2	0.3	0.4	9.2	10.4	6.7	9.8	0.68
06/24/96	09:22	0.2	0.3	0.4	10.0	11.7	6.8	10.8	0.73
06/24/96	09:31	0.2	0.3	0.4	9.7	11.3	6.7	10.5	0.72
06/24/96	09:39	0.2	0.3	0.5	9.5	11.2	6.6	10.3	0.72
06/24/96	09:48	0.2	0.3	0.4	8.6	9.5	6.6	9.0	0.63
06/24/96	09:56	0.2	0.3	0.5	10.0	11.6	7.0	10.8	0.72
06/24/96	10:05	0.2	0.3	0.4	8.8	10.0	6.5	9.3	0.67
06/24/96	10:13	0.2	0.3	0.4	9.4	10.7	6.8	10.0	0.70
06/24/96	10:22	0.2	0.2	0.4	9.2	10.5	6.6	9.8	0.70
06/24/96	10:30	0.1	0.2	0.3	9.2	10.4	6.7	9.7	0.68
06/24/96	10:39	0.1	0.2	0.3	8.8	9.9	6.6	9.3	0.67
06/24/96	10:47	0.1	0.2	0.3	9.5	10.8	6.9	10.1	0.68
06/24/96	10:56	0.1	0.2	0.3	10.0	11.6	7.1	10.7	0.70
06/24/96	11:05	0.2	0.2	0.3	9.8	11.6	6.7	10.7	0.73
06/24/96	11:13	0.2	0.3	0.4	9.3	10.7	6.7	10.0	0.69
06/24/96	11:22	0.1	0.2	0.3	9.1	10.3	6.7	9.7	0.68
06/24/96	11:30	0.2	0.3	0.4	10.5	12.8	6.7	11.5	0.77
06/24/96	11:39	0.1	0.2	0.3	9.6	11.0	6.8	10.3	0.70
06/24/96	11:47	0.2	0.3	0.4	10.4	12.6	6.7	11.3	0.76
06/24/96	11:56	0.1	0.2	0.3	10.2	11.7	7.0	10.9	0.73
06/24/96	12:04	0.1	0.2	0.3	9.7	11.2	6.7	10.4	0.72
06/24/96	12:13	0.1	0.2	0.3	10.8	12.6	7.3	11.6	0.73
06/24/96	12:21	0.1	0.2	0.3	9.7	11.4	6.7	10.5	0.72
06/24/96	12:30	0.1	0.2	0.3	10.5	12.4	7.1	11.4	0.74
06/24/96	12:38	0.1	0.2	0.3	11.1	13.2	7.3	12.0	0.76
06/24/96	12:47	0.1	0.2	0.2	10.7	12.4	7.1	11.4	0.75
06/24/96	12:55	0.1	0.1	0.2	10.1	11.6	6.9	10.8	0.73
Minimum		0.1	0.1	0.2	8.6	9.5	6.5	9.0	0.63
Maximum		0.2	0.3	0.5	11.1	13.2	7.3	12.0	0.77
Mean		0.1	0.2	0.3	9.8	11.3	6.8	10.5	0.71

Wave data statistics resulting from the deployment of the S4 on 24 (pm) and 25 June 1996 on KM2.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/24/96	21:51	0.2	0.4	0.5	8.9	10.1	6.6	9.5	0.68
06/24/96	21:59	0.2	0.4	0.5	9.6	10.7	7.1	10.1	0.67
06/24/96	22:08	0.2	0.4	0.5	9.1	10.3	6.9	9.7	0.66
06/24/96	22:16	0.2	0.3	0.5	9.7	11.0	7.1	10.3	0.69
06/24/96	22:25	0.2	0.4	0.5	9.1	10.1	7.0	9.6	0.65
06/24/96	22:34	0.2	0.4	0.6	9.1	10.3	6.8	9.6	0.67
06/24/96	22:42	0.2	0.4	0.5	7.7	8.3	6.3	8.0	0.58
06/24/96	22:51	0.2	0.4	0.5	8.9	9.8	6.9	9.4	0.63
06/24/96	22:59	0.3	0.4	0.6	8.7	9.7	6.7	9.2	0.65
06/24/96	23:08	0.2	0.3	0.5	8.5	9.4	6.6	8.9	0.62
06/24/96	23:16	0.2	0.4	0.5	8.4	9.4	6.5	8.9	0.64
06/24/96	23:25	0.2	0.3	0.5	8.0	8.8	6.3	8.4	0.61
06/24/96	23:33	0.2	0.4	0.5	8.6	9.5	6.7	9.1	0.63
06/24/96	23:42	0.2	0.4	0.6	8.7	9.7	6.7	9.2	0.64
06/24/96	23:50	0.2	0.4	0.5	8.7	9.5	6.8	9.1	0.62
06/24/96	23:59	0.2	0.3	0.5	8.3	9.0	6.5	8.6	0.61
06/25/96	00:07	0.2	0.4	0.5	8.5	9.2	6.8	8.9	0.60
06/25/96	00:16	0.2	0.4	0.5	9.0	9.9	7.0	9.4	0.63
06/25/96	00:24	0.2	0.3	0.5	8.5	9.4	6.5	8.9	0.64
06/25/96	00:33	0.2	0.3	0.4	9.0	9.9	7.0	9.5	0.63
06/25/96	00:42	0.2	0.3	0.4	9.4	10.6	6.9	9.9	0.68
06/25/96	00:50	0.2	0.3	0.5	8.6	9.6	6.6	9.1	0.64
06/25/96	00:59	0.2	0.3	0.4	9.1	10.3	6.6	9.6	0.68
06/25/96	01:07	0.2	0.3	0.4	10.0	11.2	7.2	10.6	0.69
06/25/96	01:16	0.2	0.3	0.4	9.3	10.5	6.9	9.9	0.67
06/25/96	01:24	0.2	0.3	0.4	9.6	10.7	7.2	10.1	0.67
06/25/96	01:33	0.2	0.3	0.4	9.8	11.5	6.8	10.6	0.73
06/25/96	01:41	0.2	0.3	0.4	10.6	11.8	7.5	11.2	0.71
Minimum		0.2	0.3	0.4	7.7	8.3	6.3	8.0	0.58
Maximum		0.3	0.4	0.6	10.6	11.8	7.5	11.2	0.73
Mean		0.2	0.4	0.5	9.0	10.0	6.8	9.5	0.65

Wave data statistics resulting from the deployment of the S4 on 25 June 1996 on KM2.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/25/96	10:13	0.2	0.3	0.5	8.4	9.3	6.6	8.8	0.61
06/25/96	10:22	0.2	0.4	0.5	8.1	9.0	6.5	8.5	0.60
06/25/96	10:30	0.2	0.4	0.5	8.7	9.6	6.9	9.2	0.62
06/25/96	10:39	0.2	0.4	0.5	8.6	9.6	6.6	9.1	0.64
06/25/96	10:47	0.2	0.4	0.5	8.5	9.4	6.7	9.0	0.63
06/25/96	10:56	0.2	0.4	0.5	8.2	9.2	6.4	8.7	0.63
06/25/96	11:04	0.2	0.3	0.5	8.5	9.5	6.6	9.0	0.63
06/25/96	11:13	0.2	0.4	0.5	9.0	10.2	6.6	9.6	0.68
06/25/96	11:22	0.2	0.4	0.5	8.7	9.5	6.7	9.1	0.63
06/25/96	11:30	0.2	0.3	0.5	8.0	8.8	6.5	8.4	0.58
06/25/96	11:39	0.2	0.3	0.5	8.3	9.1	6.6	8.7	0.60
06/25/96	11:47	0.2	0.3	0.5	8.0	8.7	6.4	8.4	0.60
06/25/96	11:56	0.2	0.4	0.5	8.6	9.6	6.5	9.1	0.65
06/25/96	12:04	0.2	0.4	0.5	8.2	8.9	6.6	8.5	0.60
06/25/96	12:13	0.2	0.4	0.5	8.0	8.9	6.3	8.5	0.61
06/25/96	12:21	0.2	0.4	0.5	8.5	9.6	6.5	9.0	0.64
06/25/96	12:30	0.2	0.3	0.5	7.9	8.7	6.4	8.3	0.60
06/25/96	12:38	0.2	0.4	0.5	8.7	9.7	6.6	9.2	0.65
06/25/96	12:47	0.2	0.3	0.5	9.2	10.3	6.9	9.7	0.66
06/25/96	12:55	0.2	0.3	0.5	9.1	10.2	6.8	9.6	0.67
06/25/96	13:04	0.2	0.4	0.5	9.7	10.9	7.1	10.3	0.68
06/25/96	13:12	0.2	0.3	0.5	9.5	10.4	7.2	9.9	0.66
06/25/96	13:21	0.2	0.3	0.5	9.7	10.9	7.1	10.2	0.68
06/25/96	13:30	0.2	0.3	0.4	8.3	9.0	6.6	8.7	0.60
06/25/96	13:38	0.2	0.3	0.4	9.9	11.2	7.0	10.5	0.70
06/25/96	13:47	0.2	0.3	0.4	8.7	9.6	6.8	9.2	0.63
06/25/96	13:55	0.2	0.3	0.4	9.9	11.3	7.0	10.6	0.71
06/25/96	14:04	0.2	0.3	0.4	8.9	12.1	7.8	11.5	0.70
Minimum		0.2	0.3	0.4	7.2	8.7	6.3	8.3	0.58
Maximum		0.2	0.4	0.5	9.9	12.1	7.8	11.5	0.71
Mean		0.2	0.3	0.5	8.7	9.8	6.7	9.3	0.64

Wave data statistics resulting from the deployment of the S4 on 14 June 1996 on KM3.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/14/96	13:05	0.2	0.3	0.4	11.2	12.8	7.9	11.9	0.72
06/14/96	13:14	0.2	0.3	0.4	12.4	14.9	7.5	13.4	0.80
06/14/96	13:23	0.2	0.4	0.6	10.4	11.6	7.5	10.9	0.69
06/14/96	13:31	0.3	0.4	0.6	10.7	12.1	7.6	11.4	0.70
06/14/96	13:40	0.3	0.4	0.6	10.8	12.4	7.3	11.5	0.74
06/14/96	13:48	0.3	0.5	0.7	11.9	14.1	7.4	12.8	0.78
06/14/96	13:57	0.4	0.6	0.9	11.7	13.9	7.5	12.6	0.77
06/14/96	14:05	0.4	0.6	0.8	10.0	11.0	7.5	10.4	0.66
06/14/96	14:14	0.3	0.5	0.8	10.3	11.9	7.1	11.0	0.72
06/14/96	14:22	0.4	0.7	0.9	12.3	14.7	7.5	13.3	0.79
06/14/96	14:31	0.3	0.6	0.8	9.6	10.6	7.3	10.1	0.65
06/14/96	14:39	0.4	0.6	0.9	10.5	11.7	7.5	11.1	0.70
06/14/96	14:48	0.4	0.7	0.9	10.8	12.1	7.7	11.4	0.70
06/14/96	14:56	0.4	0.6	0.9	9.6	10.7	6.9	10.1	0.69
06/14/96	15:05	0.5	0.8	1.1	10.2	11.6	7.1	10.8	0.72
06/14/96	15:13	0.4	0.6	0.9	10.2	11.4	7.4	10.7	0.69
06/14/96	15:22	0.4	0.7	0.9	10.1	11.5	7.3	10.8	0.70
06/14/96	15:31	0.4	0.6	0.9	9.9	11.1	7.1	10.4	0.69
06/14/96	15:39	0.4	0.7	1.0	10.0	11.4	7.0	10.6	0.71
06/14/96	15:48	0.4	0.7	0.9	11.0	12.6	7.6	11.7	0.72
06/14/96	15:56	0.5	0.7	1.0	10.8	12.4	7.4	11.5	0.73
06/14/96	16:05	0.4	0.7	1.0	10.1	11.5	7.0	10.7	0.72
06/14/96	16:13	0.4	0.7	1.0	10.8	12.6	7.3	11.6	0.74
06/14/96	16:22	0.4	0.6	0.8	9.5	10.5	7.2	10.0	0.65
06/14/96	16:30	0.4	0.7	1.0	10.4	12.2	7.0	11.2	0.74
06/14/96	16:39	0.4	0.7	0.9	10.4	11.7	7.4	11.0	0.70
06/14/96	16:47	0.4	0.6	0.9	10.6	11.8	7.7	11.1	0.68
06/14/96	16:56	0.4	0.6	0.9	10.0	11.4	7.2	10.7	0.70
06/14/96	17:04	0.4	0.6	0.8	10.7	12.3	7.4	11.4	0.72
06/14/96	17:13	0.3	0.5	0.7	10.3	11.5	7.3	10.8	0.70
06/14/96	17:21	0.3	0.5	0.7	10.8	12.4	7.4	11.5	0.73
06/14/96	17:30	0.3	0.4	0.6	9.9	11.3	7.0	10.5	0.71
06/14/96	17:39	0.2	0.4	0.5	9.9	11.4	7.1	10.6	0.69
06/14/96	17:47	0.3	0.4	0.6	10.6	12.1	7.5	11.3	0.71
06/14/96	17:56	0.2	0.3	0.4	10.2	11.5	7.3	10.8	0.70
Minimum		0.2	0.3	0.4	9.5	10.5	6.9	10.0	0.65
Maximum		0.5	0.8	1.1	12.3	14.7	7.7	13.3	0.79
Mean		0.4	0.6	0.8	10.3	11.7	7.3	11.0	0.71

Wave data statistics resulting from the deployment of the S4 on 15 June 1996 on KM3.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
06/15/96	02:19	0.1	0.2	0.3	9.7	11.1	6.9	10.3	0.70
06/15/96	02:28	0.1	0.2	0.3	9.1	10.2	6.7	9.6	0.68
06/15/96	02:36	0.1	0.2	0.3	9.0	9.8	7.1	9.4	0.62
06/15/96	02:45	0.2	0.3	0.4	10.3	11.7	7.3	10.9	0.71
06/15/96	02:53	0.2	0.3	0.5	10.1	11.2	7.4	10.6	0.68
06/15/96	03:02	0.2	0.3	0.5	9.7	10.8	7.3	10.2	0.66
06/15/96	03:10	0.2	0.4	0.5	10.0	11.2	7.3	10.6	0.69
06/15/96	03:19	0.2	0.4	0.5	10.5	11.9	7.3	11.1	0.71
06/15/96	03:27	0.3	0.4	0.6	10.4	11.6	7.5	10.9	0.69
06/15/96	03:36	0.3	0.4	0.6	10.0	11.1	7.2	10.5	0.69
06/15/96	03:44	0.3	0.4	0.6	9.3	10.4	6.9	9.8	0.67
06/15/96	03:53	0.3	0.5	0.7	9.8	10.9	7.3	10.3	0.67
06/15/96	04:01	0.3	0.5	0.7	10.4	11.6	7.6	11.0	0.68
06/15/96	04:10	0.3	0.5	0.7	10.2	11.3	7.5	10.7	0.68
06/15/96	04:19	0.3	0.5	0.6	9.7	10.8	7.2	10.2	0.67
06/15/96	04:27	0.3	0.5	0.7	10.1	11.3	7.1	10.6	0.71
06/15/96	04:36	0.3	0.5	0.7	10.2	11.6	7.2	10.8	0.71
06/15/96	04:44	0.3	0.5	0.7	9.6	10.7	7.2	10.1	0.67
06/15/96	04:53	0.3	0.4	0.6	9.7	10.9	6.9	10.2	0.71
06/15/96	05:01	0.2	0.4	0.5	9.9	10.9	7.4	10.4	0.67
06/15/96	05:10	0.2	0.4	0.5	9.9	11.2	7.2	10.5	0.69
06/15/96	05:18	0.2	0.3	0.4	9.9	10.9	7.6	10.4	0.64
06/15/96	05:27	0.2	0.3	0.4	9.8	11.0	7.3	10.4	0.67
06/15/96	05:35	0.2	0.3	0.4	10.2	11.4	7.3	10.8	0.70
06/15/96	05:44	0.1	0.2	0.3	9.3	10.3	6.8	9.8	0.68
06/15/96	05:52	0.1	0.2	0.2	9.7	11.1	6.8	10.3	0.71
06/15/96	06:01	0.1	0.1	0.2	9.8	10.8	7.3	10.3	0.67
06/15/96	06:09	0.1	0.1	0.1	9.4	10.4	7.2	9.9	0.65
Minimum		0.10	0.10	0.10	9.00	9.80	6.70	9.40	0.62
Maximum		0.30	0.50	0.70	10.50	11.90	7.60	11.10	0.71
Mean		0.21	0.35	0.48	9.85	11.00	7.21	10.38	0.68

Wave data statistics resulting from the deployment of the S4 on 1 July 1996 on KM5.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
7/01/96	14:53	0.1	0.1	0.2	8.2	8.9	6.6	8.5	0.6
7/01/96	15:02	0.1	0.2	0.2	7.9	8.4	6.4	8.2	0.58
7/01/96	15:10	0.1	0.2	0.3	7.9	8.5	6.5	8.2	0.57
7/01/96	15:19	0.1	0.2	0.3	7.9	8.5	6.6	8.2	0.56
7/01/96	15:27	0.1	0.2	0.3	8.4	9.1	6.8	8.8	0.59
7/01/96	15:36	0.2	0.3	0.5	8.1	8.7	6.6	8.4	0.59
7/01/96	15:44	0.2	0.3	0.5	7.9	8.6	6.4	8.2	0.59
7/01/96	15:53	0.2	0.4	0.6	8.8	9.5	6.9	9.1	0.62
7/01/96	16:01	0.2	0.4	0.5	8.5	9.0	7.0	8.7	0.56
7/01/96	16:10	0.2	0.4	0.5	8.5	9.1	6.9	8.8	0.57
7/01/96	16:18	0.2	0.4	0.6	8.5	9.0	7.1	8.8	0.56
7/01/96	16:27	0.2	0.3	0.5	8.6	9.3	7.1	9.0	0.57
7/01/96	16:35	0.2	0.4	0.5	8.3	8.8	6.9	8.5	0.55
7/01/96	16:44	0.2	0.4	0.5	8.7	9.3	7.1	9.0	0.57
7/01/96	16:52	0.2	0.4	0.5	8.4	9.0	6.9	8.7	0.57
7/01/96	17:01	0.2	0.3	0.5	8.6	9.4	6.7	9.0	0.62
7/01/96	17:10	0.2	0.3	0.4	8.4	9.0	6.9	8.7	0.56
7/01/96	17:18	0.2	0.3	0.4	8.5	9.1	7.1	8.8	0.55
7/01/96	17:27	0.1	0.2	0.3	7.8	8.2	6.8	8.0	0.48
7/01/96	17:35	0.1	0.2	0.3	8.1	8.7	6.7	8.4	0.56
7/01/96	17:44	0.1	0.2	0.2	8.2	8.9	6.7	8.5	0.57
7/01/96	17:52	0.1	0.1	0.2	8.0	8.6	6.7	8.3	0.56
7/01/96	18:01	0.1	0.1	0.1	8.2	8.8	6.8	8.5	0.57
Minimum		0.10	0.10	0.10	7.8	8.2	6.4	8.0	0.48
Maximum		0.20	0.40	0.60	8.8	9.5	7.1	9.1	0.62
mean		0.16	0.27	0.39	8.3	8.9	6.8	8.6	0.57

Wave data statistics resulting from the deployment of the S4 on 2 July 1996 on KM5.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_c	T_{HMAX}	EPSI
7/02/96	04:07	0.1	0.1	0.1	8.4	9.2	6.8	8.8	0.60
7/02/96	04:15	0.1	0.1	0.2	8.3	8.9	6.7	8.6	0.58
7/02/96	04:24	0.1	0.1	0.2	8.3	8.8	7.0	8.5	0.54
7/02/96	04:32	0.1	0.2	0.2	8.5	9.1	7.0	8.8	0.57
7/02/96	04:41	0.1	0.2	0.3	8.7	9.2	7.3	8.9	0.55
7/02/96	04:49	0.1	0.2	0.3	8.7	9.2	7.1	8.9	0.57
7/02/96	04:58	0.1	0.2	0.3	8.5	8.9	7.2	8.7	0.53
7/02/96	05:06	0.1	0.2	0.3	8.4	8.8	7.2	8.6	0.52
7/02/96	05:15	0.1	0.2	0.3	8.5	9.0	7.2	8.7	0.53
7/02/96	05:23	0.1	0.2	0.3	8.6	9.2	7.2	8.9	0.55
7/02/96	05:32	0.1	0.2	0.3	8.4	9.0	7.0	8.7	0.55
7/02/96	05:40	0.1	0.1	0.2	8.3	8.8	6.9	8.6	0.55
7/02/96	05:49	0.1	0.1	0.2	8.2	8.6	7.0	8.4	0.52
7/02/96	05:58	0.1	0.1	0.2	8.2	8.7	6.8	8.5	0.56
7/02/96	06:06	0.1	0.1	0.1	8.2	8.7	6.8	8.4	0.55
Minimum		0.1	0.1	0.1	8.2	8.6	6.7	8.4	0.52
Maximum		0.1	0.2	0.3	8.7	9.2	7.3	8.9	0.60
Mean		0.1	0.2	0.2	8.4	8.9	7.0	8.7	0.55

Wave data statistics resulting from the deployment of the S4 on 2 July 1996 on KM5.

DATE	TIME	H_{AV}	H_S	H_{MAX}	T_Z	T_S	T_C	T_{HMAX}	EPSI
7/02/96	15:57	0.1	0.1	0.2	7.5	7.9	6.5	7.7	0.50
7/02/96	16:06	0.1	0.2	0.2	7.4	7.9	6.4	7.6	0.50
7/02/96	16:14	0.1	0.2	0.3	7.4	7.8	6.5	7.6	0.48
7/02/96	16:23	0.1	0.2	0.3	7.3	7.7	6.4	7.5	0.48
7/02/96	16:31	0.2	0.3	0.4	7.4	7.8	6.6	7.6	0.47
7/02/96	16:40	0.2	0.3	0.4	7.2	7.6	6.4	7.4	0.46
7/02/96	16:48	0.2	0.3	0.5	7.4	7.7	6.6	7.6	0.45
7/02/96	16:57	0.2	0.4	0.6	7.5	7.8	6.6	7.7	0.47
7/02/96	17:06	0.2	0.4	0.5	7.5	7.8	6.6	7.7	0.47
7/02/96	17:14	0.2	0.4	0.5	7.3	7.8	6.4	7.6	0.48
7/02/96	17:23	0.2	0.4	0.6	7.3	7.7	6.4	7.5	0.48
7/02/96	17:31	0.2	0.4	0.5	7.6	8	6.7	7.8	0.48
7/02/96	17:40	0.2	0.4	0.5	7.4	7.8	6.5	7.6	0.47
7/02/96	17:48	0.2	0.3	0.5	7	7.4	6.3	7.2	0.45
7/02/96	17:57	0.2	0.3	0.5	7.5	7.9	6.5	7.7	0.49
7/02/96	18:05	0.2	0.3	0.4	7.6	8	6.7	7.8	0.47
7/02/96	18:14	0.2	0.3	0.4	7.3	7.7	6.5	7.5	0.46
7/02/96	18:22	0.2	0.3	0.4	7.5	8	6.5	7.7	0.50
7/02/96	18:31	0.1	0.2	0.3	7.4	7.7	6.6	7.6	0.45
7/02/96	18:39	0.1	0.2	0.2	7.9	8.4	6.9	8.2	0.50
7/02/96	18:48	0.1	0.1	0.2	7.3	7.6	6.5	7.5	0.45
Minimum		0.1	0.1	0.2	7.00	7.40	6.30	7.20	0.45
Maximum		0.2	0.4	0.6	7.90	8.40	6.90	8.20	0.50
Mean		0.2	0.3	0.4	7.41	7.81	6.53	7.62	0.47