Frontispiece: Sedimentary Shore Forms,
Inner Marlborough Sounds.

Plate 1

Clastic Waves on the bayhead intertidal surface of Double Bay, Mahau Sound.

View east NZMS 260 P27 Grid Ref 825 942,
April 1985.
Sea to left of photograph.

Plate 2

Shoreline linear ramp, exposed location, Queen Charlotte Sound

View east NZMS 260 P27 Grid Ref 968 942,
April 1985.

Coastal Landforms and Sediments of the Marlborough Sounds

A thesis
presented for the Degree of
Doctor of Philosophy in Geography
in the University of Canterbury,
Christchurch, New Zealand
by
Glen A. Lauder

University of Canterbury
1987

Table of Contents

Page Number

List of Maps
List of Figures
List of Tables
List of Plates
Abstract

Chapter 1
Introduction to the Investigation of Coastal Sedimentation in the Marlborough Sounds 1

Existing Models of Landscape Behaviour in the Marlborough Sounds..........3
Investigative Framework 5
A Model of Landscape Sedimentary Behaviour..........5
Sources of Evidence..........5
Thesis Format 6

Chapter 2
The Marlborough Sounds Region: Landscape and Literature 8

Literature on the Marlborough Sounds Landscape 8
Sources and Chronology..........8
Geology and Geomorphology 8
Shoreline..........11
Inlet Hydrography..........11
Physiography 12
Lithology..........15
Tectonic Setting 18
Pre-Quaternary History..........20
Quaternary History 22
Shoreline Form and Dynamics..........29
Shore Classifications 29
Wave Energy Environment 30
Inlet Sedimentation..........31

Evaluation of Some Key Postulates of the Literature..........31
Marlborough Sounds Geomorphology as a "Tilting Block"..........33
a) The Earth Block Postulate 34
b) Vertical Displacement Postulate..........35
c) Tilting Postulate..........37
d) Broader Mechanism:..........39
The "Low-Energy" Shoreline..........41
Inlet Sedimentation as the "Double-Ended Sediment Trap"..........42

Summary..........42

Page Number

Chapter 3
Catchment Modification and Sediment Delivery........................ 45

Overview of Catchment Modification 45
  Primary Occupance....................47
  Catchment Clearance by European Settlers....................48
    The Stimulus for Clearance 48
    Sub-regional Differences....................49
      Queen Charlotte Sound and Port Underwood....................49
      Inner Sounds....................51
      Pelorus and Kenepuru Sounds....................52
  Hillslope Stability of Farmed Land....................53
  Other Historical Catchment Changes....................53
  Contemporary Catchment Changes 54

Coastal Response: Cited Evidence....................54
  "Infilling" at Havelock....................54
  Channel Changes in the lower Pelorus River....................56
  Intertidal Rubble Heaps....................57
  Mahakipawa Jetty Infilling....................57
  Surveyed Shoreline Changes....................60

Review....................60
  Estimating Catchment Erosion....................60
    Burnoff....................61
    Track Construction 62
  Internal Storages and Sediment Delivery to the Coast....................62
  Investigations linking the Catchment and the Coast....................64

Chapter 4
Coastal Sedimentation: A Framework for Investigation............ 66

Models for the Variable Coast 66
  Characterising Coastal Variablity....................67

Functional Models 69
  A Functional Model 70
  An Ordered Control Model....................72
  Extending the Ordered Control Approach 73

The Ordered Response Model....................75
  Ordered Response....................75
  Transitional Control....................77
  Functional Behaviour 80
    The Sediment Transform 80
    The Morphologic Transform 81
  Summary....................83

Operationalising the Ordered Response Model....................84
  Validation of Models: Functional Statements....................85
  Validation of Models: Operational Framework....................86

Page Number

Chapter 5
Coastal Sediments of the Marlborough Sounds 89

Sampling and Textural Analysis of Coastal Sediments 90
    Sampling Criteria 90
        Shoreline 90
        Submarine 91
    Methods of Sediment Analysis 95
        Shoreline 96
        Submarine 98
    Measurement of Particle Size 100
    Statistical Presentation of Data 102

Initial Description of Sediments 103
    Summary Grain Size Statistics 103
    Grain Size and Sorting 112
    Sand Fraction in Submarine Samples 116
    Organic and Shell Content of Submarine Samples 117

Origin and Modification of Grain-Size Distributions: Discussion 120
    The Interpretation of Grain Size Patterns 121
        Elements of the Interpretation Problem 122
            Hydraulic Sorting 122
            Source Area Effects 125
            Resolving Conflicts of Interpretation 126
    Sedimentary Fractionation Viewed as Ordered Response 127
        Sediment Fractionation in the Trapping Environment 128
        The Ordered Response Model
        as a Framework for the Trapping Environment 130

Chapter 6
Shoreline Form and Function 135

Shoreline Description 136
    Shoreline Morphological Zones 140
    Examples of Shoreline Morphologies 142

Independent Shoreline Controls 153
    Morphology 153
        The Scale of Shoreline Form in Plan View 153
        Shoreline Form in Profile 158
        The Relationship Between Coastal and Shoreline Gradients 162
    Shoreline Sediments 163
        Classification of Sediment Sources 164
    Shoreline Hydrodynamics 167
        Wave Parameters 167
        Tidal Range 171

Interactive Shoreline Controls 171
    Descriptive Analysis of Interactions 171
    Functional Analysis of Interactions 174
        Transitional Control 175
        Feedback Loops 175
    Relative Mobility 178
    Relative Mobility within Ordered Response 178
    Sediment Delivery and Shoreline Relative Mobility Behaviours 179
        Tracing Response to Sediment Delivery 181

Page Number

Chapter 7
Shoreline Sediment Mobility on the Low Energy Mixed Material Shore ... 183

Sedimentary Shoreline Types ... 184
    Shoreline Sedimentary Typology ... 184

Mobile Sediment Behaviours ... 189
    Mobile Sediment Accumulations in an Immobile Frame ... 189
    Intertidal Clastic Wave Accumulations ... 189
    Shore Form Classifications and Clastic Waves ... 192
    Clastic Waves Undescribed ... 195

Clastic Waves and Sediment Fractionation ... 197
    Collective Sediment Transport Mechanisms ... 197
    Sediment Modification in Clastic Waves ... 198
    Stratigraphy and Sediment Trapping ... 207

Interpretations ... 209

Chapter 8
Submarine Morphology and Sedimentation ... 211

Bathymetric Form ... 214
    The Long Profile ... 214
        Queen Charlotte and Tory Channel ... 214
        Pelorus And Kenepuru Sounds ... 217
    The Transverse Profile ... 220
        Controls on Bathymetric Form ... 228
    Discussion ... 225

Sediment Accumulation in the Offshore ... 229
    Mean Thicknesses of Bottom Sediments ... 238
    Variation within Profiles ... 238
    Sedimentation Rates ... 239

Offshore Sub-bottom Form ... 241
    River Gradients and Terrace Remnants ... 241
    Sub-bottom Form ... 245
    Nydia Bay Case-study of Sub-bottom Form ... 247
    Tory Channel: Interpretation Extended ... 251

Interpretations ... 252

Chapter 9
Embayment Sediment Trapping ... 257

Variations in Grain-Size Distribution
Within and Between Marginal Embayments ... 258
    Grain-Size Curves Case Studies ... 259
        Pelorus Sound ... 259
        Queen Charlotte Sound ... 266
        Tory Channel ... 270
    Offshore Sediment Summary ... 273

Sediment Texture in Marginal Embayments ... 274

Discussion ... 278

Page Number

Chapter 10

Conclusions 282

Principal Findings of the Investigation 283
    Specific Findings 283
        Geomorphology: New Sub-bottom Evidence of Terraces 283
        Catchment Sediment Delivery 284
        Modelling Coastal Response 284
        Coastal Sediments 285
        Shoreline Sediment Fractionation 286
        Offshore Sediment Fractionation 287
    Recommendations for Future Research 288

Evaluation of the Investigative Framework 289

The Broader Perspective: Implications 293

Acknowledgements 299

Reference List 301

Appendices 313

Appendix 1: Maps, Charts and and Aerial Photographs
Appendix 2: Sediment Analysis: Equipment, Formulae
Appendix 3: Sediment Sample Log, Shoreline Samples
Appendix 4: Sediment Sample Log, Submarine Samples

Errata: Page numbers omitted 28, 109.

List of Maps

Map 1: Marlborough Sounds Region,
Extract from NZMS 262 Sheet 9, 1:250,000

Map 2: "Linkwater"
Extract from NZMS 260 P27 1:50,000

Map 3: "Nydia"
Extract from NZMS 260 P27 1:50,000

Map 4: "Portage"
Extract from NZMS 260 P27 1:50,000

List of Figures

Figure *Title* *Page Number*

2.1 Location Map, Marlborough Sounds Region....................................9
2.2 Lithology and Tectonic Setting...17
  2.2a Hard Rock Geology
  2.2b Displacement by Alpine Fault
2.3 and 2.4 Quaternary Setting and Remnant Deposits........................25
  2.3 Alluvial Deposits, Inner Sounds and Wairau
  2.4 Low Sea Level Geography
2.5 Pelorus Sound Submarine Profiles...32
  2.5a Sub-Bottom Profiles
  2.5b Axial Track of Sub-Bottom Profile
2.6 Drainage Reversal Hypothesis...40
  2.6a Schematic Map of Hypothesis
  2.6b Larger-scale Evidence

3.1 Catchment Clearance, 1910..50
3.2 Havelock Estuary Bathymetry, 1854...55
3.3 Cullens Creek and Mahakipawa Jetties Location Map........................58

4.1 Process-Response Model (Krumbein, 1961)..................................71
4.2 "Ordered Functional Model" (McLean and Kirk, 1969).......................74
4.3 The Ordered Response Model...76
4.4 Three Functions of the Coastal System..79
4.5 The Ordered Response Model and
and its Relationship to Other Geomorphic Concepts.........................82

5.1 Comparison of Sediment Analysis by Sieve and Settling...................97
5.2 Comparison of Mean Sizes Obtained by Settling (RSA) and Sieving...97
5.3 Shoreline Sediments, Frequency in Moments of Grain Size.............110
  5.3a Mean Size
  5.3b Sorting
  5.3c Skewness
  5.3d Kurtosis

Figure *Title* *Page Number*

5.4 Offshore Sediment Textural Class, by Sub-region of Sampling 111
5.5 Grain Size Curves For 25 Beach Samples
Showing Modal Uniformity...113
5.6 Size-Sorting Relationship in Shoreline Sediments ....113[a]
5.7 Submarine Sediments, Ranges of Grain-Sizes................................115
  5.7a Offshore Samples: Median vs Phi Quartile Deviation
  5.7b Nearshore Samples: Median vs Phi Quartile Deviation
5.8 Sand Content of Submarine Samples: variation with Depth...............118
5.9 Sand Content of Submarine Samples: Phi Mean and Sorting............118
5.10 Submarine Sediments Organic Contents 119
  5.10a Organic Content of Nearshore and Offshore Samples
  5.10b Offshore Samples: Organic Content vs % Clay
5.11 Identifying Controls on Source Area Effects
in the Ordered Response Framework...132

6.1 Morphological Shoreline Zones 141
6.2 Low Gradient and Inner Sounds Locations.....................................144
  6.2a Rubble Ramp Shore, Shallow Coast
  6.2b Stream Delta Shore Profile
  6.2c Intertidal Surface on Small Alluvial Fan
6.3 Intermediate Gradient or Bayside Locations.....................................148
  6.3a Pocket Beach Profile
  6.3b Rubble Profile
  6.3c Ramp Shore Profile
6.4 Steep Gradient or Outer bay Loactions 152
  6.4a Linear Ramp, Steep Shore Profile
  6.4b Plan View of Shore after Slump
  6.4c Shore Platform Profile
6.5 Embayment Morphometry : Scatter plot of the Embayment Index......157
6.6 Abrasional Prism..162[a]
6.7 Picton Wind Data Seasonal Velocities ....167[a]
6.8 Picton Wind Data Diurnal Variation..167[b]

Figure *Title* *Page Number*

6.8 Interactive Shoreline Controls and Shoreline Variability 173
6.9 Interactive Shoreline Controls: The Nature of Interactions................177
  6.9a Linking Long-term to Short-term Shoreline Change, Using Feedback Loops in the Ordered Response Framework
  6.9b Transitional Control Expressed as Concentric Feedback Loops
6.10 The Relative Mobility Framework and Shoreline Response to Sediment Delivery..180

7.1 and 7.2 Shore Profiles: Example and Nomenclature 191a
  7.1 Bythells Bay, Sequential Beach Profiles
  7.2 Nomenclature of Intertidal "Clastic Waves"
7.3 and 7.4 Shore Plan View: Distribution and Nomenclature of Clastic Waves...190
  7.3 Momorangi Bay Intertidal Surface
  7.4 Form and Texture of Clastic Waves
7.5 Sediment Modification in Clastic Waves, Ngakuta Bay......................203
7.6 Clastic Wave Sediments, Double Bay and Momorangi Bay................204
7.7 Clastic Waves and Beach Sediments Contrasted 206

8.1 Seabed Profiles, Queen Charlotte Sound......................................216
  8.1a Inner Queen Charlotte Long Profile
  8.1b Outer Queen Charlotte Long Profile
  8.1c Tory Channel Long Profile
8.2 Seabed Profiles, Pelorus Sound 218
  8.2a Inner Pelorus Sound Long Profile
  8.2b Kenepuru Sound Long Profile
  8.2c Nydia Bay Long Profile
8.3 Bathymetric Forms Attributable to Tidal Hydraulics, Queen Charlotte Sound..219
8.4 Echo-grams of W-form Bathymetric Profile......................................221
8.5 Bathymetric Form, Relationship of Marginal Bays to Axial Channels (Tory Channel Bathymetry)..223
8.6 Bathymetric Form, Relationship of Marginal Bays to Axial Channels (Pelorus Channel Bathymetry)

Figure *Title* *Page Number*

8.7 Relationship of Marginal Bays to Axial Channels,
Marginal Bay Depth Accordance and Discordance 226
- 8.7a Inner Queen Charlotte Marginal Bay Depth Accordance
- 8.7b Tory Channel Marginal Bay Depth Discordance

8.8 Sub-bottom Seismic Profiles, Pelorus Sound,
Examples of Profile Data...231
8.9 Sub-bottom Seismic Profiles, Inner Pelorus Sound...........................232
8.10 Sub-bottom Seismic Profiles, Kenepuru Sound 233
8.11 Sub-bottom Seismic Profiles, Pelorus Channel and Nydia Bay..........234
8.12 Sub-bottom Seismic Profiles, Tennyson Inlet 235
8.13 Location Map of Sub-bottom Profiles 236
8.14 Long Profiles of Sub-bottom Pelorus and Kenepuru Sound.............246
- 8.14a Inner Pelorus Sound Bottom and Sub-bottom Long Profile
- 8.14b Kenepuru Sound Bottom and Sub-bottom Long Profile

8.15 Sub-bottom Surface Remnants, Pelorus Sound 248
"Nydia Surface" and Channel Long Profile
8.16 Embayment Response Framework 255

9.1 Pelorus Channel Sediment Sample Locations..................................261
- 9.1a Four Fathom Bay Echo Soundings
- 9.1b Location of Pelorus Channel Samples

9.2 Four Fathom Bay Sediments, Pelorus Channel...............................262
- 9.2a Four Fathom Offshore Samples: Northern Suite
- 9.2b Four Fathom Offshore Samples: Southern and Outer Suite

9.3 Pelorus Sound Sediments: Sub-regional Variations.........................264
- 9.3a Nydia Bay: In/Mid and Four Fathom Inner
- 9.3b Maori Bay Axial Transect and Four Fathom Inner
- 9.3c Kenepuru Sound and Mid Nydia Bay
- 9.3d Mahakipawa Arm Inner and Four Fathom Inner

9.4 Queen Charlotte Sound Sediment Sample Locations.......................267
9.5 Queen Charlotte Sound Sediment, Inner and Northern Bays............268
- 9.5a Grove Arm (Queen Charlotte) and Four Fathom Samples
- 9.5b Queen Charlotte: Grove (Inner) and Marginal Bays

Figure *Title* *Page Number*

9.6 Tory Channel Sediment Sample Locations....................................271

9.6 Tory Channel Sediments: Marginal Bays and Comparisons with other sub-regions..272

9.7a Tory Channel Bays Offshore: Inner and Mid-Bay Samples

9.7b Tory Channel Bays Offshore: Relation to other sub-regions

9.8 Embayment Axial Sediment Variation "Complementarity Plots"

9.8a Bay Axis Opua Bay (Tory Channel) 276

9.8b Bay Axis, Deep Bay (Tory Channel) 276

9.8c Bay Axis (North) Four Fathom Bay (Pelorus Sound) 277

9.8d Offshore Samples, Bottle Bay (Queen Charlotte) Axis........277

9.7 Coastal Response Framework:
An Operational Statement of the Ordered Response Model............281

List of Tables

Table	*Title*	*Page Number*
2.1	Lithologic Units	16
5.1	Shoreline Sediment Sampling Locations	104
5.2	Nearshore Sediments Summary	105
5.2	Offshore Sediments Summary	106
5.4	Shoreline Sediments: Grain Size Moment Values	107
5.5	Submarine Sediments Grain Size	107
5.6	Submarine Sediments Non-Lithic Contents	107
6.1	Tidal Ranges, Marlborough Sounds	138
6.2	Ranges of Shoreline Gradient	139
6.3	Shoreline Form in Plan Sub-Regional Morphometry	155
6.4	Embayment Morphometry (Selected Examples)	155
6.5	Taxonomy of Coastal Gradients	160
6.6	Distribution of Coastal Gradients	160
6.7	Sources of Shoreline Sediment	165
6.8	Ranges of Fetch Lengths	168
6.9	Wave Forecast Parameters	170
7.1	Sedimentary Shoreline Types	185
7.2	Shoreline Sediment Bedform: Classification Schema	193
8.1	Sources of Evidence: Bathymetric and Sub-bottom Investigations	215
8.2	Sedimentation Rates, Pelorus Sound	237

List of Plates

Plate *Title* *Page Number*

2.1 Coastal Landscape, Marlborough Sounds 14

3.1 Historical Shoreline Features, Mahakipawa Arm................................57[a]

6.1 Low Gradient and Inner Sounds Locations 143
    6.1a Rubble ramp Shore, Mahakipawa, Pelorus Sound
    6.1b Intertidal Surface, Mahakipawa, Pelorus Sound
    6.1c Intertidal Surface, Bythells Bay, Queen Charlotte Sound
6.2 Intermediate Gradient and Bayside Locations 147
    6.2a Bayside shore, Ngakuta Bay, Queen Charlotte Sound
    6.2b Rubble shore, Ngakuta Bay, Queen Charlotte Sound
    6.2c Intertidal ramp, Mills Bay Kenepuru Sound
6.3 Steep Gradient or Outer Bay Loactions 147
    6.2a Steep linear ramp shore, Queen Charlotte Sound
    6.2b Hillslope processes on steep backshore, Mahau Sound
    6.2c Shore platform, Ngakuta Bay, Queen Charlotte Sound

7.1 Shoreline Sediment Surfaces...186
7.2 Intertidal Surface, Moenui, Pelorus Sound 190
7.3 Clastic Waves on Intertidal Surfaces 201
    7.3a Aussie Bay Emergent Clastic wave
    7.3b Multiple Clastic waves, Ngakuta bay
    7.3c Clastic Wave, Aussie Bay (From Boyce, 1971)
7.4 Stratigraphy of Clastic Waves...208

8.1 Alluvial Forms in the Subaerial Landscape 243
    8.1a Alluvial Fans, Northern Kenepuru
    8.1b Terraces, Kaituna Valley
    8.1c "Nydia Surface" Remnants, Nydia bay

Abstract

This thesis examines coastal form and sediments of the Marlborough Sounds, New Zealand.

An important aspect of coastal behaviour in this landscape stems from linkages between catchment and coast. Focus is therefore placed on the manner in which sediment delivered from catchment sources is redistributed within the shore and offshore domains.

Coastal response is shown to depend on two factors: the form of the receiving sites and the mobility of sediments within them. Investigation of coastal landforms at a range of scales identifies the framework within which sedimentation takes place. Consideration of landscape sediment redistribution at Quaternary, Holocene and human timescales establishes the locations in the coastal landscape in which change has taken place. A key factor in coastal response relates to the wide size range of sediments delivered.

The fractionation of sediment within the coastal domains is used as an index by which to identify the controls on coastal sedimentation. A new conceptual model of coastal behaviour, the Ordered Response Model, is developed as a framework within which to investigate coastal response. The model is operationalised in three ways. This is done first with regard to coastal sediments and their grain-size interpretation, secondly in the context of shoreline form and sediment redistribution, and thirdly in relation to form and sediment trapping within coastal embayments.

The patterns of sediment redistribution are seen to reflect trapping behaviour in the coastal landscape at a range of scales. Sediments are investigated from the viewpoint of the factors which determine their retention or accumulation in or rejection from a coastal site.

Shore sites are distinguished on the basis of the extent to which they trap materials delivered to them from catchment sources. Governing factors are shoreline gradient and size grade of materials. A primary fractionation of sediments takes place at the shore and the finer fractions are by-passed to the nearshore. Sediment fractions that are relatively immobile under prevailing environmental conditions develop paved lag surfaces at a range of scales. Sediments that accumulate at the shore are distinctive in their mixed sand and gravel composition with a dominant mode in the granule and very coarse sand grades (-2ø to 0ø).

Sediment deposited on the intertidal surfaces is found to be redistributed by a distinctive mechanism. Migratory intertidal bedforms defined here as "clastic waves" are a means by which the low energy shores disperse sediment which is delivered to them. These waves are a distinctive form of the shoreline of the Marlborough Sounds, and have attributes different from other shoreline forms identified in the literature. Clastic waves are shore-parallel, crescentic or lunate forms with longshore crest dimensions of 0.5 to 30m, length dimension perpendicular to the crest of up to 20m, and crest heights of 0.05m to 0.5m. Rates of intermittent migration vary from 1m/day to 10m/year. Key factors in their development are identified as low wave energy, tidal range, intermediate to low intertidal gradients (<1:20) and a mixed sand and fine gravel grain-size.

Bathymetric form is found to reflect the varying influence of sub-bottom morphology, sediment accumulation and hydraulic reworking. Analysis of sediment thickness identifies a mean thickness over sub-bottom of 7.33m in Pelorus Sound. Spatial variations in sediment thickness identify marginal embayments as significant sediment traps.

Mean sedimentation rates calculated over a 6,000 year timespan give Pelorus Sound a spatially averaged rate of 1.22mm/yr. Sub-bottom form is shown to have a stronger role in determining bathymetric form than previously reported. Due to the constraining effect of shallow sub-bottom form on sedimentary processes sediment thicknesses in the inner Pelorus Sound are not greater than those found in channels or embayments in the middle reaches of the Sound. A mean thickness of 5.75m from sub-bottom seismic profiles in the inner Pelorus equates to a sedimentation rate of 0.96mm/year over 6,000years, at about which time the river valleys of the Marlborough Sounds were drowned by post-glacial rising sea-levels.

Analysis of sub-bottom form reveals evidence of previously unreported drowned terrace remnants, which are correlated to subaerial terrace remnants. On the basis of both long profile patterns along these remnant surfaces and an analysis of bathymetric form of marginal bays and channels, an interpretation is developed of the origin of form in Pelorus Channel and Tory Channel.

Sediment trapping behaviour is identified as the most distinctive attribute of this coastal landscape, and shown to operate at a range of nested scales. As a

consequence of trapping behaviour, the operation of any part of this coastal landscape must be considered in relation to its operation as a whole.

Chapter 1

Introduction to the Investigation of Coastal Sedimentation in the Marlborough Sounds

This thesis is concerned with the nature, development, and functioning of the coastal system of the Marlborough Sounds, New Zealand. The specific aspect investigated is the manner in which the coast responds to the delivery of sediment. Also examined are the principles which are seen to control the operation of a tidal and largely enclosed coast with low levels of wave energy.

Because of relationships arising from both antecedent and present landscape factors it is necessary to make reference to aspects of Quaternary geomorphology, and to the historical and contemporary patterns of sediment delivery which are an outcome of catchment behaviour.

Until flooded by rising post-glacial sea level, the Marlborough Sounds was a region of dissected hill country with flat-bottomed valleys and steep hillslopes. Today, the elongated branching inlets occupy the valley bottoms of this landscape. The shoreline is emplaced against a range of landforms of river or hillslope origin. Because of the limits on the effectiveness of shoreline processes on a sheltered coast, the shore retains a varied and intricate form. These factors combine to make the region one of the most distinctive on the New Zealand coast.

An initial stimulus for this research arose from debate on the effects on the coast of contemporary and historical landuse patterns on the 1,480km^2 of catchments within the region. In the mid to late 19th century over 50% of the catchment area was cleared of native forest cover by logging and burning. Pastoral farming reached a peak of production by 1915 (Bowie, 1963), then entered a decline. Pasture over half the farmed land reverted to secondary growth forest. In the 1970's exotic forestry and aquaculture developed as new intensified uses of the land and water areas. Road and track construction extended the accessible area from the 1960's and residential and recreational use became more extensive. These uses of the environment focussed attention on the linkage between catchment behaviour and the shoreline and offshore domains. Concerns were expressed that activities which affect the sediment delivery of catchments would also bear on activities in the coast. An aspect of this was the concern over the possible incompatibility between exotic forestry and aquaculture in adjacent areas (Johnson, Mace and Laffan, 1981).

It is apparent that a step towards resolving management issues lies in identifying the specific problems within a broader framework - that of the behaviour of sediment in the landscape as a whole. The contribution of this study is twofold. The first is to develop a conceptual model within which the linkage between sediment delivery and coastal response can be systematically investigated. The second, by way of the investigation of coastal sediments, is to identify specific aspects of this linkage , and in so doing operationalise the model.

Observations of seabed sediment texture at specific sites within the Sounds have been cited as evidence for accelerated sedimentation (Johnson et al. 1981; McQueen et al. 1985). Such observations are beneficial insofar as they serve to direct attention to localised patterns of sediment distribution. However, the full interpretation of sedimentation at any particular site in a landscape can be conducted only in a context that includes adjacent sites, and in the light of sedimentary processes which prevail over a longer time span.

The coastal domains of the Marlborough Sounds are intricately varied; even without the specific addition of sediments some sites evidence extreme local variability in sediment texture. Furthermore, it is to be expected that there are sites in both the shoreline and offshore domains in which high rates of sediment accumulation, or the temporary storage of sediments, could be considered their "natural character". There is scientific and practical value in identifying the scales at which order can be recognised. One index of that order is found in the patterns of sediment distribution. The challenge for investigation is to recognise those sites which are acting under inherently different controls, so that rational comparisons can be made between them.

Within these coastal domains there are to be found a range of sedimentary deposits which have variations in form and sediment texture. The characteristics of the deposits reflect, in different ways, the controls acting upon them. The proposition to be advanced here is that the key to understanding coastal sedimentation in the Marlborough Sounds lies in the recognition of the fate of several sedimentary fractions.

At the level of field investigation, this study is concerned with the redistribution of sediment derived from catchments in the coastal domains. At a higher level, the investigation is of models of landscape change, and of the manner in which control is identified in these models.

Existing Models of Landscape Behaviour in the Marlborough Sounds

A conceptual model is a way of regarding a situation and of ordering observations pertaining to it. An initial explanatory model regarding the Marlborough Sounds was proposed by Cotton (1913), although there had been observation of the form of the landscape and interpretations made of its origin by the earliest explorers of the region (McKay, 1879, 1890; Crawford, 1874). Cotton, in his writings during half a century, developed a view of the landscape within the framework of geomorphology proposed by W. M. Davis (Chorley et al. 1973). The Marlborough Sounds landscape was described as having been:

> "dissected to the early mature stage by normal agencies in a single erosion cycle" (Cotton, 1913, p319)

The Sounds came to be regarded as "a unit group of earth blocks bounded by large converging faults" (Jobberns, 1936, p14). There has also been a broad acceptance (Beck, 1964; Gage, 1980, p337; Campbell and Johnston, 1982, p292) that the blocks were subject to

> "a tectonic subsidence.... with down-warping or tilting of the whole block towards the northeast, deeply drowning a mountainous landscape". (Cotton, 1955).

Some authors differ on the supposed direction of tilt. Brown (1981b, p477) cites northwesterly tilt. A component of this block tilting viewpoint is the hypothesis, proposed by W.R. Lauder (1970), that a reversal of the drainage of major rivers took place in some preceding era in landscape development. An emphasis on physiographic configuration at the regional scale has led to interpretations of landscape change as a local expression of a broader tectonic model, specifically to movement on the Alpine Fault and to Plate Tectonics. It is important, however, that there is an accordance found between the explanations of the broader model and the field evidence at the more local level.

In a recent review of the regional landscape, Campbell and Johnston (1982) reiterate Cotton's 1955 observation that "there are many small-scale geomorphic features of interest" within the Sounds region. Detailed observations and interpretation of Quaternary geomorphic features have not been conducted over the majority of the region. Esler (1984) made some useful observations on terrace deposits in the inner Sounds, and extended this to an interpretation of key elements of landscape change which differs radically from the conventional model of tilting and drainage reversal.

Subaerial evidences of Quaternary deposits which have been identified are only a fraction of the complete record, as most of the fluvial record is now drowned by the sea. In the course of studies relating to other aspects of landscape behaviour, Carter (1976) and Newton (1977) uncovered interesting aspects of submarine morphology. However, there have yet been no published or unpublished investigations of the relationships between subaerial and submarine forms. The relevance of such an investigation to both the interpretation of geomorphic form and to sedimentation rates and processes is fundamental. The Marlborough Sounds are a landscape which perhaps more than any other in New Zealand requires the joint consideration of subaerial and submarine forms in order to obtain an adequate interpretation of its geomorphic history.

Some of the smaller scale features referred to above, in particular the behaviour of Quaternary hillslope materials, have become significant in a developing land management debate since 1970 (Crown Study, 1976; Johnston, Mace and Laffan, 1981; Laffan and Daly, 1981; McQueen, Churchman, Laffan and Whitton, 1985). A consequence of the management debate has been a reorientation of research away from the explanatory description of landscape towards a consideration of the manner in which it functions. A principal concern has therefore become the internal redistribution of sediments within the landscape.

Published literature on subaerial landscape makes reference to the delivery of sediments to the coast (Crown Study, 1976; McQueen et al. 1985). Heath (1974) considered inflows to the Pelorus Sound in terms of the rates of flushing of material out of the Sound. Carter (1976) saw the inlet system of the Pelorus Sound as a whole acting as a "double ended sediment trap" in which material derived from both the seaward and the landward ends would be retained in the inlet. These studies have been concerned with either general patterns of sediment delivery or with the macro-scale aspects of their redistribution.

An aspect of sediment delivery and redistribution which has not been given consideration, however, is the extent to which the initial body of sediment delivered to the coast is fractionated and redistributed to different parts of the coastal domains. Lauder and Kirk (1985) made reference in particular to the omission of coarse sediments (sand and gravel) from studies of sediment delivery, and to a disregard of the shoreline domain across which all delivered sediment passes en route to the inlets. This process of fractionation, and its consequences for various parts of the coastal system, are the subject of this investigation.

Investigative Framework

A Model of Landscape Sedimentary Behaviour

Investigations of sedimentary dynamics often treat catchment, shore, and offshore domains as largely independent. But in this coastal landscape, sediment redistribution between the domains is a key expression of landscape functioning. The demand is therefore for a model in which sediment dynamic linkages can be studied across the domain boundaries.

The required model should identify the manner in which control is exercised over sedimentary fractionation. To this end, three factors are seen as having overriding importance. First, the form of the landscape as setting the boundary conditions within which change takes place; secondly, the nature and distribution of sediment delivery; and thirdly, the processes of sediment redistribution.

This investigation is structured with reference to a new model of coastal behaviour developed as part of the study. The model links the processes of sediment delivery to the response of the coast to this material. The model is referred to as the Ordered Response Model, and is presented in Chapter 4.

Sources of Evidence

Geomorphic evidence is drawn from topographic maps and bathymetric charts, supplemented by extensive field reconnaissance of sites throughout the inner Sounds recorded in sketches, photographs and field notes. The offshore system was investigated by reference to bathymetric charts, echo-soundings, analysis of seismic profiles, and sediment sampling and analysis. The nearshore zone was surveyed by echosounder and SCUBA diving, with sediment sampling by the latter. Some current and salinity data are also considered. The shoreline was extensively reconnoitred and was mapped and surveyed by a hierarchic sampling method. At the general level, the focus was on identifying type classes of shoreline behaviour. At the site scale, aspects examined were the shore-normal and longshore variations in form and sediments, while at the most local level the processes of sediment modification were examined. At the site and local level, this was accomplished by level surveys, and sediment sampling and analysis.

Thesis Format

Chapter 2 overviews the Marlborough Sounds region and the literature pertaining to it. A review is made of published and unpublished material on geology and geomorphology, inlet hydrography, and shoreline form and dynamics. This chapter and the next primarily review published and unpublished material, but reference is also made to original material. Models evaluated are those which have been used to account for the broad-scale form of the landscape, the general pattern of inlet sedimentation, and the distinctions of the shoreline.

In Chapter 3, particular reference is made to the patterns of sediment delivery to the coast within the Sounds landscape. From a review of historical and contemporary landuse changes, a number of clear distinctions are drawn between types of sediment delivery.

The purpose of Chapter 4 is to develop a comprehensive model as a means to recognise the linkages between the catchment, shoreline, and offshore domains. The model is structured on the basis of the controls operating on the coastal landscape system, and its utility is to be found in the extent to which it enables patterns in coastal behaviour and their causes to be recognised. Chapters 5 to 9 operationalise the model.

Chapter 5 presents an analysis of the general characteristics of coastal sediments in the Marlborough Sounds. It deals first, with the methods of sampling and analysis. Secondly, it presents summary statistics of analysis of sediment samples taken from the shoreline and from the offshore domains. Thirdly, it considers the interpretation of sediment fractionation which takes place in the course of coastal sediment redistribution.

A primary fractionation is shown to take place at the shoreline, and on this basis a distinction is made between the shoreline and offshore domains. Chapters 6 and 7 focus on the shoreline domain; Chapters 8 and 9 on the offshore.

Chapter 6 is a review of shoreline form, with specific reference to the controls which determine it. The shore is seen to derive some particular characteristics from its low wave energy levels, the tidal range, and the mixed size range of materials delivered to it. Chapter 7 focusses on the shoreline sediment redistribution processes, and in particular a significant mechanism of sediment dispersal. The form and behaviour of this mechanism is shown to be a distinctive feature of the Sounds shore. The associated bedform has not been previously reported in the literature pertaining to the Marlborough Sounds, nor described in the sedimentologic literature.

The extent to which offshore form reflects the antecedent river valley topography is investigated in Chapter 8. As a consequence of the manner in which this investigation links a study of subaerial geomorphology with submarine form, it is also possible in this chapter to add appreciably to the knowledge of landscape form in the early and pre-Holocene. The influence of antecedent form is central to the interpretation of the rates and patterns of offshore sedimentation that are presented. In Chapter 9, a detailed analysis of a series of suites of offshore sediments is presented as part of an analysis of the patterns of offshore sediment redistribution.

Conclusions on the investigation are drawn in Chapter 10.

Chapter 2

The Marlborough Sounds Region: Landscape and Literature

The region referred to as the Marlborough Sounds extends from Cape Soucis in the west to Rarangi in the east including the inlet systems of Croiselles Harbour, Pelorus Sound, Queen Charlotte Sound, and Port Underwood; the islands from D'Urville Island, to the Brothers and Arapawa Islands; and the hill country to the south as far as the Wairau River. (see Figure 2.1 and Map 1). The region is 70km in extent west to east, and 80km north to south. Shoreline length exceeds 1,400 km. The intricate variability of the shore coupled with the interfingering of inlets and ridges makes the coastal form of the Sounds the most distinctive landscape feature of the region

The scientific literature on the Marlborough Sounds landscape includes contributions on geology, geomorphology, inlet behaviour and shoreline dynamics. It is the first purpose of this chapter to review this material as it relates to this coastal investigation.

In the scientific literature of any region, there are elements which develop as "conventional wisdom" more confirmed than others. The second purpose of this chapter, is to distinguish those elements which are "more" and "less" confirmed.

Literature on the Marlborough Sounds Landscape

Sources and Chronology

Geology and Geomorphology

Early geological investigations of the Sounds regions were made by A. McKay (1879, 1890) and W.A. McKay (1899) reported on lithology and structure and emphasised economic mineralogy. Early reports to the Geological Survey and Mines Department, including that by Hector (1872), traced the discoveries of gold (Mahakipawa and Wakamarina), antimony (Endeavour Inlet) and coal (Picton).

Location Map

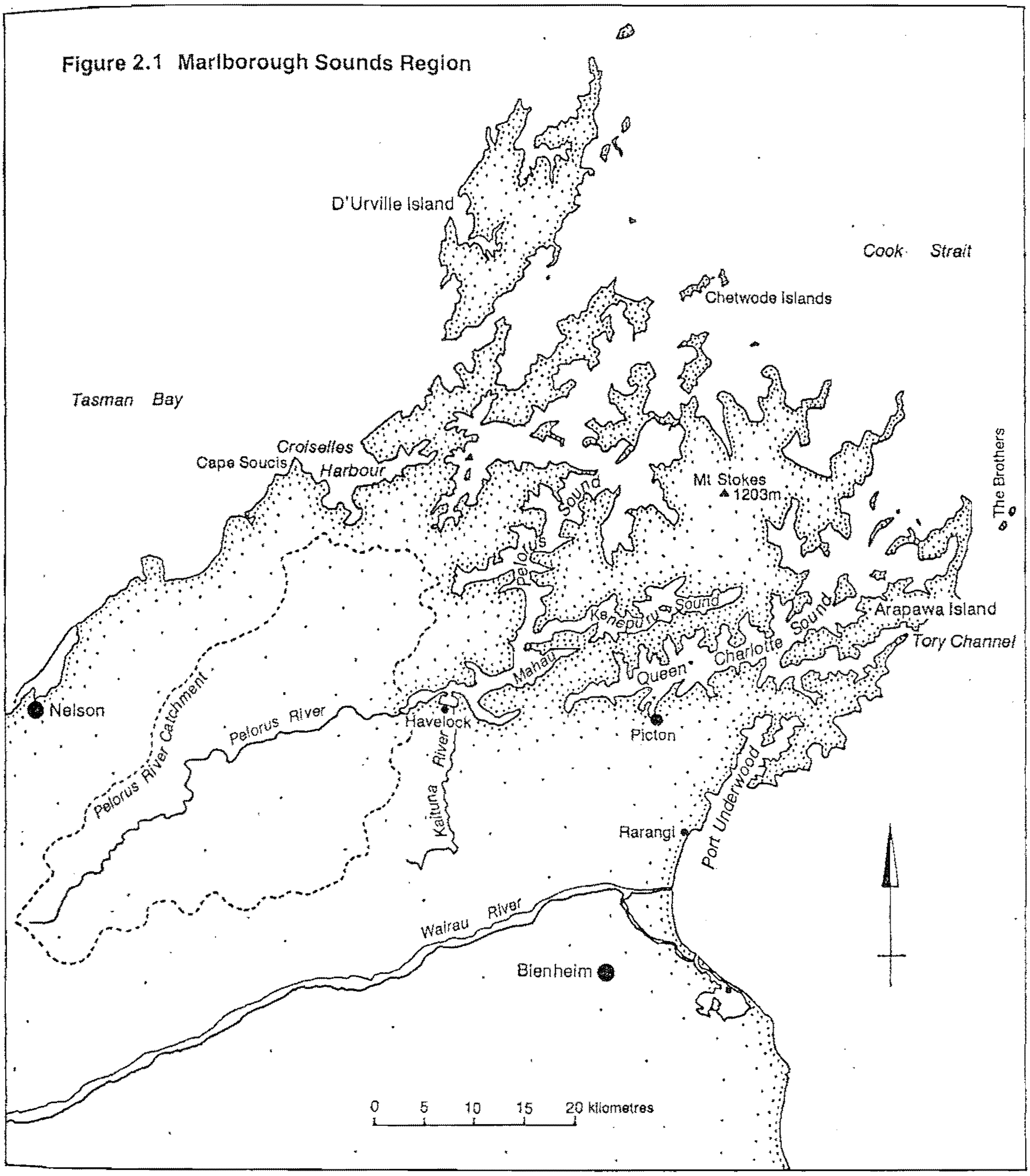


Figure 2.1 Marlborough Sounds Region

These reports included observations of terraces and "beach leads" discussed below. Gold fields and mineral occurrences were the subject of reports by Henderson (1918, 1930, 1935). The geochemistry and mineralisation of gold and antimony were later reported by Pirajno (1979) and Vitaliano (1968). The last mentioned covers aspects of the petrology and structure of part of the region. The regional structure was discussed in relation to Cook Strait by Crawford (1874). The Strait was identified as a depression thought to be part of a synclinal curve, the Marlborough Sounds having originated as subsided river valleys. Stratigraphic data were first derived from mine-shaft reports. The first use of geophysical survey is reported by Modriniack and Marsden (1938).

Geomorphic features of the region were given some attention by Buick (1900) and Marshall (1905). The dominant writer from 1913 until the 1960's, however, was Charles Cotton. The interpretations of the origin of the Sounds landscape, set out in Cotton (1913) and modified in a footnote dated 1915 when reprinted (Cotton, 1955), coupled with a string of journal articles (Cotton 1914, 1916, 1917, 1918, 1952, 1954, 1955, 1956, 1957, 1967, 1969) and a book (Cotton, 1955) have had the strongest role in shaping the conventional explanation of landscape features. Cotton took a broad approach and made relatively little reference to small-scale features such as terraces, although these had been identified by McKay (1879a), and referred to by subsequent authors (Henderson (1918, p 12; 1924, p 586). The account of the Quaternary in the northern South Island by Suggate (1965) made some reference to terraces north of the Wairau in eastern Marlborough, but in general there has been very limited investigation of small scale geomorphic form. Jobberns (1936) described some coastal features in Marlborough with an emphasis on structural features.

Important contemporary sources include reports by Brown (1981 a,b) on the Quaternary development of the Wairau Plain. Offshore seismic data from Carter (1976) are the main source of information on inlet sedimentation, although one seismic profile in the outer Sounds was reported by Winslow (1966). The detailed investigations of Evans Bay in Wellington (Lewis and Mildenhall, 1985) have some relevance in conjunction with the regional picture of Wellington and the Sounds built by Stevens (1974). A thorough review of published and unpublished geomorphic evidence in relation to the inner Sounds was made by Esler (1984). Campbell (1979, 1986) made reference to tephra deposits as a means to date landforms. Much of the original work of geomorphic value in recent years remains in unpublished theses (Eden, 1983; Esler, 1984; Kingsbury, 1987).

The first regional geological map was published in 1964 under the authorship of Beck (NZGS 1:250,000, Sheet 14). The text accompanying this map has had substantial influence on geomorphic interpretations since, as discussed later. Other maps of the region are available 1:100,000 (NZMS 301, 1982), 1:63,360 (NZMS 1, Sheets S 10, 11, 15 and 16, 1:50,000 (NZMS 260, Sheets 0, P and Q, Serials 26 and 27, from 1981). These are all contoured topographic sheets, and segments of NZMS 260 Sheet P27 are enclosed here as Maps 2, 3 and 4. A topographic sheet at 1:250,000 (NZMS 262, Sheet 9) includes topographic shading and spot heights, a segment of which is enclosed as Map 1. Maps are enclosed in a pocket at the back of thie thesis. Land Resource Inventory Sheets at 1:63,360 (MOWD, 1976) provide summary data on landuse, slope and soil type. Sheet numbers match those of NZMS 1. Soil Maps are available at 1:250,000 (NZSB, 1962).

Shoreline

Despite the prominence of the shore in the landscape of the Sounds, it rarely rated mention in early writings. While Jobberns (1935) made reference to shoreline form, it was at a scale of analysis which largely excluded the consideration of the small-scale features which characterise the coastline. Two coastal studies which emphasised shoreline features are the theses by Boyce (1971) and Newton (1977). The former was descriptive of some coastal depositions in the inner Queen Charlotte, Pelorus and Kenepuru Sounds. The latter focussed on shoreline changes arising from natural waves and ship wakes in Tory Channel.

Inlet Hydrography

Hydrographic charts are available at 1:100,000 (Marlborough Sounds, NZHS 615, 1962), 1:36,000 (Queen Charlotte, NZHS 6153, 1972), 1:25,000 (Queen Charlotte, Lowry, R.N., 1943), and contoured bathymetry maps at 1:50,000 (Queen Charlotte, Irwin, 1975; and Pelorus, Irwin, 1985). Offshore sediments are mapped at 1:200,000 (Lewis and Mitchell, 1980).

The only published work specifying depths of accumulated sediment is a study reported by Carter (1976) of suspended sediment and accumulated sediment in the axial channel of the Pelorus Sound. The depth was established by seismic profiling. The study includes measurements and descriptions of suspended sediments. Some theoretical material based on tidal flow data and morphology has been published by Heath (1974, 1976).

Physiography

Sub-parallel ridges striking north-northeast to northeast separate valleys first cut by rivers, and now filled by the sea. This can be seen in Map 1. In the northwest and southeast, the ridges are discontinuous, with the development of bays, islands and channels, such as Croiselles Harbour (Map 1 Grid Square (GS) 5601). The sea separates D'Urville Island from the peninsula at French Pass, Map 1 Grid Reference (GR) 581 032. To the south-east, the bay system of Port Underwood (Map 1 GS 6098) is of a similar scale to Croiselles Harbour. Tory Channel (Map 1 GS 6199) strikes eastwards, separating Arapawa Island from the contiguous mainland. In the "outer" Sounds, islands of a range of sizes are found, with only a small portion projecting above present sea level. The regional sea-bed slopes at a gentle gradient of less than 1° to a broad shelf to the north and is bounded by the "canyon" of Cook Strait in the east. Two principal inlet systems- the Pelorus (55km in length) and the Queen Charlotte (45km in length) - correspond to antecedent river systems.

In the outer reaches of the Pelorus Sound a broad basin extends eastwards to a series of bays including Beatrix Bay (Map 1 GS 5901) in the north and Clova and Crail Bays in the south. These outer reaches are more open than the inner Sounds and are referred to here as the *Beatrix Bays.* In the centre of the Tawhitinui Reach (Map 1 Northern GS 5801) is Maud Island. In the west, the Reach extends north to Hallam Cove (Map 1 GS 5702) and south into Tennyson Inlet (GS 5701). The mid reaches of the Pelorus (south of Tawero Point, GR 590 015), including the Hikapu Reach (GS 5800), are referred to here as the *Pelorus Channel.* The north-south orientation of the axis is apparent in Map 3. Flanking bays including Nydia Bay are orientated east-west (see Map 3," Mid Pelorus").

At the southern end the Pelorus Channel is a confluence with the largest of the Pelorus tributary inlets, the Kenepuru Sound extending to the east for 20 km. The inlets south from this confluence are referred to here as the *Inner Pelorus* (GS 5799 and GS 5899). These reaches include the Mahau Sound, the Mahakipawa Arm, and the Havelock Estuary (upstream of Cullens Point, Map 1 GR 575 993. See also Map 2, "Inner Pelorus"). While there are deeper channels at points of tidal scour, the Pelorus Sound generally deepens from the inner to the outer reaches. Reference to the topographic sheets (Maps 2 to 4) and to the bathymetric profiles in Chapter 8 shows the Sounds to be a landscape which has been drowned to a very limited vertical extent, with the subaerial portion far exceeding that of the submarine depth.

The Pelorus Sound has at its head the considerable Pelorus River Valley and its catchment system, with an area of 89,400 ha, shown on Figure 2.1. At the inner end of the Pelorus Sound the Kaituna Valley connects the Sounds south to the Wairau Valley. The Kaituna lacks a transverse head or saddle, and is referred to by Esler (1984) as a "windgap valley" (Map 2 GR 740 900). The Mahakipawa Arm joins to Okiwa Bay of Queen Charlotte Sound through the Linkwater Valley (Map 2 GR 905 835), a similar windgap. The Mahau Sound links onto the flank of the Kenepuru through the third regional windgap (Map 2 GR 880 978). This valley can be seen in Plate 2.1b. The origin of this geomorphic pattern is discussed later. The Queen Charlotte has no equivalent modern catchment like the Pelorus Valley.

The Queen Charlotte Sound comprises a series of arms orientated north-east including the Grove Arm (Okiwa Bay), Picton Bay and Waikawa Bay (Map 1 GS 5999, see also Map 4 "Portage"). A second major orientation of bays is north-northwest, including Whatamango and the northern bays from Onahau to Endeavour Inlet. The typical landscape form in the Queen Charlotte Sound can be seen in Plate 2.1a. The bed of the Sound is generally planar and gently sloping seaward, with scour holes around headlands and shoaling between Arapawa Island and Resolution Bay. Tory Channel is deeply incised.

The highest point in the mid to outer Sounds is Mt. Stokes (1205m Map 1 GR 603 013), with subordinate peaks in the southeast of Mt McCormick (1007m GR 599 989) and Mt Robertson (1026m GR 596 984), in the west of Nydia Bay, Lookout Peak (1006m GR 573006), and in the south of the "flooded" Sounds is Mt Cullen (1055m GR 580 985). Summit elevations lie mostly between 400m and 800m.

Plate 2.1
Coastal Landscape, Marlborough Sounds

Plate 2.1a

Intricately embayed coast, Queen Charlotte Sound.

Lochmara bay, Looking ESE from Ref Onahau,
NZMS 260 P 27 GR 925 984

Feb 1986

Plate 2.1b

Windgap valley, Broughton Bay- Mahau Sound.

NZMS 260 P 27 GR 883 978

Looking west

Photo: Mr. R. Sutherland, Marlborough Catchment Board

Plate 2.1c

Alluvial fan surfaces at Nopera, northern Kenepuru Sound.

Looking ESE from Ref Onahau,
NZMS 260 P 27 GR 925 984

Feb 1986

The Sounds are often refered to as a "ria" coast, but the term "ria" is in its strictest sense applied only to a drowned coastal landscape whose folded structure lies normal to the strike of the coast. Cotton (1956) rejected the application of the term as proper in the Sounds (sensu stricto), as they were, he determined, not of folded structural origin. The term "drowned river valley" is a preferable description, being genetically accurate, specifying the principal origin of landscape but not the cause of drowning.

Lithology

The Sounds are composed principally of metasedimentary rocks with variations in their texture in bands aligning to the northeast as illustrated in Figure 2.2a. The stratigraphically lowest rocks are also the most metamorphosed. These were mapped by Beck (1964) as Marlborough Schist of chlorite subzones II and III, and described as quartz-albite-muscovite-chlorite schists. The term "Haast Schist Group" (applied by Suggate in 1961) is now applied to the Otago, Alpine and Marlborough Schists which vary in metamorphic grade but share a common origin. These have been displaced by the dextral movement on the Alpine fault, shown in Figure 2.2b.

The metamorphic displacement of less and more resistant minerals into schistose layers (in the Marlborough Schist this is parallel to the bedding of the sand and silt parent material) has geomorphic implications. Weathering of the weak minerals (especially of micas to clay) produces planes of weakness prone to both deep and surficial slippage (Esler, 1984; Kingsbury, 1987), and sediment detritus of characteristically flat (platy) form. Where the planes of schistocity dip sub-parallel to the hillslope angle, for example at a dip of 40° in Onahau Bay (Map 4, GR 910 960), 5° to 15° steeper than the hillslope angle, the hillslope form tends in part to be rock controlled, with a planar form on the dip slope, and a tendency for bluff development across the strike. This is especially apparent at the shoreline. Where the coast cuts "across the grain" the result is the division of the shoreline into compartments containing separate beaches.

Overlying the schist is a layer of indurated sandstones and siltstones, mapped as the greywacke and argillite of the Pelorus Group, with a mapping label of "Epe" (see Lithologic Units, Table 2.1). Beck (1964) shows in schematic

Table 2.1
Lithologic Units

Group/ Series/ Formation	Lithology	Mapping Symbol	Stage	Era
	Gravel, sand and silt	f	Holocene	
Speargrass Fmn	Gravel, sand and silt	sg	Otira (last) glaciation	Quaternary
Landon Series	Calcereous mudstone	L wh-d		Tertiary
Lee River and Maitai Gps	Argillite and intrusive	Y		Upp Paleozoic
Pelorus Group	Greywacke and argillite	Epe		Mesozoic (Brown, 1981)
Marlborough (Haast) Schist Group				
Chlorite Sub-zone 2		II		Paleozoic
Chlorite Sub-zone 3		III		

From Beck (1964) and Brown(1981a).

Figure 2.2

Lithology and Tectonic Setting

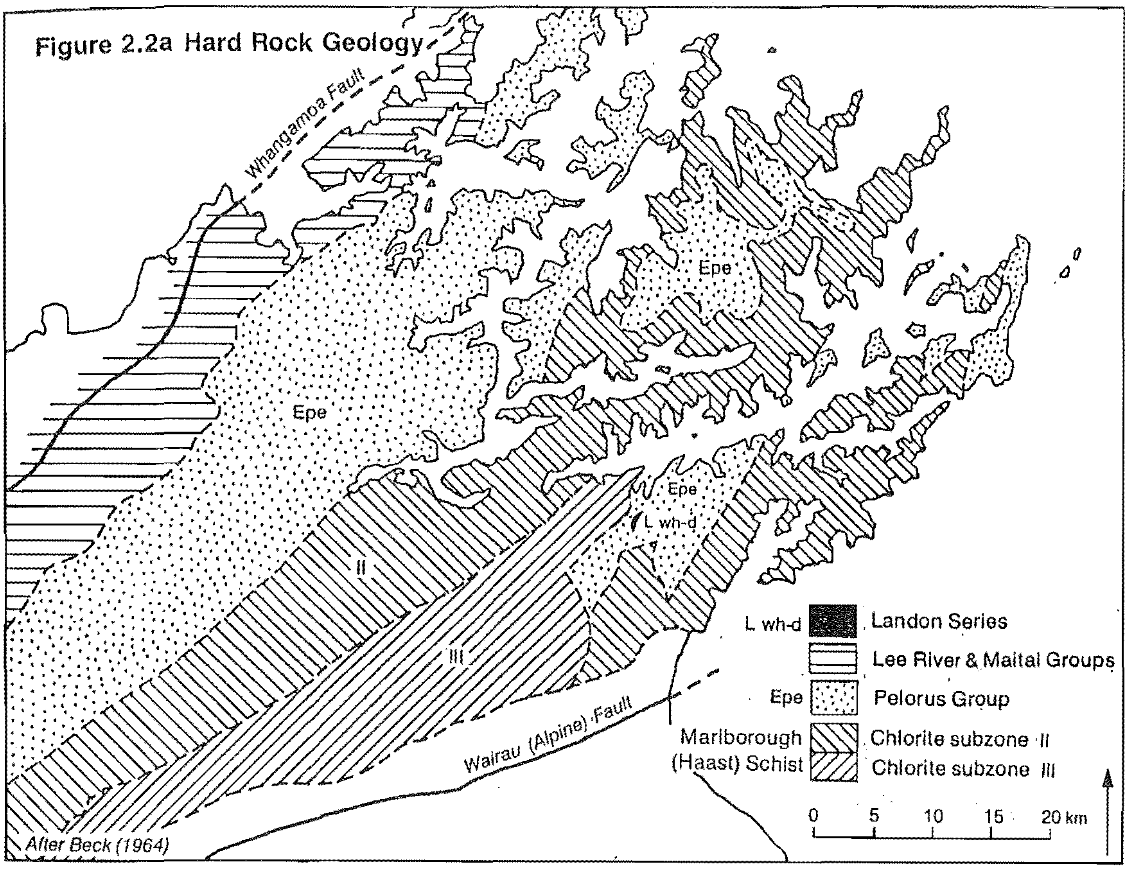


Figure 2.2a Hard Rock Geology

After Beck (1964)

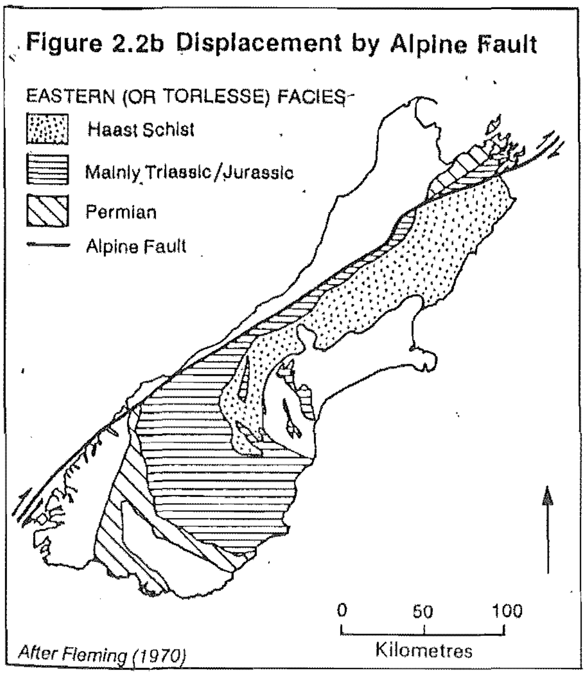


Figure 2.2b Displacement by Alpine Fault

After Fleming (1970)

Above: Textural bands in hard rock lithology align northeast, parallel to the axis of the Pelorus Regional Anticline (Beck, 1964). Pelorus Group greywacke-argillite rocks (epe) overlie metamophosed Marlborough schist.

Left: Dextral strike-slip movement along the Alpine Fault has displaced rocks of related lithology in Otago and Marllborough.

profile a much greater thickness of these sediments before their erosion. In places the overlying sediments have been removed to expose the schist. This upper Paleozoic material is mineralogically distinct from the Mesozoic Torlesse greywackes found south of the Wairau (Brown,1981a, p5). In the west of the Sounds, thick bands of relatively more resistant sandstone form the ridge crests, controlling ridge and valley formation (Campbell and Johnston, 1982, p293). Detrital sediments of the Pelorus Group are more blocky than platy in comparison to the schist. The lithology is largely undifferentiated with an absence of contrasts which could provide good natural sediment tracers.

Deposition during the middle and late Oligocene (post 36 million years ago) yielded a Tertiary rock cover that was largely stripped away with the initiation of the uplift in the Kaikoura Orogeny about 5 million years ago. Isolated outliers occur, for example, in the fault angle depression south of Picton. Infaulted narrow strips of marine calcareous mudstone of Landon age are underlain by coal measures containing a thin coal seam. The rank of the coal implies a previous thickness of Tertiary sediment exceeding 4,000m (Beck, 1964). Quaternary materials are discussed later.

Tectonic Setting

The landmass of New Zealand "straddles the boundary between the Pacific and the Indo-Australian plates" (Stevens, 1980, p149), and this placement in the schema of plate tectonics has regional implications for the Marlborough Sounds. The plate boundary is defined by New Zealand's Alpine Fault, a transform fault linking the Tonga-Kermadec Trench with the Macquarie Trench (Stevens, 1980, p149). Dextral movement on this fault beginning about 12 million years ago with the Kaikoura Orogeny and still ongoing (Stevens, 1980, plate 4 text) led to lateral displacement estimated at 480km (Wellman, 1956). Outcomes were the distortion of lithological distributions and the creation of extensive zones of fault lines.

The Marlborough Sounds area is bounded on the south by the Wairau Valley which has developed along the Wairau or Alpine Fault. South of the east-northeast trending Wairau fault, are a series of blocks forming the Kaikoura Ranges, which are separated by faults identified as branches of the Alpine Fault (Campbell and Johnson, 1982, p286). These faults form part of what Stevens (1980, p149) described as the "New Zealand Shear Belt". Tension has resulted in the tilting of these blocks, while fault angle depressions between them are occupied by the Clarence, Awatere and Wairau Rivers. Tilting of the Awatere Block between the Wairau and Awatere rivers towards the northwest has resulted in the main tributaries of the Wairau River flowing from catchments on the south side of the valley (Brown, 1981b, p6). Geophysical studies including the displacement of terraces have confirmed the tectonic mobility of this southern country (Lensen, 1976).

While the structure of the Sounds block is complex and poorly documented (Esler, 1984, p3), a measure of structural control is widely cited to account for the alignment of major valleys. The northeast trend of the Queen Charlotte Sound axis, parts of the Pelorus River Valley and Kenepuru and Mahau Sound align with the Wairau fault. Other trends include that of the north-northwest of the Kaituna Valley, the Hikapu Reach and Cullens Creek. The coincidence of this with the economic lodes of gold, tungsten and antimony ores was noted by Henderson (1930), Vitaliano (1968), and Pirajno (1979). Complex faulting near Picton referred to by Beck (1964) is currently being remapped, with the discovery of faults not indicated on the Beck (1964) Sheet. (A. Nicholls, Geology Department, University of Canterbury, Pers. comm. 1987).

This overall structure of the "eastern mountains" of the South Island was recognised by Hochstetter (1864, p23). Buick (1900, pp40-1) saw the development of these mountains into Sounds as being attributable to

> "the general subsidence which took place when Cook Strait was formed, the whole of the northern part of Marlborough was deeply affected, and, although not entirely submerged, was so reduced in level as to make deep-sea channels of what might previously have been compared to Scottish glens."

Campbell and Johnston (1982) describe the ranges in the north east of Marlborough as "tilting towards Cook Strait", and thereby forming the drowned valley system of the Marlborough Sounds (p285). The view largely accords with that of Buick (1900). In the intervening 80 years, a range of evidence has been cited which apparently supports a view that the Sounds are tilting (see in particular Beck, 1964; W.R. Lauder, 1970; and Stevens, 1974). The extent to which this view could be regarded as "confirmed" is evaluated below.

Subsidence has been used to account for the absence of emergent coastal features (Cotton,1969, p70) such as raised shorelines associated with a post-glacial high sea level. No correlative submerged features have been reported with the exception by Gibb (1979). The latter profiled irregularities in the long profiles of submerged ridges at a limited number of locations in Queen Charlotte Sound and Tory Channel. These submergent features were attributed to stillstands in the late-glacial/post-glacial rising sea level curve, and with an accompanying assumption of "zero uplift or very slight tectonic downdrop" (Gibb, 1979, p195). The data used were spot soundings on the 1:25,000 hydrographic chart of Lowry (1943). From the same data, the present author has been unable to identify widespread evidence of submerged coastal features.

Esler (1984) makes particular reference to steps in the profiles of ridges in the Queen Charlotte which occur at approximately 20m above sea level. The steps could be interpreted as structural coincidence, or as emergent coastal features. These "notched" hillslopes include shell accumulations on their surfaces. Brailsford (1981) notes, however, that the notches were probably modified by the Maori, and the shells derive from middens. This makes sea level interpretations difficult to assess (Esler, 1984, pp19-25). There is thus possible evidence of remnant shoreline features both above and below sea level. None can be regarded as conclusive.

Pre-Quaternary History

Most of the displacement of the Alpine Fault is thought to have taken place since early Oligocene time (32 million years BP), and continued through the Miocene and Pliocene (from 5 until 2.5 million years BP) during the Kaikoura Orogeny. The "various faults that branch off the Alpine Fault and traverse Marlborough and Wellington were probably formed entirely in the Kaikoura Orogeny" (Stevens, 1980, p315). Stevens attributes the origin of Cook Strait to a marine transgression of this period (1980, p317). The origin of present geomorphology of the Wellington region has been attributed by Stevens (1958, 1974) to the late Pliocene faulting and folding leading to the breaking up of what had been interpreted as a regional peneplain, the "K" surface. Such a control does not apply apparently in the Sounds since there is no true accordance of summit elevations, as established by Cotton (1957).

While there can be differences accorded the role of subsidence in landscape formation, it is generally accepted in the literature that the overall valley form of the landscape was established before the Quaternary.

> "With each transgression throughout the Pleistocene... the pre-Pleistocene condition of deep branching embayments, like those of the present day, would be restored."
> (Cotton, 1969, p66).

An hypothesis was proposed by Winslow (1966) that the Sounds were originally submarine canyons. It was proposed that prior to the Kaikoura Orogeny:

> "much or all of the Sounds block was beneath the water and was dissected by a number of well-developed and intersecting marine canyons."
> (Winslow, 1968, p630).

Soons (1968) in a detailed rebuttal rejected this view, mainly on the basis that evidence had been incorrectly cited, and adopted a conventional fluvial interpretation.

There are aspects of the river valley interpretation which are problematic, most notably the distribution of "wind-gap valleys" and the apparently limited catchments for some of the larger valleys. While Pelorus Sound has at its head the Pelorus River, and the Kenepuru Sound and most subordinate valleys such as Kaiuma Bay and Nydia Bay (shown in Map 3) have their respective headwater valleys, the Queen Charlotte Sound lacks such a catchment. The windgap extending to Linkwater, as with the Kaituna Valley, appears to be

> "not formed by the underfit streams they contain now, or did contain before sea level rose."
> (Esler, 1984, p12.).

A general model of valley formation was proposed by Soons (1968, p611) for Pleistocene conditions:

> "The present small streams in the valley heads would have been tributary to a river system adjusted to the size of the valleys, and the valley sides subject to erosion processes equally appropriate to the prevailing climatic conditions."

This model appears to account well for the behaviour of the landscape throughout the Quaternary. It may not account for the origin of the windgaps. Depending on the rate of development of the landscape frame as a whole through the Quaternary, it may not be possible to attribute the origin of windgaps to that era. If the mechanism of their formation was headward erosion along a major shear zone a more rapid development might be expected to have occurred.

Present evidence does not necessarily constrain their development to either the Quaternary or previous to it.

An explanation of the windgaps was proposed in a brief research note by W.R. Lauder (1970). His proposition was, that as a consequence of northward tilting, the rivers which immediately before drowning had flowed northwards through the Sounds, had in some previous time flowed southwards, as shown below in Figure 2.6a. The explanation was shown to be in accord with the idea of tilting promoted by Beck (1964). Two sources of evidence cited were "branch streams" (bays) joining the main channels at acute angles that point "southwards"; and the existence of the valley wind-gaps at Linkwater and Kaituna, through which these "reversed rivers" once flowed.

Quaternary History

Cooling temperatures in the late Miocene and Pliocene preceeded the fluctuating climates of the Pleistocene. Contemporary subaerial and submarine form reflects in large degree the landscape form of the Quaternary. To interpret present landscape, the identification of Quaternary changes and the ages of forms are of central importance. Three aspects of Quaternary conditions which leave their imprint on the Sounds landscape are hillslope processes, river processes, and the alternative occupation and abandonment of the valleys by the sea.

(a) Hillslope Processes

The influences of late Quaternary climatic changes are identified by Campbell and Johnston (1982, p293) as "clearly discernable":

> "Many hillsides are steep, straight-sided, and extensively veneered with fossil screes (in places incorporating 20,000 year-old Kawakawa Tephra), having clearly suffered extensive frost weathering during the Last Glaciation."

Fossil scree can be seen in the bayhead of the far left bay in Plate 2.1a.

The occurrence of Kawakawa Tephra is reported in Marlborough by Campbell (1979, 1986). The sites identified by Campbell (1986) specify the deposits as lying in or under colluvial fan detritus or "periglacial slope detritus". There is an important distinction to be made between the finding of traces of the material in a landscape, and its preservation in sites which usefully constrain a geomorphic explanation.

While valley glaciation south of the Wairau is evidenced by cirques, there is no evidence for valley glaciation in the Sounds. This would be unlikely, due to the relatively low elevations in the area and its proximity to the sea, to the east.

Soil development provides an index of the amount of hillslope erosion that took place in the Quaternary. Whitton et al. (1985) reports a transition in clay types in the soils from higher to lower elevations. The widespread occurrence of red-weathered deposits in the Sounds, apparently correlated to similar deposits in Wellington (Te Punga,1964,1984), identifies hillslope sites which have retained a measure of long term stability. Weathering of soils to reddish tints ranging from deep red to pink is visible in a number of sites in the Sounds. Typical sites of occurrence are on the tops of gently sloping round-topped ridges; the material being found from sea level to moderate elevations. The implications for landscape history depend on the weathering mechanism. If, as has been interpreted in the Wellington district by Te Punga (1964, 1984), the weathering is indicative of interglacial warming, then the distribution of the red-weathered material gives an index of the relative age of limited parts of the landscape. In particular, it has considerable implications for the rate of evolution of the ridge-and-valley frame in the Pleistocene as it indicates slow modification of these parts of the landscape. However, if the weathering can be accounted for by some other mechanism (by the mix of rainfall, temperature, and lithology) then the red weathering is of no chronological significance.

(b) River Processes.

Terrace remnants and dated lake deposits comprise two of the best "keys" to the Quaternary history of the Sounds, a landscape with very few indices of ages.

Remnant river aggradation terraces in the Pelorus Valley near Havelock were assigned by Campbell and Johnston (1982, p295) to the late Pleistocene. Esler notes that Quaternary terrace formations in the Wairau Valley had been recognised by Lensen (1962), Beck (1964), Suggate (1965), Brown (1981a,b) and Eden (1983). Only Beck (1964) related these to terraces within the Sounds - namely those at Linkwater, mapped as Speargrass (sg), as mapped in Figure 2.3. Eden (1983) mapped the most recent phase of loess accumulation (25,000 to 10,000 years BP) as being derived from the Speargrass Formation. The mapping of loess does not extend to the Sounds. The contrasts which Eden (1983) had found between terraces in the Awatere and the Wairau dictates caution in applying findings from the Wairau to the Pelorus or the Sounds (Esler, 1984). The Pelorus has a smaller and less alpine catchment than the Wairau, and a more confined valley.

The terrace remnant upon which Havelock is built was first identified by McKay (1879a). A higher terrace remnant, estimated by Esler at 29m above river level, was identified by Henderson (1935). Two or more terrace levels can be traced up the Pelorus Valley, mostly on the true right bank. Campbell (1979, p31) described "poorly sorted clay bound gravel containing subround to rounded clasts" as constituting the undifferentiated alluvium in a terrace at 10m above river level. In the Rai Valley, Beck (1964) identified remnants of terraces to which are assigned an age intermediate between Moutere Gravel and Speargrass Formation (Refer to Lithological Units, Table 2.1). The author has traced three terrace levels from the Upper Opouri Valley to Rai Valley using aerial photographs. The terraces become indistinguishable in Rai Valley. While terraces are again obvious in the Pelorus Valley, no correlation can yet be made.

The gradient of the Pelorus river bed over its lower 40km is 1:400, a value comparable with the lower reaches of the Wairau (Brown, 1981b, p680). The remnants of a terrace outcropping at Havelock are referred to as the "Havelock Surface" (Esler,1984). At an equivalent gradient this surface would appear to correlate with terrace remnants in Whakaretu Bay opposite Havelock, and in Kaiuma Bay. Terrace remnants in Kaituna Valley can be seen in Plate 8.1b.

Esler (1984) identified blue-silt terrace remnants at Oruaputaputa (Map 2 GR 791 907). The terrace remnant on the south of the Mahakipawa Arm is 14m above sea level. The stratigraphy appears to indicate two successive lake deposits. An infilled channel suggests a break in sedimentation during which drainage occurred before refilling. Alluvial aggradation in the Pelorus River valley could cause constricted drainage in the Mahakipawa Arm, by forming a gravel "barrier" across the inlet mouth damming local drainage. This interpretation was favoured by Esler (1984, pp37-47). Brown (1981b) showed that damming of the northern tributaries of the Wairau River is occurring, with gravel aggradation in the latter. Major aggradation of the Pelorus would result in ponding and the

Figure 2.3 and 2.4

Quaternary Setting and Remnant Deposits

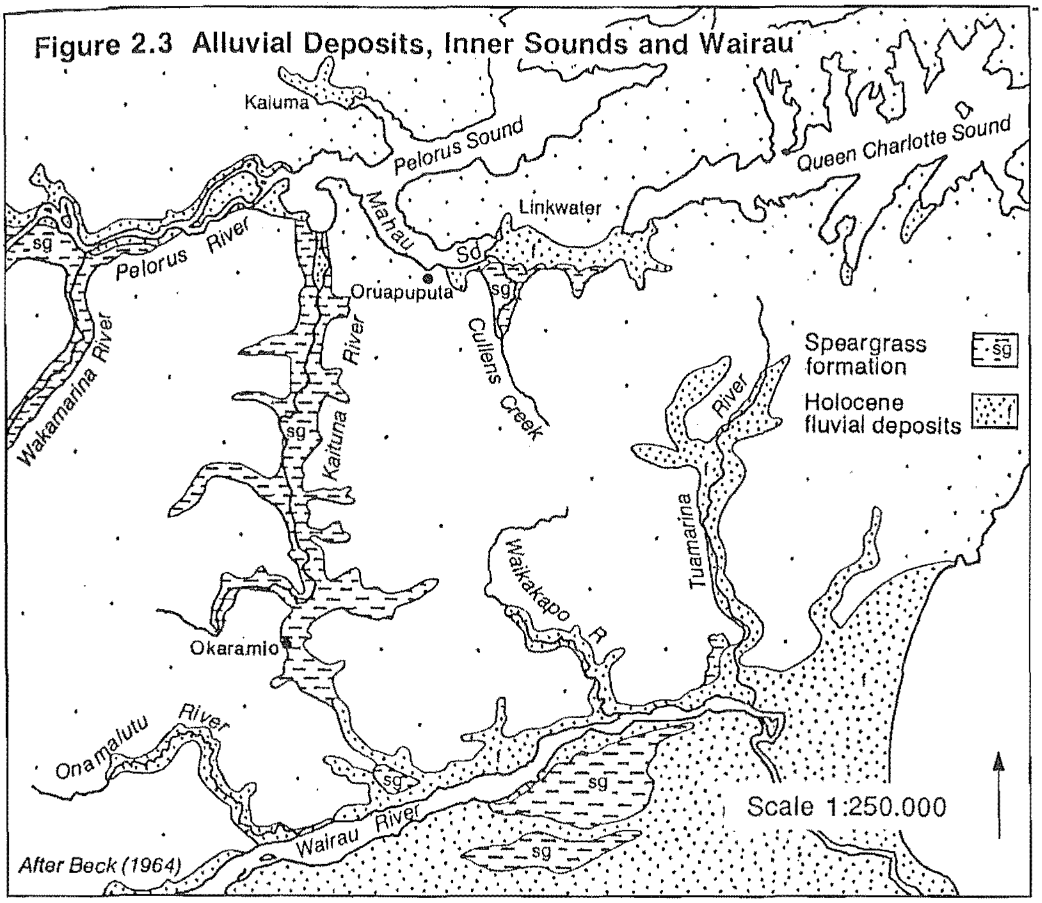


Figure 2.3 Alluvial Deposits, Inner Sounds and Wairau

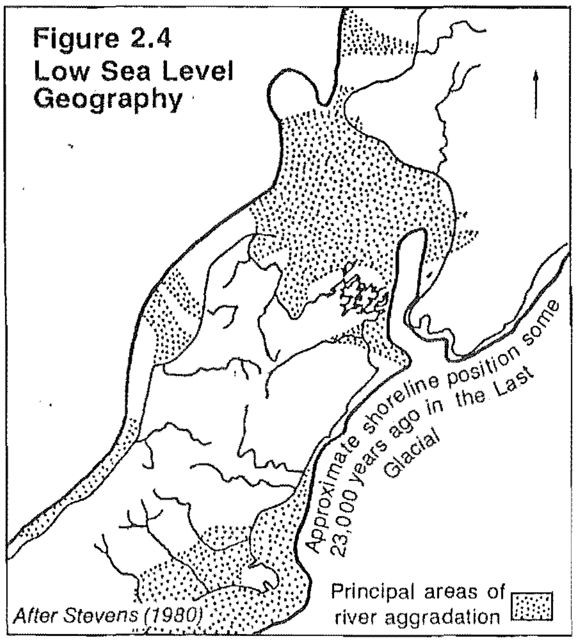


Figure 2.4 Low Sea Level Geography

Above: Units mapped as Speargrass Formation (from Beck, 1964) are identified with Otira (last) glaciation. Formation outcrops as incised terrace remnants in Kaituna and Pelorus River Valleys. Remnant terraces are found in Cullens Creek, at Oruapuputa, Kaiuma Bay, and in northern reentrants of the lower Pelorus Valley as well as in bayheads throughout Pelorus Sound.

Left: Marlborough Sounds shown as abandoned by sea during glacial low sea levels.

formation of a lake, fed by water from Wheadons and Cullens Creeks, and possibly also from the Pelorus.

Other silty deposits in the Mahakipawa Arm also suggest a history of lake-ponding. A 30m long exposure of lake sediments at Bellvue Bay, first identified by the author at GR 777 908 (Map 2), was shown by Esler to have been subject to rotation by slumping. Organic matter preserved in a 2m thick deposit, comprising leaves (?Nothofagus), and twigs was dated by ^{14}C. A "new half life" of 35,900 ± 2,200 years BP (N.Z. 6594 B) corresponds to a phase of major aggradation of the Pelorus and infilling of an early lake. Esler suggested (1984, p38) that this 36 Kyr lake is much older than the other lake deposit remnants, and that these probably date to the end of the Last Glaciation. Lake sediments of unknown age were identified in the upper reaches of Wheedons Creek bed at GR 784 890 by the author and P. Kingsbury (Dept. Geology, University of Canterbury) in 1986, at an elevation below the surface of the 14m terrace.

There are no other published references to terrace remnants in the Sounds. In view of the development of terraces in the Cullens Creek/Linkwater area, they might be expected in other small catchments in the Sounds and further reference to terraces is made in Chapter 8.

Alluvial fans of low (1-5°) gradient are found in bay heads and extensively in some locations such as the Northern Kenepuru. These can be seen in Plates 2.1c and 8.1a. They are the most dominant alluvial forms throughout the Sounds and have a partly Quaternary origin. The extent of these features is wider than appears as in most parts of the Sounds the original forms are drowned. The Linkwater area and the Kenepuru are the two most elevated, upstream or "inland" parts of the Sounds. In less elevated locations, alluvial fans which may have developed are now concealed under mud deposits on the sea bed. The extent of those fans presently exposed depends therefore on their antecedent position in a fluvial landscape. That there are more extensive exposures of alluvial fans in the Pelorus Sound (Nydia Bay, Clova Bay) compared with the Queen Charlotte, indicates the relatively deeper drowning of the Queen Charlotte inlet system, as well as possible difference in their pre-flooding distribution. Bayhead gradients as they now appear tend to reflect the degree of "drowning" of former alluvial fans.

(c) Flooding by Fluctuating Sea Level

Sea level reached a minimum of about 150m below its present level in the last glaciation (Chappell, 1983), and with fluctuations in successive glacial and interglacial episodes would have caused the sea repeatedly to occupy and abandon the Sounds. Fleming (1962, p89, in Soons, 1968) estimated the geographic effect of sea level fluctuations. Soons (1968, p611) concluded that even if sedimentation had occurred in the Holocene, "virtually the entire Sounds area would have been dry land during the last glaciation". A map of the shoreline location during the period of low sea level is shown in Figure 2.4.

Sea level rose at a rate estimated at 1m per 100 years over the period 14,000 years BP until 5,500 years BP (Stevens, 1974, p204). During these long periods of rising and falling sea level, the valley bottom vegetation would have been transformed to swamp. Cotton (1969, p66-7) considered that the repeated flooding would lead to successive deposition and the gentling of the valley bottom gradients.

> "After the last of the regressions the gradients of the upper reaches of the streams flowing on exposed ria floors would, judging from soundings in rias, be only about 3 in a thousand. Thus these rivers, though they flowed over unconsolidated silts, would not entrench themselves, because they would be small streams draining small catchment areas. Withdrawals of the sea would not therefore result generally in rejuvenation."

Seismic profiles in Pelorus Sound reported by Carter (1976) (Figure 2.5 with the addition of subsequent profiles made available by him to the author, and discussed in Chapter 8, show (Recent) marine muds overlying a surface attributed by Carter (1976) to fluvial or marginal marine conditions. The seismic reflection is attributed to a gravel surface in the case of a "hard" line, or to an organic or gas-rich horizon in a less defined line. Carter (1976, p275) encountered shell rich greywacke gravel in piston cores taken in the Pelorus Channel.

A ^{14}C date from "Peat/Wood" in Ohingaroa Bay (P27 GR 841 951) below sea level gave a date of 2,000 years BP. The source of the material would appear to be tree roots and stumps exposed in the lower foreshore, and the author has identified similar roots at other sites in the vicinity. This post-glacial date can be interpreted as reflecting active marine erosion of the earthy surface materials in which the plants were rooted. It might be tempting to attribute to this date some evidence of either sea level rise or local submergence. However, local slope evidence indicates that this site is subject to deep-seated mass movement and that the apparent submergence is strictly local.

Shoreline Form and Dynamics

Unpublished work on shore type and wave energy environments on enclosed shores include two theses by Boyce (1971) and Newton (1977). These comprise the main body of research completed within the Marlborough Sounds.

Shore Classifications

Both Boyce (1971) and Newton (1977) produced four-category shoreline classifications. The elements were:

(a) *Hard-rock shores*

Attributed to the removal of unconsolidated material from steep hillslopes, Newton (1977) distinguished three sub-groups.

i) "Rock wall" shores in hard rock

ii) "Abrasion ramp" shores in softer rocks, including some surficial lag deposits

iii) "Reef" shores where differential hardness and vertical structure produces barriers to longshore flow of material.

(b) *Pocket beaches*

Characterised by a small depth of material overlying a hardrock abrasion ramp. The distinction between subgroups is made on the basis of the importance of upslope supply of materials.

(c) *Linear Deposits*

Associated with a gentle subaerial profile, linear deposits are found to extend hundreds of metres alongshore, in contrast to the spatially varying pattern of the other shore types. The deposits are associated with a wide, low angled foreshore, along which longshore transport of material takes place.

(d) *Bay-head beaches or deltas*

Newton (1978) distinguished bayhead beaches initially on energetic grounds, noting their protection from all but direct onshore winds by protruding headlands, and their protection from strong tidal action. The

> latter is a feature of Tory Channel. Reference was made also to the underlying materials (derived from the hinterland) and the working of material into the bayhead by marine processes. The latter reference suggests that the bayhead beaches of the Sounds are akin to bayhead beaches on typical embayed coasts described by Zenkovich (1967).

This classification is discussed in later chapters. While Zenkovich (1967) noted that such shore types are characteristic of enclosed, embayed coasts, such a diversity within a small area is rarely discussed systematically in the coastal literature. While the literature includes classifications of complex shores, to address the factors which determine shore form sedimentary character and dynamics requires reference to the underlying controls.

Wave Energy Environment

Newton (1977) made reference to repeated surveys of shore profiles taken on various types of shoreline over a six month period. As well as distinguishing between sites, a key finding of this analysis was that parts of the profile were more responsive than others, notably those portions with the more abundant and finer sediments. Consequently, pocket beaches were the only (shore) type which showed morphological responses directly comparable to beaches on the open coast, which are more commonly refered to in the literature. Newton showed by gravel tracer experiments that sediment transport did take place on "linear ramp" shores, though intermittently. Large portions of the bayhead deltas showed no morphological response to wave action over the measured timescale, although multiparametric correlations of some morphometric variables relating wave fetch length to profile characteristics indicated an apparent correlation. This is discussed in the Shoreline chapters.

Measurements of waves derived from wind events and from the wakes of the 4800 to 6800 tonne Road/Rail Ferries by Newton (1977) pointed to the characteristics of the energetic environment. The characteristic wave shape derived from local winds was shown to be steep and of short wave-length. The waves were akin to those found in a lake environment. A significant difference from the lake wave environment is the presence of tides, of the order of 1.5m in the Queen Charlotte Sound, and 2.5m in the Pelorus.

Inlet Sedimentation

The study of Carter (1976) is the prime reference on inlet sedimentation in the Sounds. This study was restricted to the axis of the Pelorus Channel and to a traverse from Tawero Point to the Heads, as shown in Fig 2.5b. The lines do not extend inland ("upstream") of Putanui Point. He concluded that, although sediments were scoured near headlands (see Figure 2.5a), sediment thicknesses increased towards the inner end of the Sound. The source of this sediment was attributed to the inflow of the Pelorus River, and to estuarine processes pertaining to this inflow. On the basis of the identification of planktonic diatoms in sediment in the Outer portion of the Sound (Burns, 1977), Carter suggested that sediment was being swept into the Sound from the seaward end. The interpretation given the Pelorus Sound axial channel on this basis was that of a "double ended sediment trap".

Carter described the estuarine circulation behaviour as "moderately stratified" (p265), noting that in summer it may change to almost vertically homogeneous. In extreme high river flow conditions such as identified by Carter in June/July 1973, the Pelorus River developed a surficial brackish layer within the top 5m. No intermediate sampling points within this layer are available to indicate the detailed thickness of the layer. The brackish layer extended down the Pelorus Channel to Tawero Point. This was suggested as being the condition under which most sediment enters the Sound from the Pelorus River.

Evaluation of Some Key Postulates of the Literature

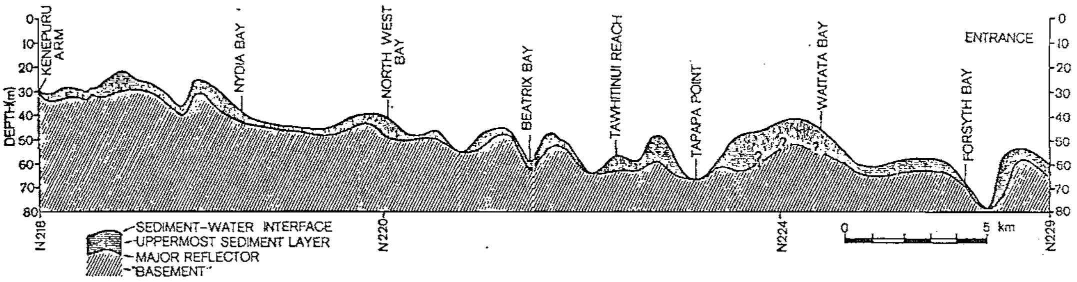
Earlier views of the landscape of the Sounds have highlighted its physiographic characteristics, and in particular the manner in which the Sounds are regarded as a "tilting earth block". The shoreline studies have illustrated the variety of coastal types and its low-energy character. Hydrographic study has given rise to a description of the Pelorus Sound as a "double-ended sediment trap". Each of these descriptions of the character of the landscape of the Sounds contribute to present understanding. The aim of this section is to evaluate the extent to which the present literature has general applicability to the coastal landscape of the Marlborough Sounds.

Figure 2.5

Pelorus Sound Submarine Profiles

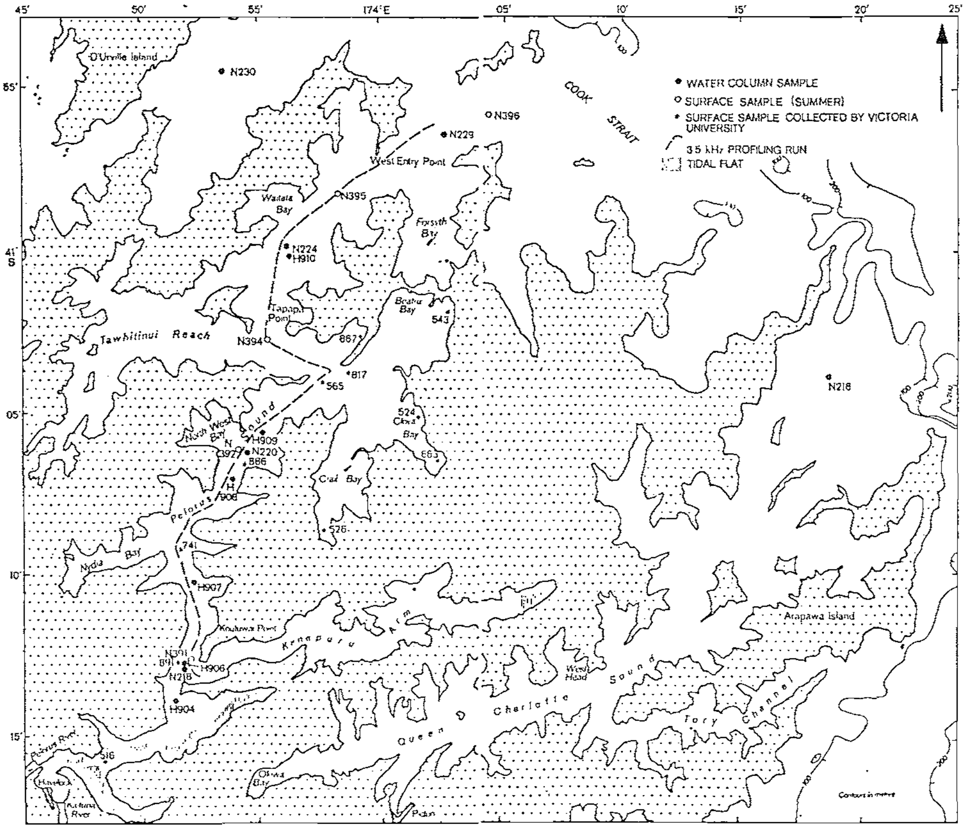
(from Carter, 1976)

Figure 2.5 a. Sub-Bottom Profile



Original Caption: Variation in thickness of the modern mud cover (uppermost sediment layer) along the length of the Pelorus Sound, interpreted from the 3.5k.Hz sub-bottom profile track shown [below in Figure 2.5b]

Figure 2.5 b Axial Track of Sub-Bottom Profile



Locality map of Marlborough Sounds and the track of the sub-bottom profile, above.

First Postulate
Marlborough Sounds Geomorphology as a "Tilting Block"

Reference has been made to descriptions of the Marlborough Sounds as a "tilted (and submerged) earth block". It has not been established at what rates this subsidence occurred, or may still be occurring. Part of what has come to be regarded as the "conventional wisdom" of the Sounds landscape is the hypothesis of the reversal of drainage of the river systems which were responsible for shaping the Sounds. Any interpretation of subaerial or submarine morphology must give due heed to these elements of conventional explanation, since it is possible that if tilting is on-going, it may materially affect the interpretation of sedimentation rate data, and the interpretation of coastal forms.

It was noted by Esler (1984), that there may be grounds for questioning the widely repeated hypothesis of "block tilting" and of subsequent drainage reversal. The following section comprises an assessment of the stated evidence for the Tilting Block view.

The development of a "tectonic view" of the Sounds stems from four postulates. These are:

a) That the Marlborough Sounds is an earth block
b) That the Sounds block has been subject to vertical movements
c) That the Sounds block has been subject to tilting
d) That block dynamics can be related to a broader tectonic mechanism.

The postulates develop in the literature in chronological order. The first arose in the context of the initial geologic regionalisation of New Zealand. The second in the attempts to contrast the regional physiography of the Sounds with adjacent regions. The third evolved from the first two, and is defined in the 1964 Geological map. This map was a benchmark of explanation, in which a coherent physiographic interpretation of the landscape was advanced for the first time on the basis of a regionally extensive base of observations. This accounts in part for the adoption of certain widely held views into the subsequent literature. The fourth postulate has been adopted since as a further explanation of this third view.

(a) The Earth Block Postulate

Since the first reference by Cotton (1913, p139) to the area as the "Sounds block", the region has been widely regarded as one of the "concourse of earth blocks" which comprise New Zealand. (Cotton, 1916, p319). Jobberns (1936, pp24-26) discussed the proposition advanced by Henderson (1924, p592) that the Sounds consisted of a system of fault-bounded earth blocks. Regardless of its internal structure however, Jobberns concluded that "the country contained within ....two converging faults has behaved as a unit whether or not it be composed of fault-bounded blocks of a minor order" (Jobberns, 1936, p26). This view was formed on the evidence of the large-scale physiographic appearance of the area, rather than on quantitative or local evidence. His reference to the major ridge-and-valley forms as corresponding to features of "minor order" is significant of the scale of analysis.

The "fault-block" conception of the Sounds was a break from an earlier phase in which the structure of New Zealand was interpreted as "simple anticlinal up-arching" (see Gage, 1980, p270). In this form, Cook Strait had been interpreted by Crawford (1874) as a "down-warped" feature. Gage (1980, p271) characterised the period up until 1937 in geological investigation in New Zealand as one having "an obsession with explanation involving faults". A key proponent had been a head of Geological Survey, J. Henderson (Gage, 1980, p271). The Geological Survey maps of that period pictured the country "as a mosaic of raised or tilted rigid blocks, having either moved vertically or rotated about horizontal axes". Importantly, Gage noted "there was little field evidence to support either [the anticlinal or the fault-block] version" (1980, p271).

That the Sounds area is lithologically and physiographically distinct from adjacent areas is not in doubt. The proposition in question contains the seed of the assumption that the Sounds area is behaving tectonically as a single block, and thus that more attention should be focussed on its regional behaviour with reference to its neighbours, than to the evidence contained within so called "minor" landscape features.

b) Vertical Displacement Postulate

The first regional physiographic description of the Sounds area was by Cotton (1913, p318). The landscape had been "dissected to early mature stage by normal agencies in a single erosion cycle", before being drowned by the "accident" of downwarping. This statement reflects his Davisian training. A "single erosion cycle" was initiated from an "initial surface", proceeded through a series of stages from youthful V-cut valleys, through maturity to an "old-age" of low-relief. Although one might be tempted, mused Cotton (1913, in 1955, p70), to project the steep valley-side slopes to a deep V - a "veritable canyon"- i.e. to a form that would approximate "youth"- he rejected this in favour of an interpretation of the landscape as "mature".

He pointed to the evidence of the flood-plains at the heads of valleys, and concluded that the valleys at drowning were "graded, flat-floored and broadly opened". In this, his early view, Cotton thus attributed the flat-bottomed form of the Sounds, not to sedimentary infilling, but to the stage of erosional development. Tectonic downwarping was the necessary step to achieve flooding by the sea. No other mechanism (such as sea level change) was "available" for explanation in his model, which did not postulate for sea level changes.

The mechanism of glacio-eustatic sea level change was not widely recognised until the early 1950's. The evidence that sea level had varied by up to 130m or more in the Holocene (whereas Cotton had previously put the last glaciation at least 100,000 years BP), prompted Cotton to observe that it was now "necessary to recast most generalised theories of shoreline development" (Cotton, 1952). Cotton's response to the eustatic mechanism was the addition of a footnote to his 1913 paper (dated 1951, in Cotton, 1955) which incorporated a sea-level mechanism. The 1951 revision proposed a two-stage hypothesis of drowning. The first stage involved the tectonic down-warping of what had developed as a "mountainous landscape". The accompanying photograph (Plate 4, 1955) suggests this is to be interpreted as youthful (V-form) valleys. As noted by Esler (1984), this is a revision of his 1913 view. The second hypothetical stage was to involve the submergence of the landscape by post-glacial sea level rise. By this time, however, the rivers were to have achieved "grade". During the glacial period, valleys were to have infilled by "profound sedimentation".

This view makes a very different interpretation of evidence from the 1913 view, although the significance of the change is scarcely reflected in its placement as a footnote. The landscape would now be erosionally "youthful", and the river valleys only appear "mature". The importance of this is the amount of subsidence which was interpreted from the landscape as having to have taken place. If in fact the Sounds had eroded to a "deep V" form, then the "block" would have to have been much more elevated in order to sufficiently lower base level to cut the gorges. From this line of argument developed the necessity for the block to "founder" or be substantially submerged by down-warping.

If the landscape in fact developed to what Cotton would call a "mature" form such as it appears to be today, then no down-warping would be required to obtain the present physiography. Because upper hillslope development will have proceeded regardless of a flooded condition or not (aside from micro-climatic changes), the only area of debate relates to the lower 0 to 50 m of the hillslopes presently comprising the submarine slopes, the broad bay (valley) bottom flats and what underlies them. The physiographic requirement is for there to be a sufficient lowering of baselevel for a sufficiently long time, for the river systems to remove detrital materials from the valley floors down to the level of rock basement.

Preliminary geophysical surveys by Modriniack and Marsden (1938) suggested a flat-bottomed valley form to the Sounds. This survey was restricted to the Linkwater area, and showed an overcapping by fan sediments. Subsequent submarine profiles have identified only the gravel sub-bottom and not underlying bedrock.

Eustatic variation can account for present physiography. The hypothesis of downwarping is not required, therefore, to account for any specific landscape evidence. The debate hangs only upon the rate of development of the landscape, in particular its rate of sediment production. Assuming, as is discussed in a later chapter, that the effects of marine occupation act at only small scale, then the crucial factor is whether eustatic lowering of baselevel could have given a sufficiently long period for the landscape to form. If not, a warping mechanism may be necessary. Cotton's early work (pre 1964) cited no evidence for tilting associated with inferred tectonic downwarping.

(c) Tilting Postulate

In 1964, a coherent view of the physiographic origins of the Sounds was espoused by Beck (1964), in the text of the 1:250,000 scale geological map. The key tectonic element was now interpreted as tilting rather than simple downwarping. Cotton had based his initial reasoning on baselevel changes, and restricted his quantification to the necessary depth of incision of the seaward end of the valley systems. The revised 1964 interpretation made reference to two elements of the landscape as implied evidence for tilting - summit elevations, and remnant terraces. Subsequent literature developed interpretations of other landforms in the light of this model, particularly with respect to various drainage patterns.

(i) *Summit Elevations*

Beck (1964) began his description of physiography : "Ridges rise to more than 5,000ft in the south and to 3,000ft in the north". This would appear to accord to a model of tilting northwards, which was proposed in the same paragraph. The origin of the tilting hypothesis was traced by Esler (1984, p23) to Henderson (1935). In the earliest physiographic description of the central and southern Sounds area McKay (1879b, p100) had speculated that the district had been part of a "plain of marine denudation, highest along its south and south-east boundary and sloping gently north". Marine planation had been a dominant explanation in the 19th century, after the views of Andrew Ramsey, 1814-1891 (Tinkler, 1985, p116).

It is not apparent whether McKay intended his "plain" surface to be interpreted as inclined by mode of origin or by subsequent tilting. Henderson (1935, p14) took the implication from McKay's article that there had been elevation and tilting, and allocated this to the late Tertiary period. Cotton (1957) explicitly rejected the existence of any evidence for an "initial surface" in Marlborough, correlative or akin to the "K" surface of the Wellington district, and thus by implication rejected McKay's original hypothesis.

Reference to the topographic sheet (Map 1) shows that in the north, Mount Stokes reaches 1203m (3951 ft), well over the 913m (3000ft) of Beck's approximation. Furthermore, evidence of altitude differences does not serve as evidence of tilting, because in the absence of any "initial" remnant surface, altitude differences reflect primarily the extent of dissection.

(ii) *Terrace Remnants*

Beck (1964) stated "downwarping and tilting towards the north has drowned the large terraces that were developed". On the 1:250,000 scale Geological sheet, remnants of low terrace gravels (mapped "sg" or Speargrass Formation gravels, Table 2.1) are mapped in the lower reaches of the Cullens Creek Valley, mid to southern Kaituna Valley, and the Pelorus Valley above Canvastown as shown in Figure 2.4. Lake silts in distinctive terraces had been identified in the Mahakipawa as early as 1878 (McKay, 1879,1890). and were not mapped on the Beck sheet. At the 1:250,000 scale, small-scale features cannot be mapped precisely.

The "large terraces" referred to by Beck have not been described in any published source. In the light of the tectonic physiographic model, however, such a pattern of terraces might have been expected. The interpretation is akin to that advocated by W.M. Davis:

> "The chief object of physiographic analysis is to provide a safe explanatory theory with respect to the origin of certain observed features, so that the imagined counterparts of the observed features and of many related features may be systematically deduced from the theory"
> (Davis, 1915, p71)

It is quite important, in the light of subsequent work which has taken the model of Beck as confirmed, to make a clear distinction between what is "evidence" and what is theory, model or hypothesis.

(iii) *Reversal of Drainage*

The research note proposing a hypothesis of drainage reversal for the Sounds (W.R. Lauder, 1970) was cited as evidence in support of the Beck model of tilting, acute angled "branch streams" (bays) joining the main channels, and the valley wind-gaps at Linkwater and Kaituna, as shown in Figure 2.6a. The model of tilting referred to above now appears to gain a measure of confirmation from the hypothesis of drainage reversal. The two sources of evidence specified were the acute angles with which marginal bays joined the main channel; and the windgaps. There are alternative explanations available for the windgap valleys.

Furthermore, when the "evidence" of acute angle form is examined on a map of larger scale (Figure 2.6b), the argument is seen to be unsubstantiated.

The drainage reversal hypothesis has been widely cited in major earth science texts since its inception (Stevens, 1974, 1980; Gage, 1980; Thornton, 1985; Campbell and Johnston, 1982), and, if not necessarily accepted, the view is cited without critical comment. The amount of tilting which would be required to displace or reverse a drainage system which was already deeply incised would be very substantial. (J. Soons, Department of Geography, University of Canterbury. Pers comm. 1987) .

Brown (1981) referred to the tilting hypothesis to account for constrained river flow of south-flowing tributaries in the Sounds block as they emerge onto the Wairau. The alternative hypothesis proposed by Brown that the constriction of drainage is related to aggradation of the Wairau is a valid explanation and accords with his evidence for rapid post-glacial aggradation of the Wairau bed. Aggradation of the Wairau was, coincidentally, the mechanism by which Cotton (1913) accounted for the constrained drainage in the lower reaches of the Tuamarina Valley.

While the hypothesis of drainage reversal cannot be rejected, it can nonetheless be regarded as one of the less confirmed hypotheses relating to the origin of landforms in the Marlborough Sounds.

d) Broader Mechanism: *The Tilting Block and Plate Tectonics*

Jobberns (1936) described Marlborough as a series of tilted blocks with valleys in the fault angle depressions between. The implication has apparently been broadly taken that the Sounds area has behaved in a similar manner, although the possibility of different behaviour because of positioning on the north side of the Alpine Fault has not been raised in the literature. The tectonic mobility of parts of New Zealand has been recognised since last century and attributed to a number of causes. In recent years this might be said to have "taken on the mantle" of Plate Tectonics. Tectonism is commonly attributed to New Zealand lying athwart the boundary between the Indian and the Pacific Plates, and regional differences attributed to the differring situations with respect to the plate boundary (Suggate, 1982, p1). In the most extensive tract relating New Zealand regional tectonics to the Plate Tectonics control Stevens (1980) interprets the Sounds in relation to the

Figure 2.6

Drainage Reversal Hypothesis

(after W.R. Lauder, 1970)

Figure 2.6 a. Schematic Map of Hypothesis

Hypothesis proposed that large-scale physiographic form of the Marlborough Sounds could be accounted for by the cutting of the landscape by rivers which flowed southwards from catchments at the northern boundaries of the region.

A catchment divide in the outer Queen Charlotte was proposed to have subsided with regional tilting towards the north. Evidence cited included the location of valleys in the south which lack headwaters, and the oblique alignment of bays in the north of Queen Charlotte Sound.

Reference to the actual orientations (Fig 2.6 b below) shows that the claimed orientation is an artefact of the analysis of physiography on small scale maps.

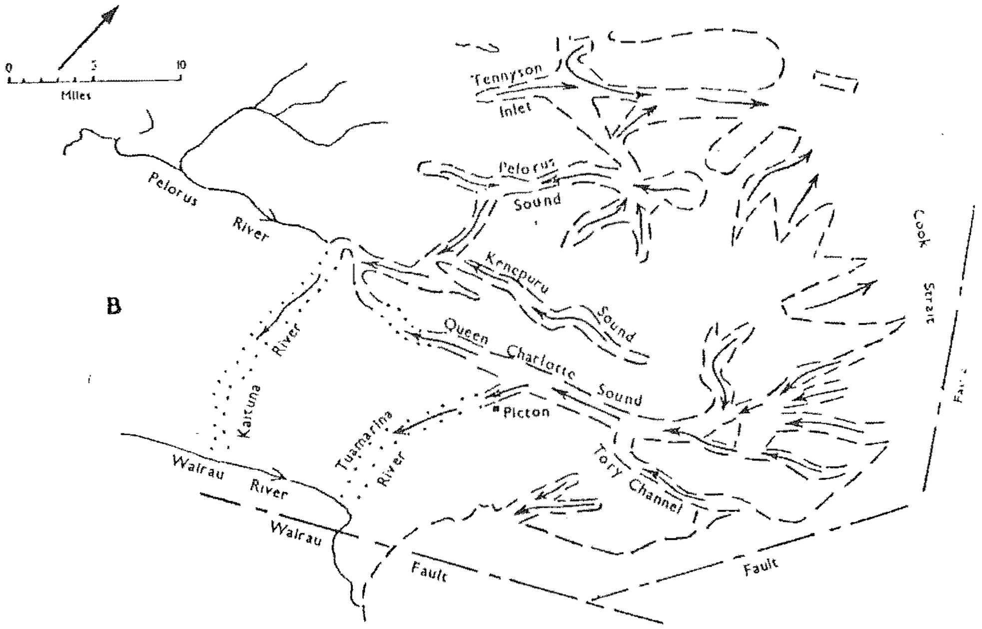
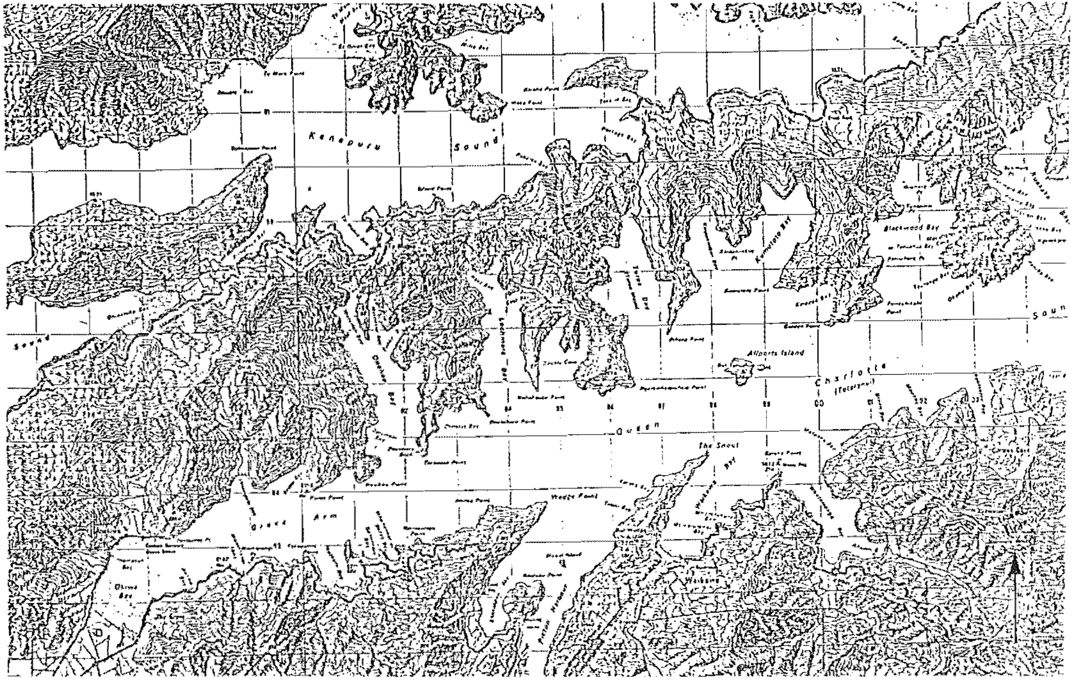


Figure 2.6 b. Larger-scale Evidence (Source : NZMS 260 1:50,000 sheet P27)



Alpine Fault. Some lithological similarities to the Sounds prompted Stevens to identify Kapiti Island as being on the leading edge of the tilted "Sounds block".

Evaluation

In investigation and interpretation of the tectonic behaviour of the Sounds block a number of hypotheses have been advanced. None is yet definitively constrained by available evidence. There is a need in review, however, explicitly to distinguish evidence from hypothesis. There has been little detailed investigation of geomorphic features within the Sounds area to serve as a base of evidence against which to assess the tectonic viewpoint.

Suggate (1982, p1) noted: "It is probably more pertinent here to note that studies of many landforms can contribute vital data that needs to be taken into account in considering the plate tectonics hypothesis". The priority, it would appear, is to identify more completely in the landscape those "remnant" features both subaerial and submarine, that can serve as evidence by which to test models of landscape change before a conclusion can be reached as to whether the Sounds are most usefully described as a "tilted earth block".

Postulate 2
The "Low-Energy" Shoreline

Newton (1977) characterised Tory Channel as a "low-energy" shore system. Such a classification is accurate as a relative gauge of wave energy levels in comparison to an outer-sea coast subject to swell and storms. However, it can be reasonably asserted that it is not so much wave energy, per se, as "wave effectiveness" (with respect to its ability to transport sediment and modify shore form) which is of most relevance in coming to a better understanding of shore dynamics.

If part of a shoreline is responsive to incident energy (in terms of sediment transport or changing form), then the waves are in this instance more effective than on the unresponsive shore. Wave effectiveness can thus vary, even while wave energy levels remain broadly similar; and it is wave effectiveness which has cogent implications for the form, the sedimentary character, and the dynamics of the shore. Thus while the description of the Sounds shoreline by an index of wave energy can be a useful relative index, the key to understanding the variability of the Sounds shoreline would appear to lie in a consideration of those factors which influence wave effectiveness. In the investigation which follows, the two factors which are given prime consideration are shore gradient, and shoreline sediment composition.

Postulate 3
Inlet Sedimentation as the "Double Ended Sediment Trap"

The seismic profiles presented by Carter (1976) showing sediment thicknesses in the axial channel of Pelorus Sound added appreciably to the knowledge of the offshore system. However, some caution must be used when interpreting this evidence for other inlets in the Sounds. The Queen Charlotte Sound lacks entirely the substantial external catchment of the Pelorus River and even the Pelorus Sound is only dominated by the sediment discharge of the Pelorus when it is at its highest flows. Thus, without laying aside Carter's conclusion that the largest flow events may be those which feed most sediment into the Pelorus Sound, there are inlet and bay situations in the Sounds to which the Pelorus model may have little or no relevance. It is a matter for investigation to what extent bayhead streams determine the sedimentary patterns in their adjacent bays and the extent to which marginal bays flanking major channels act as independent traps for catchment derived sediments.

Summary

This chapter has reviewed the scientific literature pertaining to landform history, shore character and inlet dynamics in the Marlborough Sounds. The literature on geomorphic and geologic aspects shows the strong imprint of various eras of thinking about the landscape. While not all of this material appears as valid in the light of contemporary views, a substantial body of knowledge has nonetheless been developed. The literature on the shoreline and the inlets has had a geographically limited scope but serves to stimulate further research.

The geologic literature points to the role of both lithologic and structural factors as playing a role in landform development. Lithologic aspects important to contemporary landscape behaviour are weathering characteristics, especially the development of clays and planes of weakness, and detrital characteristics, especially the platy shape of schist clasts. Structural factors influence geomorphic processes directly through dip slope angles on hillslopes, controlling intricacy of shoreline form, and indirectly by way of the effects of faults and earthquakes on hillslope stability.

No well confirmed pattern of dated deposits or forms has yet emerged, on which to constrain the timing of landform development. The initial "mature dissection" of the hardrock form constitutes the earliest phase of landscape development, the impress of which can be observed in the contemporary landscape. Windgap valleys have been attributed to variation in the courses of early rivers (Esler, 1984) which have modern equivalents rather than to hypothetical subsided catchments. If the development of the windgaps was related to the diversion of rivers through them, this diversion preceded the aggradation phases which gave rise to at least two levels of terraces in the Kaituna Valley. These terraces indicate drainage in the same pattern as that in the Holocene.

Reference was made to Quaternary hillslope development, river processes and sea level change. Few dates constrain any consideration of landform age in the Sounds, but some weathering evidence points to the stability of at least parts of the hillslopes since the penultimate interglacial. Other soil evidence points to upper slope erosion in late Quaternary times. Morphological and some colluvial materials evidence point to the effects of Pleistocene cold conditions in colluvial fan development. Related morphologies are terrace remnants, which point to variations in catchment sediment production, probably in cold-warm transitional periods of the Pleistocene thought to be associated with environmental instability. Further reference is made to terrace systems in the discussion of offshore morphology in Chapter 8, in which offshore form is shown to contain substantial information to tie together observed subaerial landforms. Sea level fluctuations have been crucial both in effecting river incision, and in the alternating transformation of the Sounds from a terrestrial to a coastal landscape.

The shoreline in particular is a distinctive set of landscape features. An aspect of shoreline character which has been given only limited consideration is the sedimentary character. This aspect is of particular interest with respect to the wider landscape, because of the role the shoreline plays as a depositional location for backshore and catchment sediments. This aspect is addressed in Chapters 5 to 7.

While there is a limited literature on inlet dynamics, aspects of it point to a number of interesting relationships. Of particular interest is the trapping behaviour of the inlets with respect to sediments. Two aspects are in need of further investigation: first, the scale at which trapping occurs, and secondly, the mechanisms of trapping. The aspect of scale is relevant both to the interpretation of sedimentation rates data and to determining the most appropriate sampling interval for the investigation of mechanisms. This is addressed in Chapters 5, 8 and 9.

Chapter 3

Catchment Modification and Sediment Delivery

The development of the form of the Marlborough Sounds landscape has taken place by the redistribution of sediments. In the previous chapter, landform development was discussed in a Quaternary time frame, with some reference to shorter and longer timespans. Evidence of the sedimentary functioning of the Marlborough Sounds landscape over a Quaternary time span is seen in hillslope (colluvial) fan accumulations, alluvial fans in the valley bottoms and in the river terrace remnants which have been found in the inner Sounds. In the Holocene (since 10,000 years before present) the development of the accumulational forms has continued. Descriptions of the contemporary coastal form include references to ongoing infilling of bayhead locations (Boyce, 1971; Newton, 1977; Campbell and Johnson, 1982).

Reference was made in Chapter 1 to contemporary concerns regarding the effects of catchment modification on the coast. The possibility of such effects was identified in a major planning document (Crown Study, 1976) as part of the "planning problem" for the region. In 1981, Johnson et al. raised concerns with regard to some specific effects of forestry landuse practices, and McQueen et al. (1985) cites these concerns as grounds for further study of soil erodibility. The purpose of this chapter is to place these observations in a broader framework of landscape change.

The extent of catchment modification over different time frames is reviewed in the first section. In the second, a consideration is made of some cited cases of coastal changes. In the third section, analysis identifies certain difficulties in obtaining estimates of sedimentation rates, but points to specific means by which investigation can proceed to a better understanding of catchment-coast linkages.

Overview of Catchment Modification

With regard to the manner in which evidence is retained in the landscape, Walling and Webb (1983) note that the consequence of catchment modification is closely related to that of changing climate. Over the long term, warming and cooling temperatures influence sediment yield by the mechanism of vegetation change. They note that:

> "in the shorter term, the impact of human activity in modifying catchment condition and therefore sediment yields must be examined" (Walling and Webb, 1983, p84)

The extent to which sediment yields differred under Quaternary climatic conditions from those currently prevailing is not established. Schumm (1968) concluded that peak sediment yields may have been of the order of four times higher during geological eras when vegetation was absent. Walling and Webb (1983) consider this an underestimate, and suggest that in areas where the difference between modern vegetation and the Quaternary cover was radical (i.e. well-developed vegetation against bare ground) the rates may have differred by ten times i.e. an order of magnitude. It is significant that Walling and Webb (1983, p71) also identify a New Zealand example in which two estimates of contemporary sediment yield, obtained by different methods, differ by nearly two orders of magnitude (Cleddau River, West Coast).

A distinction must be made in all investigations of sediment yield between the contributing factors of erodibility of the terrain, and the erosivity of the hydrometeorological regime (Walling and Webb, 1983). The abiding problem with the assessment of the effects of human activity on landscape sedimentary behaviour is the absence of long term records of either climate, or of landscape responses to changes. Selby (1982, p223) demonstrates that the rate of change in most landscapes is extremely variable, yet notes that terms such as "accelerated" and "normal" erosion rates are in common use. The preferred term for erosion resulting from human interference is "induced" erosion.

Throughout New Zealand, catchment changes attributed to the actions of Polynesian and European peoples characterise the history of human occupation (Williams, 1980). Sedimentary deposits in the landscape show evidence of both natural and anthropogenic fires. From the late 1930's, studies of the high country by Zotov, Cumberland and others (Whitehouse, 1984) highlighted a view that the burnoff of catchments by early European settlers had been responsible for much of the observed erosion in the high country. Whitehouse (1984, p29) reports on a changing perception of erosion in the preceding decade:

> "Traditionally, early European farming practices have been blamed for a large share of [high country] erosion. Modern researchers, however, question this view, and seek to place the impact of the European

> pastoralist into perspective against the effects of natural factors and the fires of the earlier Polynesian era."

Radiocarbon dating of charcoals found in soil profiles in Canterbury, Marlborough and North Otago dates fires at about 600-1,000 years, and about 130 years ago. A set of river terraces might be expected to result from such burnoffs, yet Whitehouse records that such terraces have not been identified. Soil profiles throughout the Southern Alps are reported to record "local instability resulting from soil slips, debris avalanches and debris flows triggered by high intensity rainfalls". (Whitehouse, 1984, p33). The implication of this observation emphasises the role of the hydrometeorologic factors in initiating changes in landscape stability. The role of the clearance of catchments may be seen as lowering the threshold of response to these events.

No review has been completed of the chronology of clearance in the Sounds from the perspective of sediment delivery. Such a review is the first step in the investigation of contemporary sedimentation, by placing it in a broader

Primary Occupance

Limited historical evidence of the period preceding European settlement indicates that occupance of the Sounds by Maori peoples had been widespread, but at low intensity. Migrating in waves from the north, their life focussed around the canoe and small bayhead settlements. Midden shell accumulations, accompanied by argillite tools or flakes, are common relicts in the bayhead flats and are evidence of Maori occupance. The argillite was sourced from Elaine Bay (Ponder, 1986, p141), or D'Urville Island. Pits are found on ridges adjacent to the argillite flake accumulations.

The first written record of the Sounds Maori is Captain James Cook's observation in 1770

> "The people lie dispers'd along the shore in search of their daily bread which is fish and fern roots, for they Cultivate no parts of the lands". (In Bowie, 1963)

Totaranui (Queen Charlotte Sound) was then populated by the Rangitane tribe, and Te Hoiere (Pelorus Sound) by the Ngati kuia. Accounts of previous occupance vary in details. It is related by Bowie (1963, p25) that until the arrival of the Ngati kuia about 1550, and the Rangitane about 1650, the region was occupied by the Ngati Mamoe. It is recorded that the staircase earthworks, pits and shell middens found throughout the Sounds are attributed to the Ngati Mamoe, who were apparently successful cultivators of the shoreline flats.

The Maori population greatly diminished following the inmigration of the Ngati Awa and affiliated tribes from Kapiti under the leadership of Te Rauparaha in 1828, who conquered the resident tribes. In 1843, many of the Maori in the southeast fled north fearing European reprisals after the Wairau Incident.

Other than the limited modification of shoreline and ridgeline areas, it would appear that during several hundred years of Maori occupance there was no extensive modification of catchments, and that modification did not extend to widespread use of fire. A possible exception is the Port Underwood region.

Catchment Clearance by European Settlers

On 15 January 1770 Cook discovered and named Queen Charlotte Sound. After a landing at Ship Cove in the outer Queen Charlotte Sound, exploration was restricted to the outer Sound.

With the transfer of "ownership" of the lands from the stewardship of the dominant Maori groups to European interests, the catchments of the Sounds were subject to clearance of vegetation to an extent and at a rate with no historical equivalent. Feral goats on Arapawa Island and at Ship Cove, and pigs, deer and oppossum, have had an effect on vegetation in those regions where they became established. The effects of this on hillslope stability has not been assessed.

The Stimulus for Clearance

Large-scale clearance and land development began in the southeast and inner Sounds in the middle of last century and proceeded "outwards" over the next 50 years. Clearance of the lands stemmed first from the demand for timber for the growing colony towns, especially Christchurch. The transition to burning as a means of land clearance began as the flats were cleared (Bowie,1963, p29).

It is significant that the stimulus for this expansion of cleared lands came not from the demand for production, but from the demands of new settlers for land of their own. The introduction of the national regulations governing Perpetual Lease, in 1882, and Lease in Perpetuity, in 1892, meant that:

> "Even during the depression [of the 1880s] when hill country already cleared was becoming infested by Tauhinu and the cut-over flats reverted

> to fern and scrub, new hill clearing was stimulated by leasehold farm tenures."
> (Bowie, 1963, p29)

Sub-regional Differences

There were variations in the original vegetation of these catchments, and in the timing and type of modification. The sub-regional pattern of development is examined in four areas: the Queen Charlotte and Port Underwood area, the Inner Sounds area, the Pelorus and Kenepuru area, and the Outer Sounds.

Queen Charlotte Sound and Port Underwood

The districts of Tory Channel and Port Underwood were first settled by Europeans for reasons of good access. Shore-based whaling stations were established by Guard at Te Awaiti in 1827 and Port Underwood in 1828. In 1836 Port Underwood was the main whaling port in New Zealand. There was cultivation of grain and vegetables on the river flats, and potatoes under shifting cultivation on the lower hills. (Dieffenbach, 1850, in Bowie ,1963).

By 1854, hill country on Arapawa Island as in Port Underwood had been cleared by burning, and used for sheep grazing. The expansion of the sheep industry developed from the Depasturage Regulations (1853), and by 1870 "almost every bay in the Sounds had its clearing, and sheep were running both on the clearing and in the bush" (Bowie, 1963, p28). By 1880, slopes up to 100 and 300m were clear of bush (Bowie, 1963). With the exception of the high country of Mt. McCormick to the west, over 70% of the sub-region was clear by 1910, as can be seen in Figure 3.1

The vegetation of the more exposed parts of Port Underwood was not forest at the time of the European arrival. On his arrival in 1839, Dieffenbach (1840, p85) noted that

> "The chain of hills which forms the bay to the southeast (of Ngakuta in Port Underwood) is barren in the extreme; only here and there is a patch of brushwood or trees."

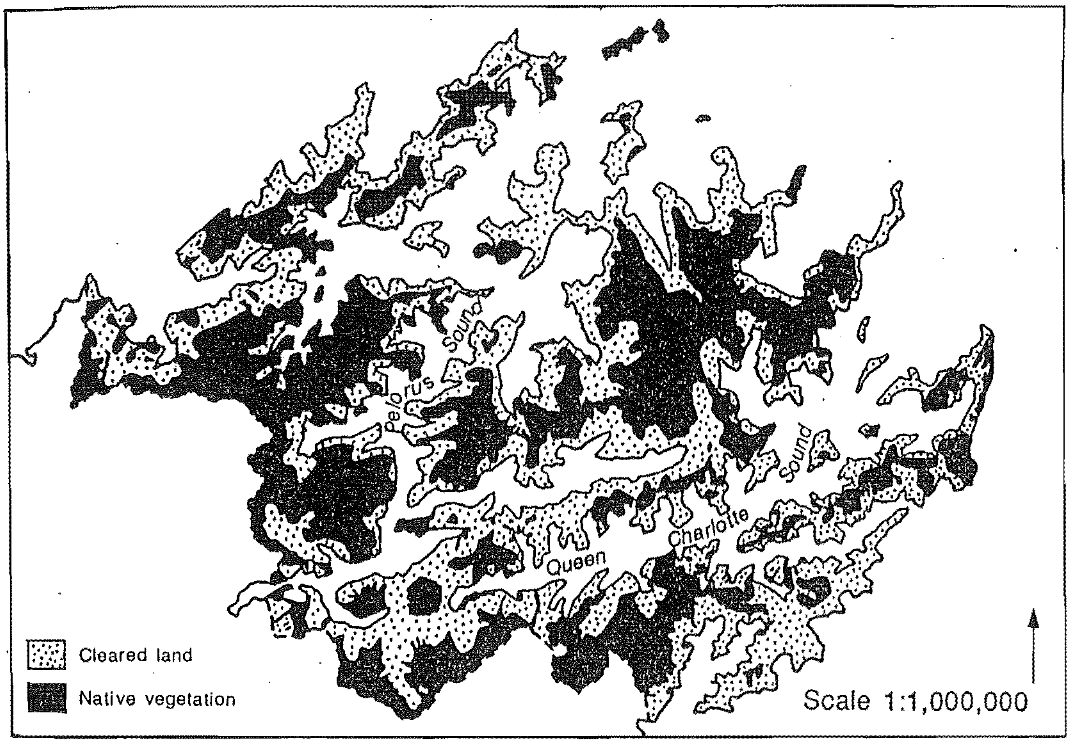
Bowie (1963, p15) identified this grassland association as Danthonia pilosa and bracken fern Pteridium aquilium var. esculentum, occasionally broken by manuka (Leptospermum ericoides) or Tauhinu scrub with some broadleaf shrubs in the gullies. It is possible that Polynesian fires played a part in establishing this land cover.

Figure 3.1

Catchment Clearance, 1910

(from Bowie, 1963)

Catchment burnoff and logging from 1850 had cleared over 50% of Sounds region by 1910.



Catchment clearance by European settlers began in the southeast and on Arapawa Island by 1854. Flatter areas were logged, then burnt, while hills were burnt to extend area of pasture. By 1910, over 50% of the 1,480km^2 of catchments had been cleared of native bush.

Following the Waitohi Land Purchases of 1850 and 1854, logging and clearance began for European settlement. The resident Maori peoples had been reserved 10% of the land, and largely migrated to the Waikawa district. By 1880, all the hills about Picton had been cleared, the southern slopes of the Grove Arm, and most of the "peninsulas" on the flanks of bays on the north of the Sound. By 1910, all of the land on the ridge from the head of the Mahau Sound to the head of the Kenepuru had been burnt, with the exception of the bush behind Umungata (Davies Bay), Kumutoto and the ridgetop to the northeast (Bowie, 1963), as shown in Figure 3.1.

Inner Sounds

The inner Queen Charlotte was first penetrated by Europeans in 1832. There is no recorded further visit until 1843 by a party from Nelson (Wilson, 1962, p16).

The Victoria Mill was established by Duncan at the Grove in 1861, and began to log a grove of Kahikatea from which the district got its name. Kahikatea was found on the swampy areas, Totara, Matai and the dominant Rimu on higher ground, and Beech associations on the steeper land. The latter was not favoured, and rarely logged. While the land at the Queen Charlotte end of Linkwater was freehold (Wilson, 1962, pp26-30), most of the milling proceeded from the release of land by the Crown starting at the Mahakipawa in 1857 (Bowie, 1963, p27; Paton, 1982; Wilson, 1962). In the 1860's, five sawmills operated at Linkwater (Bowie, 1963, Appendix 2), and 1867 was the peak year of local production. By the end of that decade, the district comprised ploughed fields, and the sawmills moved to the Pelorus and Kaituna rivers.

Logging in the inner Pelorus began with Brownlee, who landed in 1864 at Mahakipawa, having been granted government cutting rights to a 1000 acre block in the valley. A small engine and boiler drove a single travelling sawbench. A wooden tramway was built, the trams being hauled by horses. Bullock teams hauled the logs to the tramway (Paton, 1982, p7). The sawn timber was stacked near a jetty. Punts were floated in on the high tide, and let rest on the shore while the timber was loaded at low tide. The punts were then towed to the ship anchorage off Cullens Point. A similar method was used at the Grove. The timber at Mahakipawa was cut out between 1864 and 1870, and the pioneer sawmills moved to the Kaituna Valley from 1870 to 1885. The mills had abundant labourers who had migrated into the area after the short-lived Wakamarina goldrush of 1864. The Wakamarina River discharges into the Pelorus 14km upstream from Havelock.

During the period 1866 until 1871, logs were floated out of adjacent bays to Havelock, to a competing sawmill. After this operation failed financially, Brownlee floated the mill to Nydia Bay in 1876, and cut out the 1000 Freehold acres that were available to him by 1880. The mill was then moved back to Kaiuma Bay, and by 1887 had cut out the accessible timber. In this operation, as for the Mahakipawa, the logs were loaded at Cullens Point. After 1885, when the Kaituna mills closed, the Brownlee operation worked up the Pelorus River from Havelock. The new mill was at Blackball, 13km west of Havelock (Paton, 1982).

Pelorus and Kenepuru Sounds

After landing at Port Underwood in August 1838, Lt Chetwode in HMS *Pelorus* sailed with Guard as pilot to the inner end of "Te Hoiere", to Black Point, then by pinnace to Kaituna, the site of Havelock. In 1839, the *Tory* with Wakefield aboard sailed also with Guard, and penetrated further up the Pelorus River.

The logging which was conducted at Nydia Bay was completed by 1880. By 1910, partly by the use of fire, the lower slopes of all the bays in the mid Pelorus from the Hikapu Reach to Tawera Point had been cleared, with the exception of the south facing slopes, possibly because the higher rainfall in the west (locally over 2500mm) and shade prevented a full burn.

By 1880, the centre of sawmilling had shifted from the inner to the mid Pelorus, especially to the Kenepuru. In the period 1880 to 1895 , milling declined as a major economic activity. The Kenepuru mills were moved, or timber was rafted to the mill, sometimes long distances. In 1910, the condition of the Sounds was described by Owen (1956, p133) as

> " a log strewn landscape with blackened stumps of forest relics".

Logging of the Manaroa Valley in the outer part of Pelorus Sound began in 1869, by Godsiff and Beauchamp (Ponder, 1986). By 1880, only limited areas of the valley floors had been cleared, a shoreline strip around Crail and Clova Bays, and isolated sites such as Maud Island (Bowie, 1963, Figure 13). At Harvey Bay in Tennyson Inlet, Will Harvey began logging on the flat in 1879. Alexander Duncan later set up a mill at Tuna Bay (Ponder, 1986).

By 1910, only the flats in Tennyson Inlet had been logged. It is likely, though, that the better trees had been taken from Tawa Bay and Godsiff Bay. However, the hillslope of the north-facing Brightlands Bay frontage had been cleared, as had the land northwest of Crail Bay, all the northern shore of Beatrix Bay, and the lower slopes of Hallam Cove at the foot of Mt Shewell around to Waitata Bay. Bowie (1963, p37) suggests that the native vegetation was dominantly beech forest.

Hillslope Stability of Farmed Land

Residents recount periods after heavy rains when hillslopes were extensively "scarred" by surficial slips. After a storm in the Kenepuru in the early 1930's, Mrs B. Scott (Hopewell,1983, Pers. comm.) reported the hillslopes of the southern Kenepuru having upward of 30 large slips from Broughton Bay to Portage (10km). Most reports of hillslope instability after burn off or during the farming era relate to high intensity rainfall. An inventory of historical slips could be acquired today, but no systematic record is yet available. Regeneration of secondary growth over many of the less productive areas (including the steepest country) hinders the assessment of slip scars.

Other Historical Catchment Changes

The discovery of gold in the Cullens Creek catchment (Map 2 GS 8186) in 1888 led to a short-lived gold-rush, but one which involved over a thousand miners. A report (in Wilson, 1962, pp86-87) on the field for the Mines Department by Henry A. Gordon in September, 1891 described the workings as follows:

> "As the principal workings have been confined to the bed of the creek there have been many difficulties to encounter owing to the floods which have occurred from time to time. The shallow workings near the head of the creek still have to be carried on with open face, and the open workings are still carried on where the depth does not exceed twenty feet. These open workings are liable to be filled up with every flood and flood debris has to be removed before any returns can be obtained. The creek above Prospectors' Claim has all been worked, so that the miners are confined to about two miles of the creek bed and a small portion of the flat near the township on Mr Cullen's freehold."

The other site of gold-mining within the region was in the Wakamarina River, as referred to above. The significance of goldmining as a disturbance of detrital materials is possibly more apparent than any other single catchment modification, although effects were localised. These effects are discussed in the following section.

Contemporary Catchment Changes

The four primary landuses which involve the modification of catchments today are farming, forestry, residential development and roading. Activities associated with these include changes to vegetation cover, track construction, soil cultivation, dragging logs, excavation for roading, side casting and dumping of spoil. The effects on the hillslope stability arise through disturbance of hillslope hydrologic factors, notably flow channelisation, disturbance of the structure of the detrital and soil profile, and the over-steepening of slopes.

Coastal Response: Cited Evidence

In the regional literature, various instances are cited as evidence of coastal changes in historical times. Most specific references are to channel changes in the Lower Pelorus River, and infilling in the Havelock Estuary and in the Mahakipawa Arm. There are also general references to the effects of burnoff on hillslope stability, with an implication that coastal changes were a consequence. This section reviews some of the specifically cited instances of change.

"Infilling" at Havelock

It has been claimed that much larger ships could once sail into Havelock than can at present. This is attributed to sedimentary infilling of the Havelock estuary. In 1854, Capt Drury aboard HM Survey Vessel *Pandora* anchored off Moutapu. He recorded, with regard to the navigability of the inner channels:

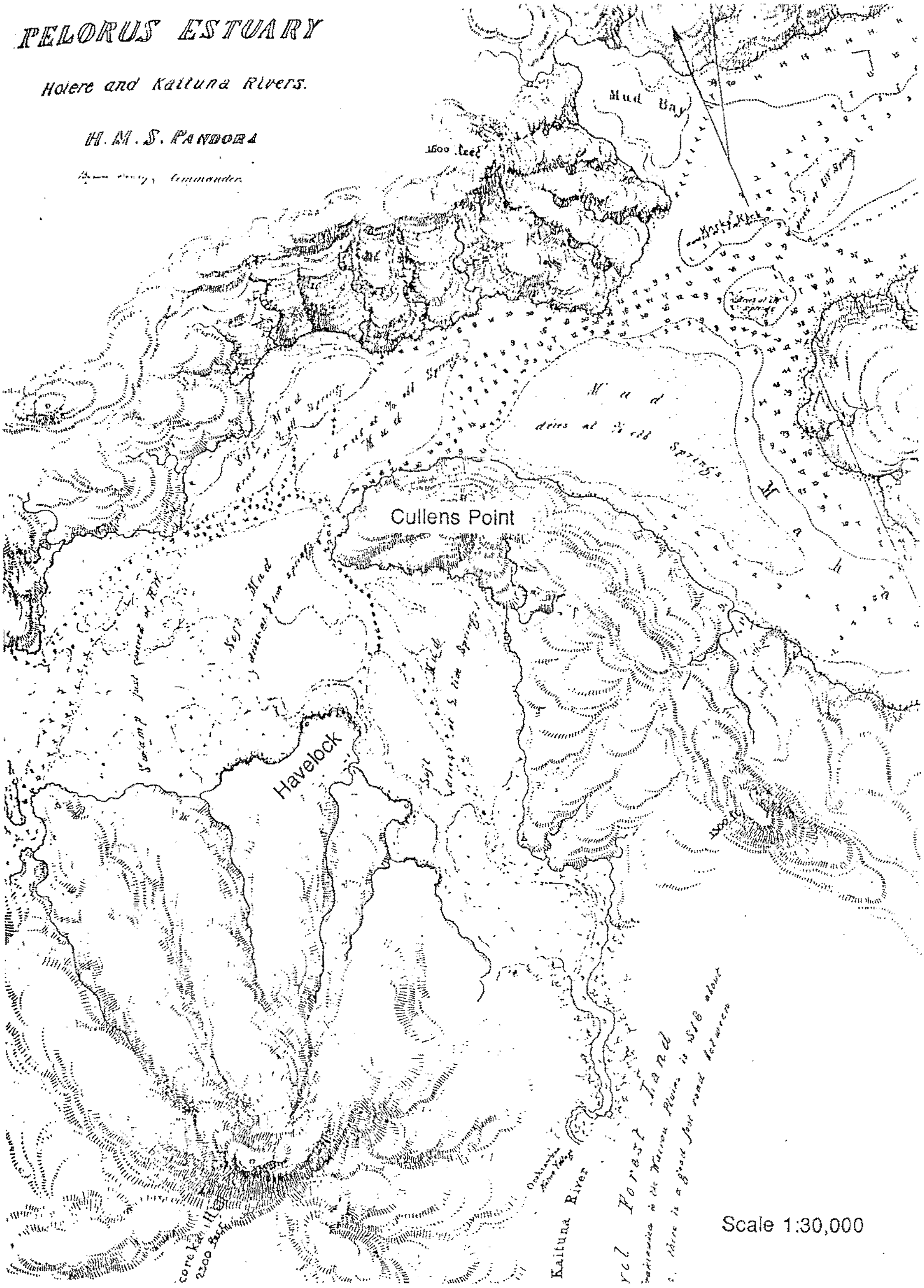
> "Near the East Head of the Mahakipawa the rivers Hoiere [Pelorus] and Kaituna meet forming banks and leaving channels only navigable for small boats".
> (in Wilson,1962).

An early map (Drury, 1854) shows the channel pattern in the "Pelorus or Hoiere Estuary", a portion of which is reproduced in Figure 3.2. The map shows substantial mudflats in the Kaituna embayment of the estuary, drying at mid tide and with a form similar to those found today. A notable difference stems from the

Figure 3.2

Havelock Estuary Bathymetry, 1854
(from chart by Drury, H.M.S. Pandora1854)

Chart indicates extent of mud-flats and tidal deltaic deposits in pre-Clearance period.



location of the shoreline at the mouth of the Kaituna River (cf Map 2), which relates to the construction of the Kaituna River causeway.

The Marlborough Harbour Board reports migration of the Cullens Point Channel over the period since 1945 (D. Jameson, Marlborough Harbour Board, Pers. comm. 1985). This migration is a lateral phenomenon, associated with some modifications in channel geometry. The channel characteristics of the estuarine area in the lower Pelorus are deltaic, with one or a few principal channels. Depositional sand bars swathed in and incorporating mud occur at the divergences of flow. Dredging of the approaches to the Havelock marina has been necessary but no trend towards a much smaller channel (as distinct from the trend towards larger boats) has yet been established. Even the natural dynamics of a delta system could be highly variable.

The observation of Drury does not exclude sedimentation having occurred but it does suggest that channel conditions which restrict navigation today were also applicable then.

Channel Changes in the lower Pelorus River

Buick (1900) makes reference to channel changes in the lower Pelorus Valley. Photographic and documentary evidence shows that, notwithstanding the evidence of Capt Drury from the *Pandora* cited above, substantial vessels sailed up the Pelorus River to load timber at Blackball, 8km up the Pelorus from 1885 onwards. Paton (1982, p22) quotes his primary sources:

> "Adjoining the mill there was a wharf, where vessels drawing from seven to ten feet could berth at low tide. Three vessels were kept continually employed loading timber for the Canterbury market."

Most notable here is that while the vessels of this draught could berth at low tide, it is not suggested that they could leave the harbour at the low tide. While there is less depth at the Blackball meander of the Pelorus today than there apparently was then, this could be accounted for either by the fluctuations in hydraulic geometry of a meandering river, or by increased bedload transport with possible increased peak flow since catchment clearance. However, it cannot be assumed that the character of the Pelorus River has been transformed since initial clearance, as Buick (1900) cites floods in 1838 raising the lower Pelorus River level by 10 feet (3m), in the era before European clearance began.

A further factor could stem from sediment mobilised by gold-mining in the Wakamarina catchment in 1864, as this material will have tended to migrate down-river over a period of years. Assuming that the limiting factor was channel depth in the lower reaches of the river, the fact that ships of up to 10 feet (3m) draught could sail from the river mouth in those days, but could not today at low tide does not contradict either historic or contemporary observation. The tidal range of around 2.5m is adequate to lift the tidal river reaches to an amount sufficient to accommodate that draught.

Intertidal Rubble Heaps

Heaps of cobbles and boulders of mixed lithology are to be found on the intertidal surfaces in a range of locations including Okiwa Bay , Moutapu Bay, Kenepuru Head, Mahakipawa Arm and elsewhere. A rubble heap in the Mahakipawa Arm is shown in Plate 3.1c. There has been speculation that such rubble heaps, in areas of shallow water, may serve as evidence for infilling on the grounds that large ships could not sail to those locations today.

The use of flat-bottomed punts to ferry logs from shore to ship has been well documented (Wilson,1962; Paton,1982). This involved the transfer of ship's ballast on the shore-going trip. The ballast would be unloaded when the punts were in the shallows or lying dry at the low tide. Therefore, no profound nearshore sedimentation need be invoked in order to allow for a deep-draught vessel to drop large rocks in what is today shallow water. Boyce (1971) reported that the ballast stones were not deeply buried in mud. Field checks show that this is correct and that in most cases the ballast stones rest on a gravel sub-bottom underlying the mud.

Mahakipawa Jetty Infilling

Boyce (1971) reproduced photographs (reproduced here as Plates 3.1a and 3.1b) of the jetty on the inner Mahakipawa Arm near the Linkwater cemetery (Map 2, GR 806 904), one taken in 1973 and the other taken last century (from Wilson,1962). The photograph aligned with jetty piles that were taken to be in-situ remnants of the early jetty.

A local farmer (now retired) D. Jennings ("The Rock", Mahau,1986, Pers. comm.) reports that excavations in the upper intertidal surface near the "old" stream mouth, shown in Figure 3.3a, encountered replicate deposits of the surface rush vegetation at several depths down to 9 feet (3m) below the surface.

Plate 3.1

Historical Shoreline Features, Mahakipawa Arm

Plate 3.1 a

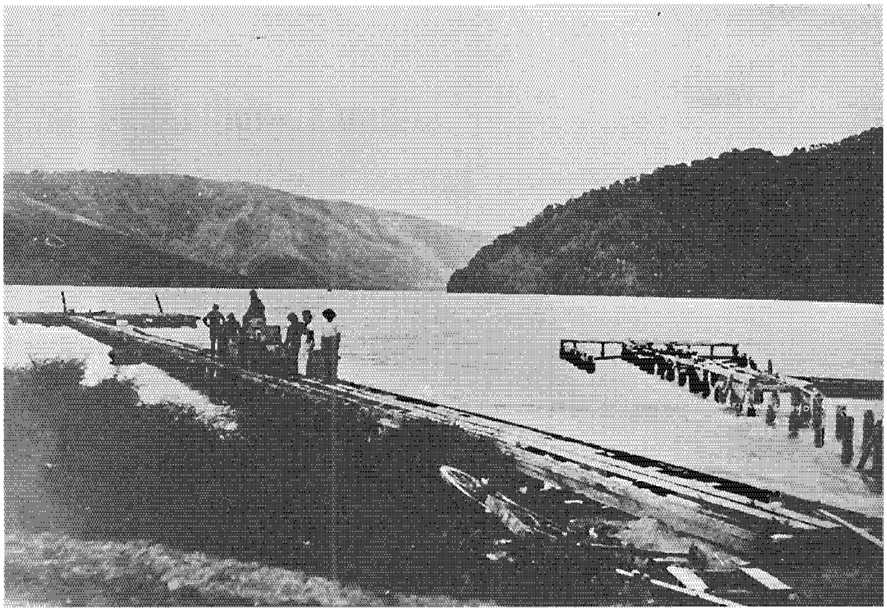
Mahakipawa jetties 1896, (from Wilson, 1962).
Historical reports conflict over the depth available at high water.
It is unlikely that the jetties could have been used at low water, although sedimentary evidence points to measurable changes in the upper tidal flat..

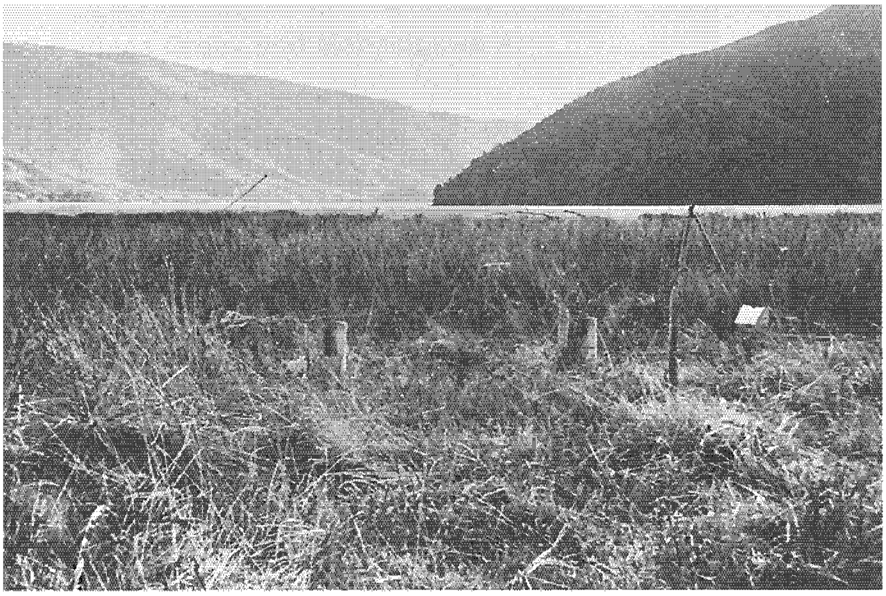
Plate 3.1 b

Remnant piles of the right hand jetty in 1971 (from Boyce, 1971).
Seaward vegetation limit then 300m beyond piles.
Piles can not longer be located. Boyce concluded on the basis of the stability of vegetation patterns on the delta 1943 to 1971, observed in air photographs that the apparent rapid advance of the vegetation front and the retreat of the high tide level took place between 1896 and 1943.

Plate 3.1 c

Heaps of ballast stones on the intertidal surface at Oruapuputa, Mahakipawa Arm. The heaps have been interpreted as evidence of sedimentary infilling of the embayment, because ships could not sail inshore to these locations today. However, flat-bottomed punts which were used to carry logs to ships moored off Cullens Point.carried ballast on the inward journey. Ballast was dumped on the intertidal surface
when the punts came to rest on the shore at low tide. Mud thickness around the heaps varies from 0.1m to 0.3m. Most heaps rest on firm fluvial gravel surfaces.





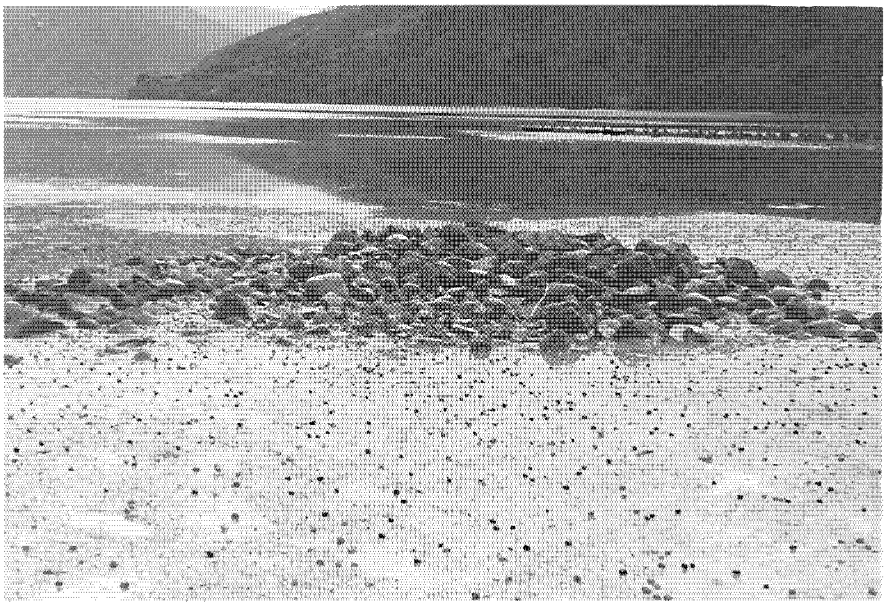


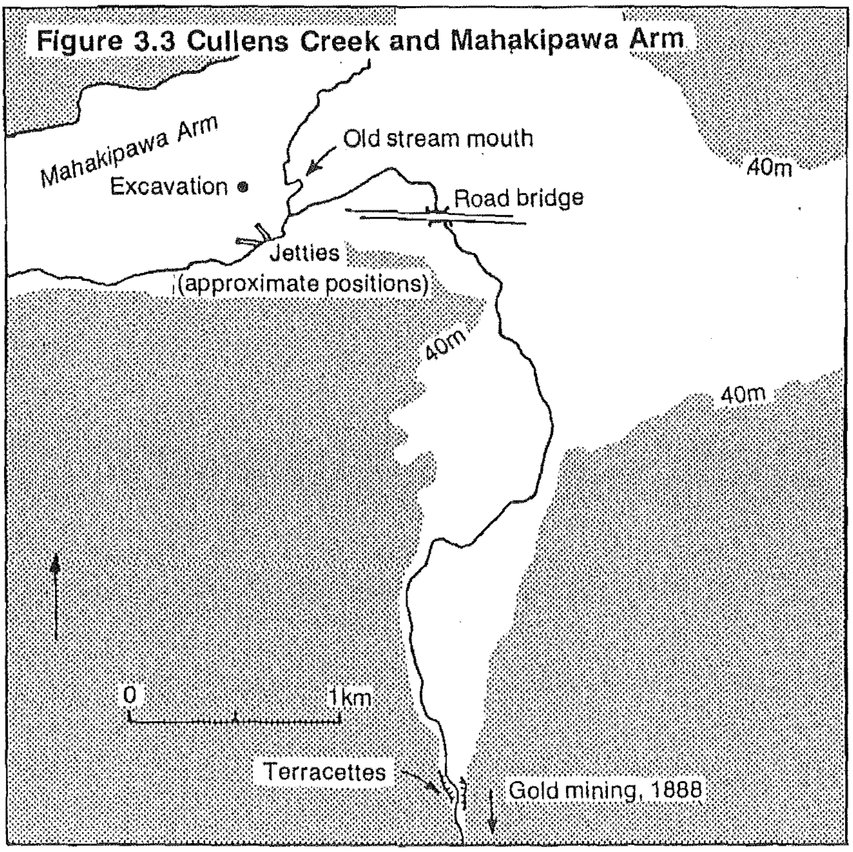
Figure 3.3

Cullens Creek and Mahakipawa Jetties Location Map

Gold-mining in the Cullens Creek catchments in 1888 involved sluicing of valley sides
and delivery of sediment into a steep narrow gully.

Terracettes at the mouth of the gully record palaeo flood events in chaotic particle orientations and silt prisms.
Channel straightening on agricultural land on the lower reaches took place earlier this century.

Marked changes in the elevation of the intertidal surface in the proximity of the stream mouth is recorded in the photographs in Plate 3.1 between last century and 1971.



The intervening deposits comprised "river gravels". He also reported river gravel deposition on the delta during his occupation of the property adjacent to the stream channel mouth, over the period 1963-1970.

Jennings reports that in the lower Cullens Creek adjacent to his property, the channel bed was up to 20' (6m) below the surface of adjacent paddocks. On the Title Deed the stream was classified as a "sludge channel". The bed of the creek is today only 2m below the paddock surface at the road bridge (Map 2, GR 808 907). The creek bed is comprised of gravels up to 200mm in size, but predominantly finer with a sandy matrix. During floods today, the channel tends to broaden rather than deepen, with substantial marginal scour which led to the damage and replacement of the bridge in 1983-84. This behaviour would seem to contradict the cited historical pattern. However, a similar stream in the lower reaches of a Kenepuru bayhead stream, seen from the bridge at GR 052 048, is as deeply incised as Jennings reports the Cullens Creek had been.

The apparent infilling of a deep channel can be linked to channel changes in the lower reaches of Cullens Creek. The channel naturally meandered, but with property development on the flats earlier this century some of the meanders were cut off. The morphologic consequence of this would be the steepening of stream bed gradient. An increase in mean velocity would increase shear velocity, and consequently shear stresses; and hence increase bedload transport capacity. If the supply were available, this would lead to an increase in the sediment transport rate along the lower reaches, and deposition where gradient diminishes - logically in the lowest stream reaches and on the Mahakipawa intertidal surface.

These changes are predicated on the availability of sediment for transport and deposition. The straightening of natural channels is not liable to produce a river channel plan-form which remains stable. Lewin (1983) found that artificially straightened reaches tend to develop meanders quite quickly, which leads to bank erosion and thus a source of sediment. The straightening of itself in the lower reaches may have resulted in an increased bedload supply to the shore.

The reaches of Cullens Creek immediately below a narrow gorge today show evidence of incision of terraces and terracettes at Map 2 GR 815 977. The general imbrication of gravels indicates fluvial processes, but the interspersing of silts and sands and locally chaotic imbrication suggests flood deposition. Historical sources correlate the period of gold mining with extreme floods in Cullens Creek.

The historical changes in the lower reaches of Cullens Creek, coupled with the historical catchment changes, identify this as a site in which a high historical sediment discharge down the stream has occurred. A conclusion of measurable intertidal aggradation is coherent with other evidence.

Surveyed Shoreline Changes

In 1985, only three sites on the shore had been identified by surveyors as warranting a redefinition of the "line of Mean High Water" since first surveyed (J. Henderson, Chief Surveyor, Blenheim, Pers. comm. 1985). The three sites identified related to the displacement of the shore seawards in front of small streams by up to four metres, or to shore displacement by slippage in the backshore.

Review

The historical record of catchment changes and coastal modification is incomplete, but points to a number of ways in which investigation could proceed to a better understanding of the factors involved.

Estimating Catchment Erosion

The analysis of contemporary erosion and sediment yield is widely used as a means to hindcast and forecast the magnitude of changes in sediment yield produced by land use changes (Walling and Webb, 1983). The Universal Soil Loss Equation (Wishmeier and Smith, 1965, 1978) has been a standard model in the analysis of erosion rates, but most investigations are empirically based. The distribution and severity of erosion at the national scale in New Zealand have been mapped by Eyles (1985) but the work does not make a distinction between geologic and man induced erosion and does not estimate erosion with respect to the movement of sediment into stream courses (Griffiths and Glasby, 1985).

Present knowledge of sediment yield in catchments draining into the Sounds is limited. No continuous monitoring of water or sediment discharge is conducted for the Pelorus or smaller streams (Rae, 1981). Hewitt (1982) has calculated rating curves for small catchments in the Sounds, but with data for mainly low flow conditions. Griffiths and Glasby's (1985) estimation of the mean annual discharge of 319,000 tonnes per year of largely suspended sediments (basin specific annual suspended yield of 357 tonnes/km^2/yr) was based on an estimate of mean rainfall, and correlated to catchment area by the use of a regression equation of data from a number of rivers in the South Island. The Pelorus is the largest river which enters the region, with a catchment area of 894 km^2. Other catchments are at least an order of magnitude smaller than this.

A study of the response of small catchments to landuse practices by O'Loughlin et al. (1980), has some relevance to the Marlborough catchments. Several small catchments in the Tawhai State Forest (42° 05' S, 171° 48' E) in the Mawheraiti River headwaters 5 km northwest of Reefton were used in a paired catchment experiment to evaluate the effects on sediment yield of burn-off and forestry logging practices. The mean rainfall at Tawhai of 2600mm compares with an estimate of 2500mm in the west and 1500mm in the east of the Sounds (Hewitt, 1982). The Tawhai basins were of small size- from 1.6 to 8.3 ha. Three basins with a vegetation of mixed beech/podocarp/hardwood forest were monitored in particular. A control basin was not subject to modification. One was completely clearfelled then logged with a skyline system. Logs were dragged downhill to a log loading landing near the basin mouth. Another was logged with rubber-tyred skidders, using an access track near the perimeter of the basin. Both basins were burnt following logging.

The two significant changes reported, with direct relevance to the Sounds, are the effect of burning, and the effect of disturbance of slopes and streambanks.

Burnoff

O'Loughlin et al. (1980, p288) note that "for the first 18 months after the burn, the stream water ... was often discoloured grey-brown, due to the presence of fine suspended ash materials during higher flows and dissolved organic materials." The burnoff of the entire basin had removed most of what was recorded as "heavy logging debris accumulation" in the stream channel region. It was observed that:

> "the filtering effect of the wood debris which remained in the stream channel after burning, and the rapid growth of grass, fireweeds and the liverwort Marchantia on the lower slopes and streamside areas, restricted sediment transport."
> (O'Loughlin et al.,1980, p289).

Track Construction

In one Tawhai Basin, wheel skidders were used and a perimeter track constructed. In this basin, sediment yields were recorded which were eight times that in the control and six times those in the basin which was logged by skyline hauler. In the tracked basin:

> "most of the sediment supplied to the stream derived from the track surface or the loose soil and gravel accumulations which were sidecast onto the steep slopes below the track during its construction. A study of the track surface erosion rate ... indicated that the sediment yield rate from the track surface approximated ... 60 per cent of the stream sediment yield rate. During storm rainfalls track surface runoff diverted via artificial cutoffs or natural cross track rills into first order tributary gullies and flowed downslope through the riparian protection zone into the main stream".

The significance of these findings for the Sounds lies in the relative importance of catchment modification which is restricted to burning of the vegetation, as compared to the effects of the direct disturbance of the surface materials.

It has been shown in the international literature, that at some sites, severe fires coupled with instability of the soil have apparently accelerated erosion. However, the long-term efects of burning in most localities are uncertain due to poor knowledge of the soil-formation/erosion balance under different vegetative covers. There is no unequivocal evidence for long-term landscape degradation as a result of burning and Walling and Webb (1983) suggest that the recovery time will depend on local conditions. Observations in the Sounds suggest that most hillslope instabilities are relatively quickly revegetated. The downstream effects may be of a more persistent nature, however, due to the enclosed nature of the receiving environment.

McQueen et al. (1985) also highlight the effects of the disturbance of sub-soils within the Marlborough Sounds. In particular, the sub-soils were found on investigation to be relatively more erodible, and the clays more dispersive, than those found in the upper layers of the profile.

Internal Storages and Sediment Delivery to the Coast

The difficulty in linking estimates of catchment erosion to their coastal effect lies in the indeterminate extent to which sediment eroded from hillslopes reaches the coast. The concept of the sediment delivery ratio (Robinson, 1977) involves an assessment of the proportion of gross erosion and mobilised sediment which actually leaves a catchment.

Walling and Webb (1983) note that most existing studies attempting to relate the delivery ratio to catchment characteristics have employed a simple inverse relationship with catchment area. From a range of compiled values, they show that for large catchments of around 1,000km^2, the ratio could range from 5% to 50%. In small catchments of 1 to 100km^2, values of 50% to 100% are typical.

Increasing awareness of the significance of internal storages in catchment systems makes the task of assessing sediment yield much more than one of measuring sediment discharge over a short sampling period and correlating this with catchment conditions. Complex response is to be expected in middle-sized catchments in which the cumulative effects of local variability are not damped by an overall regional uniformity (Slaymaker, 1987). A lagged response is characteristic of systems with internal storage, and the extent to which the small to middle order catchments in the Sounds operate with significant storages has not been established.

Not only fine material is mobilised as the result of land use practices, as was demonstrated by the Cullens Creek case study. The results of hillslope instabilities on the shoreline are discussed in Chapter 6, and illustrated by Plates in that chapter. In terms of sediment delivery, a prime distinction can be drawn on the basis of the location of the detrital disturbance. When catchment disturbance has taken place on slopes or in stream channels adjacent to the sea, a notably greater proportion of material which is eroded is delivered to the shore. Not only is this a matter of volume of material, but also of the range of grain sizes delivered.

"Proximal" erosion is found to deliver the full range of particle sizes that are found in the hillslope detrital profile, from clay to cobbles. Steep streams discharging directly onto the shore, with little or no fan surface in their lower reaches, are observed to deliver a higher proportion of coarse material, as would be expected with the relative importance of the bed-load component in transport. Erosion in larger catchments, further from the sea, may include initially a wide range of particulate sizes, but the relative importance of suspended-load in the sediment discharge of larger rivers determines the nature of material delivered.

Therefore, while present knowledge of catchment disturbance is insufficient to establish the amount of material delivered historically to the coast, it is possible to distinguish a range of sediment delivery regimes on the basis of the range of material sizes which are delivered to the coast. The recognition of this textural component of sediment delivery is of prime importance when coastal sediment patterns and behaviour are analysed in the context of catchment delivery.

Investigations Linking the Catchment and the Coast

Fleming (1975, 1981) advocates the development of integrated erosion-transportation-deposition models to investigate sediment transfers at the basin scale. Such models would appear to be of primary importance to the further investigation of catchment behaviour in the middle-order catchments in the Sounds.

The shoreline and the offshore domains can each be regarded as acting as storages, either temporary or permanent, for material delivered from catchments, and Walling and Webb (1983) suggest that attention could be given to lake sedimentation studies as a means to reconstruct temporal patterns of sediment yield. In particular, the work of Davis (1976) shows the potential role of submarine sedimentation studies in the attempt to reconstruct the temporal pattern of sediment yield over the historical timespan.

The primary requirement of submarine sedimentation studies in the investigation of catchment change is to identify volumes of material accumulated, and not simply rates of vertical sedimentation (Walling and Webb, 1983, p93). The reason identified, is that the patterns of sedimentation over the bed cannot be assumed to be uniform or to remain constant through time.

The investigation of shoreline and offshore sedimentation in a tidal inlet system is expected to be more complex than in a lake setting. The key difference is the extent to which material is liable to be actively redistributed. The first step in investigation is therefore to establish the patterns of distribution and the mechanisms of redistribution of sediment in each step in the "sediment cascade" from catchment to coast.

It would appear that the best estimate of catchment sediment behaviour in the contemporary, historical, or geologic timeframes will require correlative investigation at a number of space and time scales. It will be necessary also to bridge the gap between the catchment and the coastal domains.

The observation that catchment sediment delivery has a dimension of texture as well as volume is of fundamental importance on a coast in which catchments are small and abut directly a sheltered coast.

A key distinction between landuse practices in the Sounds can be made on the basis of the size range of materials delivered to the coast as an outcome of human activity. This being so, the further investigation of the effects of landuse practices must begin with an assessment of the manner in which material is redistributed in the coast. From this basis, interpretations can be made from the distribution of materials found in the shore and offshore domains. The task of the following chapters is first, to identify a framework within which these factors can be considered; and secondly, to proceed with the investigation of the patterns of sediment distribution and the mechanisms of redistribution.

Chapter Four

Coastal Sedimentation: A Framework for Investigation

This thesis is concerned with the response of the coast to sediments derived from adjacent catchments. In Chapter 1, reference was made to the manner in which the sediment transfers have become of practical interest to those responsible for the management of the catchment and coastal environments. It is also a matter of substantial scientific interest, because the delivery of sediment to a semi-enclosed coast relates fundamentally to its functioning as part of the landscape system.

The purpose of this chapter is to develop an investigative framework within which it is possible to identify the manner in which a coast responds to catchment sedimentation. There are two key aspects to this problem. One is the historical aspect of sediment delivery, the other is the functional response of the coast to its redistribution.

The mechanisms by which sediment is delivered to the coast are a function of the operation of the sediment cascade. The sediment cascade in the Marlborough Sounds landscape contains a number of storages. Included in these are the shoreline and the marginal bays of the Sounds, through which locations sediment derived from catchments has to pass before finding a resting place in the deeper reaches of the Sounds.

Within these domains, a range of processes are acting which are distinctly coastal. These processes determine the manner in which sediment is redistributed. In order to investigate the effects of sediment delivery on a coast, it is necessary to have a model of what is controlling this redistribution.

The model developed in this chapter establishes a relationship between the historical element of the catchment sediment supply and the functional nature of coastal response.

Models for the Variable Coast

The coast of the Marlborough Sounds is highly variable in form and sedimentary composition. It is not altogether apparent whether this variability is attributable to complex controls acting on the coast or to a complex response to more uniform controls.

The purpose of a model is to simplify our view of a complex system by showing the relationships between elements previously regarded as independent. If the model is a successful one, it should also point unequivocally to the direction of cause-effect relationships between elements. The purpose of the model developed in this chapter is to illustrate relationships between those factors which control the coastal domain and their effects - i.e. the patterns of forms and sediments in the shore and offshore domains.

The coastal system at many scales is characterised by recirculatory and oscillatory behaviour. The reversal of the direction of material flows means that these cannot be used as a surrogate for "control", as control implies a transfer from cause to effect. While material flows may change direction, cause does not "become" effect. Feedback in a system is not a reversal of control, but an expression of the response of a complex system to imposed change. The purpose of a functional model is to illustrate how cause is related to effect.

It is the proposition advanced here, that the variability observed in the coastal system of the Marlborough Sounds can be attributed to the functional relationship between the factors of topography, sediments and energy which constitute the coastal controls. This section identifies some concepts used to order spatial and temporal variability. The following section looks at how models have been used to resolve some complexities in relationship between cause and effect in the coastal zone. This is followed by the presentation of a new model.

Characterising Coastal Variability

In many regions, it has been found that characteristic forms are found to typify a landscape (Brunsden and Thornes, 1979). These are often an expression of more than one process in the landscape, and can thus be regarded as the expression of the mutual coadjustment which has taken place between the range of controlling factors. That characteristic forms arise at all, is one of the distinctive features of the operation of a complex system.

The geomorphic review in previous chapters illustrated that the Marlborough Sounds landscape includes elements developed over various time spans and nested at a range of scales. The broadest frame is that of the hardrock valley forms, attributable to river and hillslope processes operating over a long time span and with the largest spatial extent. This frame sets the configuration of bays and channels in the modern coastal landscape. Within this frame are hillslopes, river and offshore deposits of mesoscale spatial extent, which define the detail of coastal form in plan view, and set the initial conditions on the shore and offshore profile. Within this narrower frame again are a great variety of small-scale features on hillslopes and in stream channels, and the shore and offshore also have wide ranges of shoreline types and depositional locations. Within and upon small-scale features are found micro-forms, which are groupings of sedimentary particles acted upon by processes. The importance of these latter groupings and micro-forms is the extent to which they provide a "fingerprint" of contemporary processes in the landscape.

The observation that forms in the landscape can be found at this wide range of scales could be regarded as an expression of what is called here the "ordering principle". The fact that a characteristic form is found only at a limited range of scale, and that at a different scale a different characteristic form prevails, illustrates the general proposition that the landscape is subject to a discrete ordering. What are referred to as "geomorphic thresholds" have been cited as the cause of this discrete ordering. Schumm (1979, p 488) suggested that geomorphic thresholds are essential to distinguish regional response from local response. Thresholds would appear to be one interpretation of the patterns which arise from the ordering principle. This ordering gives rise to what appears as the tendency of an environment to move towards a series of "preferred states".

The ordered appearance of the landscape does not arise from a teleological tendency inherent in the materials or the forms, but from the operation of process mechanisms which serve to disequilibrate or equilibrate behaviour. The proposition that "form expresses function" (Brunsden and Thornes, 1979) indicates a tendency of all geomorphic systems to evolve to that point where there are no "relicts" of past conditions; but the form of a landscape at any one time will usually be an expression of both past and present process-conditions.

"Equilibrium" can be regarded as "a delicately adjusted balance among activity, three-dimensional geometry and sediment transport such that the system will tend to correct short term or minor interference" (Tanner, 1974). At equilibrium or what is referred to as steady state (Pethick, 1984, p3), energy inputs are dissipated without any net sediment transport. Energy and sediment are thus two key disequilibrating elements. After a change in conditions, morphology tends to begin to move to a new equilibrium or steady state. This pattern is referred to as dynamic equilibrium. The time taken to return to a steady state is referred to as the relaxation time (Chorley, 1962).

Functional Models

Coastal geomorphology has had a traditional concern with coastal classification, which enables the recognition and naming of coastal features. Yet as noted by Pethick (1984, p2), classification tends to describe rather than explain, and he went on to note:

> "...the task of the coastal geomorphologist must be to understand the relationships between form and process, not merely to describe forms."

The aim of investigation in this sense is to understand the mechanisms or processes which are operating. If a landform is viewed as a machine (Bloom, 1974), then the processes are part of the function of the landform (Pethick, 1984).

A functional view of a coastal landform is determined by what it achieves, rather than how it appears. It should be noted that this use of "functional" differs from what is referred to in the philosophy of science as "functionalism", in which appearance is used as the measure of function. This may represent the opposite to what is meant here.

There is an identity in structure between a functional view in the coastal setting, and a function as used in mathematics. In the latter, a mapping function defines the relation between two sets, such that elements of the domain are mapped by way of the function onto elements of the range. In the coastal setting, the domain comprises literally those controlling elements which characterise a given part of the shore or offshore domain. The range is those elements of the coastal system which have been acted upon by the function: i.e. which evidence the effects of its operation.

This section shows the development of a functional approach with reference to three models, two derived from earlier work, and one original. The first was significant for its initial adoption of a functional approach. The second is significant in that it resolved some complexities relating to the interpretation of coastal sediment patterning. The third is the Ordered Response Model, the significance of which lies in the manner in which it illustrates the functional mechanisms which give rise to the characteristic shore form when there is wide variability in form and sediment in the coastal domain.

A Functional Model

Sediment supply is only one variable which affects coastal behaviour, and consequently the specification of a "sedimentation rate" is an inadequate description of the behaviour of a coastal system.

Krumbein (1963) developed a process-response model for the analysis of beach phenomena. Processes and deposits were regarded as "separate though closely related aspects of shoreline phenomena". Three controlling ("Process") elements were identified: the energy factor (waves, tidal range, winds), the material factor (natural beach materials), and the "overall geometry of the shoreline". (Krumbein, 1963, p7). The latter were regarded as the "boundary conditions".

Two response elements were identified, as shown in Figure 4.1a. The first was the geometry of the beach deposit (volume, and shape - slopes, height and width). The second was the properties of beach materials, (grain-size etc).

Geometry and material properties were listed on both sides of the model. The distinction between the geometries was one of scale (boundary condition as compared to internal rearrangement). The distinction between the two "materials" variables was between initial properties which could be functionally modified by winnowing or new material inflow, and response properties which were the outcome.

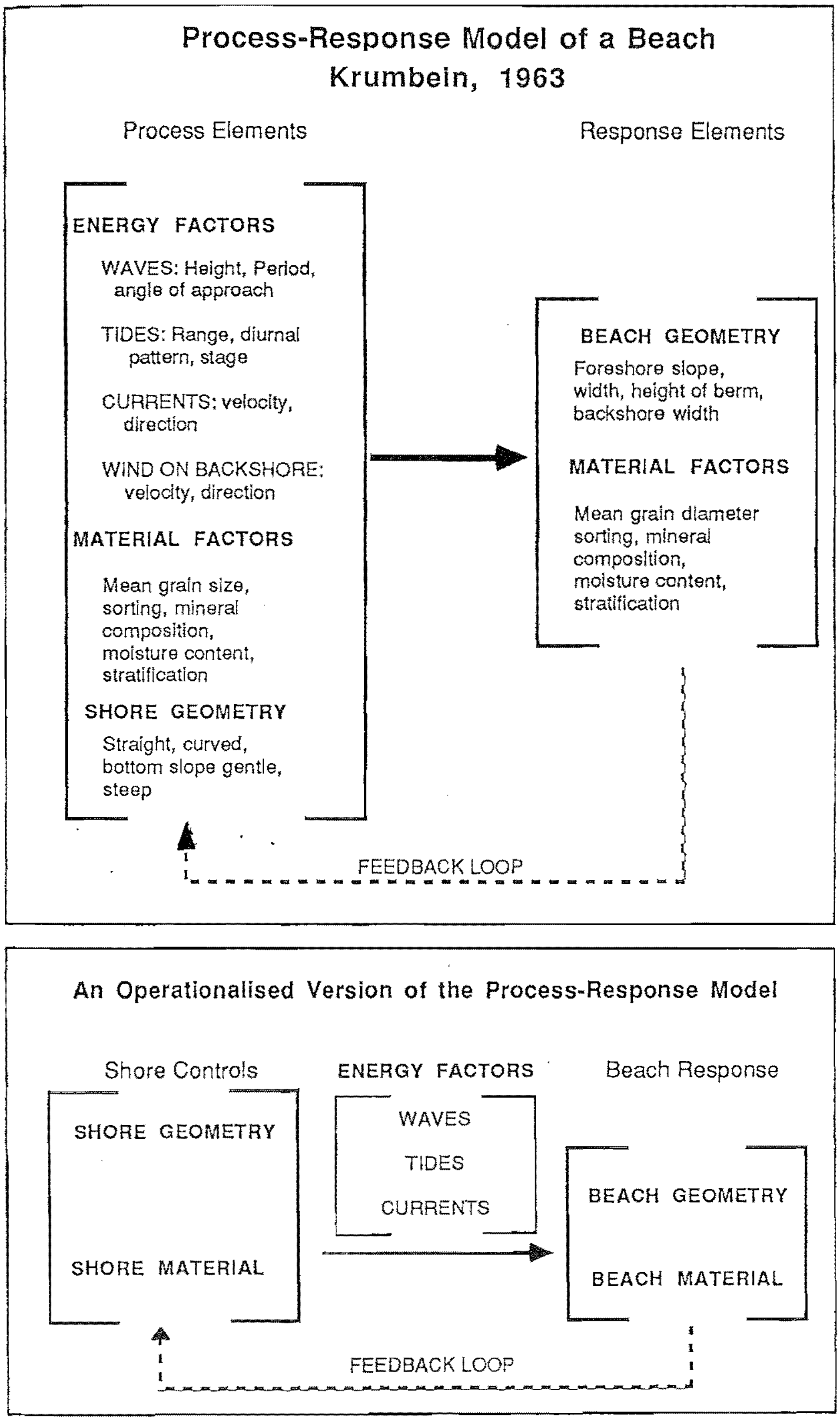
The pattern of areal variation was common to all elements; the expression of which would be recognised when the model was operationalised.

As shown in Figure 4.1a, a feature of the model is a negative feedback loop, whereby a response element may exert a feedback control on one or more process elements. Feedback arises because the process elements of geometry, materials and energy are not independent, but can be modified by the changing condition of another. Changing sediment composition, for example, can lead to a modification of beach slope.

The simplicity and functional elegance of Krumbein's Process Response model makes it a valuable means by which to recognise order in the spatial patterning or temporal change of a beach system. The manner in which the model has been operationalised has not, however, produced the simple and functional mathematical relationships which were apparently anticipated,

Figure 4.1

Process-Response Model,
General and Operational Statements



Process-Response model of beach forshore adapted from the process-response model to show energy factors separate from geometry and material factors judging by Krumbein's reference (1963, p6) to the operationalisation of the Process-Response model by the use of "specific models, some statistical, and others based directly on least squares analysis". In practice, it is found that very few shoreline relationships are linear or even continuous. A distinction can be drawn between the value of the model as a conceptual framework, and the manner in which it has been operationalised. It is not the intention here to discuss the latter.

Krumbein (1963) was quite specific in confining the model to the beach deposit, although it is apparent that the process-response model with the same grouping of controls (essentially Form, Material, Energy) and responses (Form, Materials) with a feedback loop could have wide applicability in geomorphic investigation (M. Church, University of British Colombia, Pers. comm. 1986). Krumbein (1963, p7-8) made indirect reference to outside controls on the model in noting that

> "The properties of the beach materials on the response side of the model are controlled by the kinds of material originally available at the beach site or brought in by currents and tides. The average grain diameter of the foreshore sand, for example, is controlled by the particular combination of process elements that have recently occurred or are going on at some given time."

Krumbein distinguished verbally between what are two distinct controls on response deposit grain size characteristics: the original availability and the process modification. The former contains a certain "memory" whose imprint remains even after hydraulic modification. However, the distinction was not carried forward into the Process-Response model.

A model which does make this explicit distinction was developed by McLean and Kirk (1969).

An Ordered Control Model

McLean and Kirk addressed the problem of reading the process "signature" from sediments, and relating process to beach morphology on mixed sand and gravel beaches. The distinguishing feature of such beaches is the wide range of grain-sizes presented to swash flows. The wide grain-size range offers potential for both strong "initial" imprinting of sediment characteristics, and large variations between different process signatures, with very direct effects on beach morphology.

Because of this, the authors found it necessary to make reference to those factors which determine grain population characteristics and distinguished two sources of variation: one attributable to "Source Area Effects" and the other to "Hydraulic Sorting". These two propositions, the former identified with Folk and Ward (1957) and the latter with Inman (1949), are discussed in more detail in the following chapters. On consideration, McLean and Kirk were led to the recognition that while source area effects determined the initial sediment characteristics, hydraulic modification (sorting) acted subsequently to modify them. Mobile sediments are "permissive" of the morphologies that hydraulic conditions can create. The "Source Area" effect was identified as the first order control on sediment character, and the "Hydraulic Sorting" as the second order control, as shown in Figure 4.2.

This distinction is a useful one here with respect to the activity of model building for the purpose of investigating coastal sedimentation in the Marlborough Sounds. In the chapters which follow, extensive reference is made to sediment textures as signatures of environmental processes. The explicit distinction made here between textural factors attributable to source area (catchment) effects, and those attributable to subsequent hydraulic modification, is a valuable tool in assessing coastal behaviour.

Extending the Ordered Control Approach

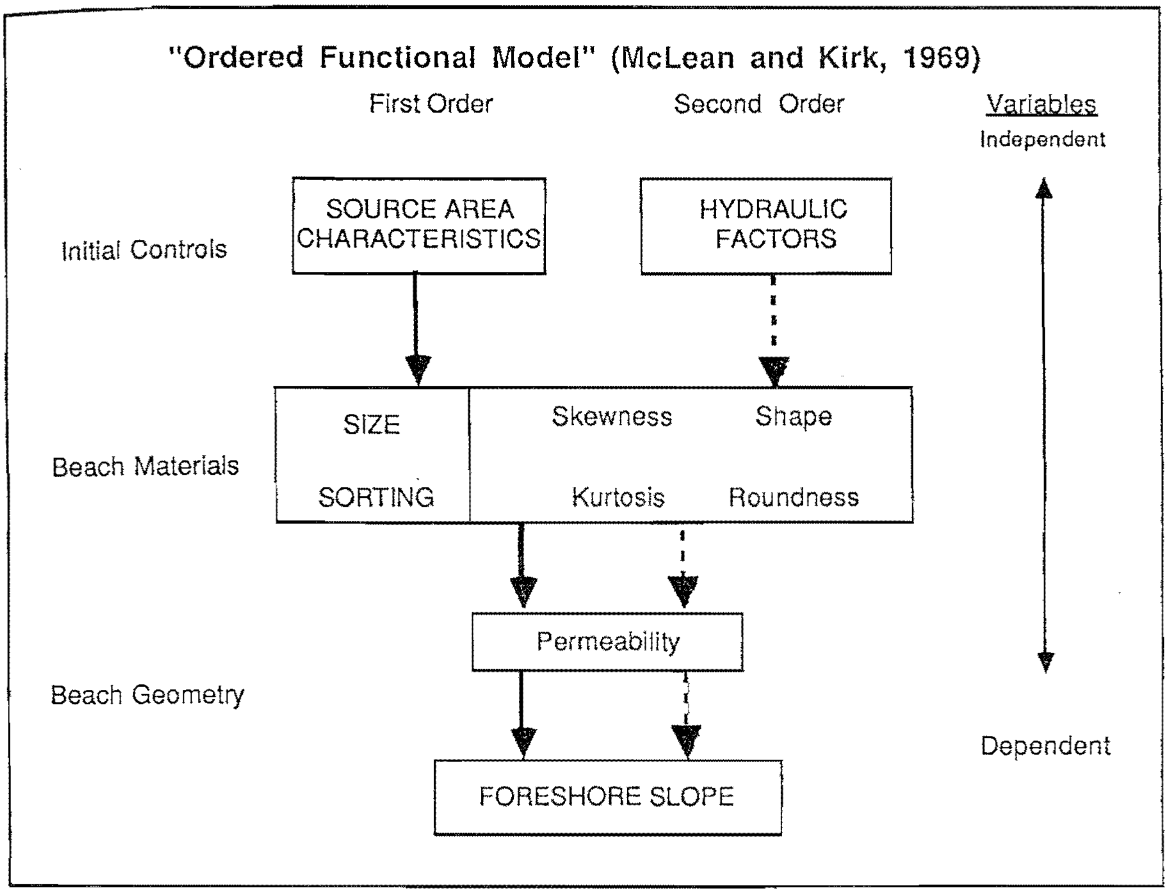
The Process-Response model of Krumbein (1963) established that beach geometry was set by "boundary" conditions. Reference to the geomorphic frame, within which the coast is developing, shows however that this is the factor which determines these boundary conditions. The ordered control model proposed by McLean and Kirk (1969) did not set out to illustrate those factors which determined the source-area first order effects.

The concept of a sediment cascade (Schumm and Chorley, 1985) is one which links together adjacent environmental domains. In an environment in which catchment and coast are closely linked, reference to the sediment cascade concept suggests that source area effects will be related to antecedent catchment behaviour. There is a prospect, therefore, of extending the ordered control model in such a manner as to illustrate those external factors which determine the character of the coastal zone.

In the model which is developed in the following section reference is made to the ordering principle as applied by McLean and Kirk as a means to recognise the distinction between regional and local controls and the local response of the coastal system.

Figure 4.2

An Ordered Functional Model of the Controls on Sediment Grain-size



Original caption reads: (McLean and Kirk, 1969)
Conceptual model relating initial controls, material factors, and foreshore slope to show levels of dependency.
First order controls indicated by solid arrows. Second order controls indicated by dashed arrows

The Ordered Response Model

While Krumbein illustrated that beach responses ("effects") were a function of process controls, the Process-Response model did not identify those external factors which controlled form or sediment. The McLean and Kirk model illustrates that sediment "effects" are the outcome of two orders of control, but did not identify what factors determined the first-order source area effects. The proposition embodied in the Ordered Response model developed here is that large-scale morphology is the implicit variable which both determines the "boundary conditions" of geometry in the former model, and is a key control on the Source Area effect of the latter. The model sets out the functional relationship in the coastal system as comprising four levels, as illustrated in Figure 4.3.

In this section, three key aspects of the model are discussed: its horizontal structure, its vertical structure, and the placement of feedback loops. Their relationships are shown to have implications for the recognition of spatial and temporal order in the coastal system, with particular relevance to the Marlborough Sounds.

Ordered Response

The four levels of the Ordered Response model shown in Figure 4.3 can be regarded as comprising three orders of control, and three orders of response. The first order of controls is the external environmental coastal controls. The next two levels can be seen as either controls (of the levels below) or as responses (to the levels above). The lowest level is the coastal response, the observable pattern of form and sediments on the shore or in the offshore.

The flow of control is vertically downward from cause to effect, the latter being identical with the morphology and textural characteristics of coastal sites. The three coastal controls are essentially those identified by Krumbein, but generalised such that Morphology can refer to the spatial expression of form at any scale under consideration; Materials include the quantity and textural characteristics of sediments and water, the two principal elements in the two-phase coastal system; and Energy refers primarily to energy gradients arising from gravitational and hydraulic forces.

At the second level, Morphology and Material controls are shown to interact to define what is labelled the Morphologic Trap. An implication arising

Figure 4.3
The Ordered Response Model

Conceptual model relating independent landscape controls to coastal response.

Control is seen to act on the coast at three orders of control, identified by the shaded triangle. The first order control is morphologic, determined by the initial form of the landscape. The second and third order control arise from the interaction of morphology and coastal materials.

A morphologic trap determines the materials which are retained at a given coastal site.

The third order control arises from the interaction of materials within a site with hydraulic forces. Material is either trapped and retained within the site, or by-passed.

If material is mobile in the site of retention, it is subject to the mobility trap (F1 feedback).

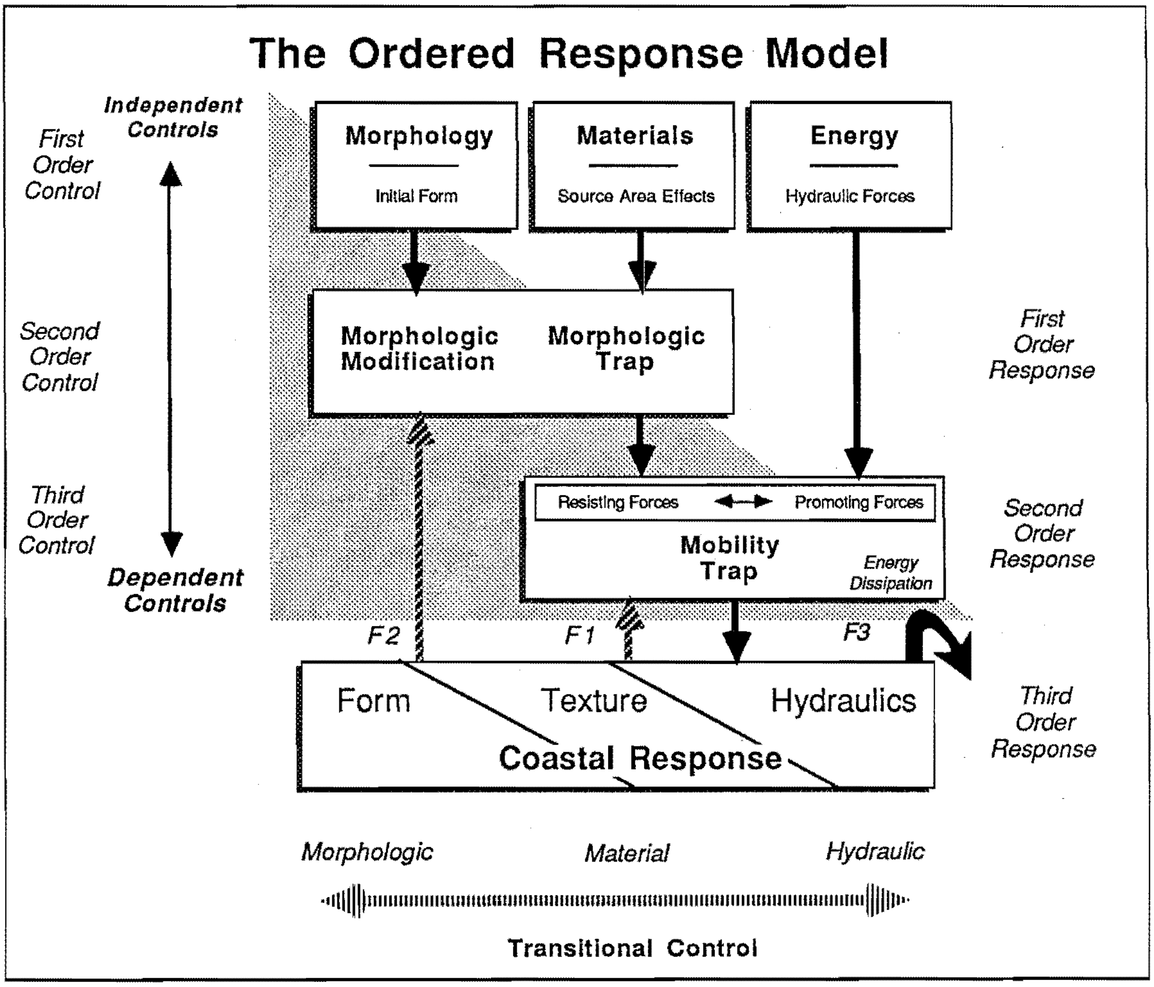
If the material retained is immobile, it is subject to the morphologic trap (F2 feedback).

If material is too mobile to be retained, it is by-passed (F3 outflow)

Coastal responses ranging from those dominated by morphology, to those arising from interactions with sediments, to those dominated by hydraulics, are subject to a transitional control acting laterally across the model.

Figure 4.3

The Ordered Response Model: A Framework for Investigation



from the sediment cascade concept is that there are morphologically determined sites in the landscape which are inherently prone to sediment accumulation. At the most general scale, these include the shore and offshore domains in toto. At the more detailed scale which is the subject of this investigation, it is found that morphologic traps occur in a range of shoreline types and offshore locations. As is shown in the following chapter, certain sites are characterised by distinctive sediment compositions: an illustration of the proposition that the Morphologic Trap is a response to both morphology and sediments. An outcome of the Morphologic Trap is the determination of a range of sediment textures. This identifies the first order trap as the determinant of Source Area effects.

At the third level, the sediment populations determined by Source Area effects are acted upon by energetic factors in what is termed the Mobility Trap. Hydraulic conditions impose an imprint on sediments, through a mechanism whereby mobile sediments are distinguished from relatively less mobile particles. The mechanism of differentiation according to relative mobility stems from the process-response relationship between force and resistance. The outcome is the determination of sediment populations which have similar behaviour under the prevailing energetic conditions.

The fourth level of the model comprises the "effects" of the operation of the Morphologic and the Mobility traps. The residual effects of each are reflected as the patterning of forms and sediments in the coastal zone. This is the Coastal Response.

The behaviour of the coastal system is thus characterised as the response of the shore and offshore to controls operating at more than one order.

Transitional Control

As well as the horizontal, ordered structure of the model, there are structural elements in the vertical dimension. The patterning observed in the coastal domains can be explained further by reference to what is called here "Transitional Control". This arises from the interaction of the three coastal controls of morphology, sediment and energy.

The initial operationalisation of the Process Response model by Krumbein (1963) showed the placement of the energy process element in a central position between process and response (Figure 4.1b). The purpose was to illustrate the functional significance of energy in mapping the process domain to the range of responses. The identification of energy as a primary control on coastal systems holds a dominant position in the literature. Pethick (1984, p4) stated, for example,

> "The function of the steady-state coastal landform is to dissipate wave-energy."

Such a view accounts in part for the use of energy variations as the basis on which to classify coastal types (Tanner, 1960; Davies, 1980). Inman and Bagnold (1963) took an energy-dominant approach to shoreline behaviour when they assumed that on the equilibrium beach profile, sediment is already moving. Such views can in part be attributed to the characteristically high-energy coastal environments in which most coastal investigations have been conducted.

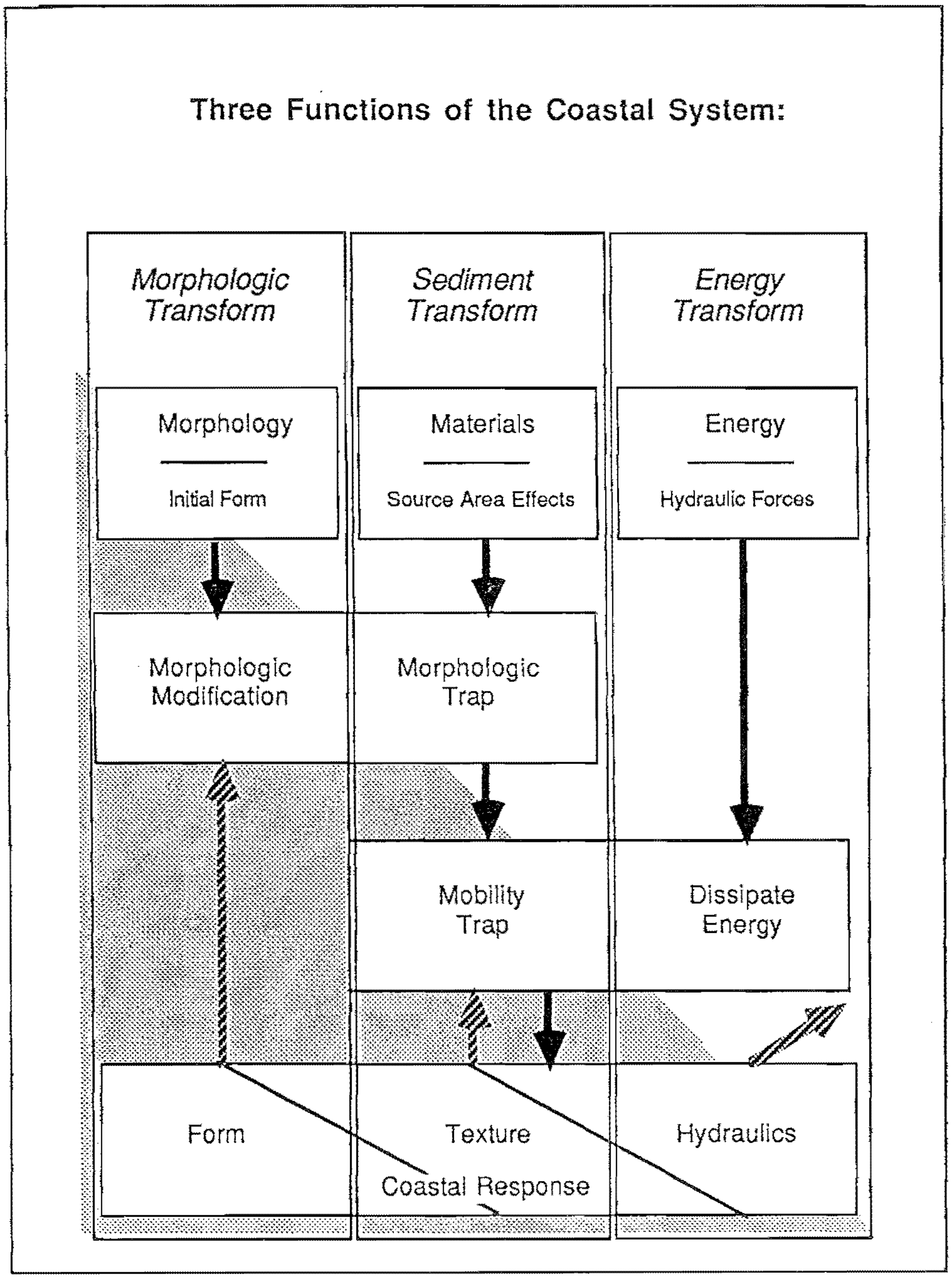
On a "low energy" coast, certain propositions relating to hydraulic behaviour become apparent which are not so evident in the high energy setting. Notably, sediment on the "static equilibrium" shore cannot be assumed to be already in transport. Mobility depends on the balance between promoting and resisting forces, and where energy levels diminish, explicit reference must be made to the threshold of movement. This is especially so on the coarse-grained or mixed sand and gravel beach, because the range of relative mobilities is wide and thus the threshold of motion intersects the mobility range of the sediment population. Coastal control on the "low energy" "mixed sediment" coast is thus seen to be transitional between energy and sediment factors.

Where energy levels intermittently drop below the threshold of mobility, profile behaviour becomes akin to that on a hard-rock shore. Where the sediment particles comprising the shore are not moving, it is largely irrelevant to characterise them on the basis of hydraulic characteristics. It is not their individual characteristics which count in this circumstance, but the profile morphology which the particles collectively present to the flow. Even though no sediment transport is occurring, the shoreline is still "functioning" (Pethick, 1984, p3). Where profile form is not changing due to immobility of the particles comprising it, control is characterised here as "Morphologic".

The concept of "Transitional Control" of coastal sites is thus illustrated as transiting, from morphologic to sedimentary to energetic domination, according to variation in topographic form, sediment character and energy level. Most commonly, the character of the coast of the Marlborough Sounds is seen as reflecting the transitional control which develops between controls rather than

Figure 4.4

Functions of the Coastal System in the Light of Ordered Response



In the light of the ordered response framework, a coastal system is pictured as having three functions- to transform morphology, to transform sediment, and to transform energy.

Threse functions correspond to the three vertical components of the Ordered Response Model.

control exerted by any one factor. This transitional character appears a coherent way by which to account for the variable character of the coastal zone.

Functional Behaviour

The functional characteristics of coastal behaviour become more apparent when reference is made to the systematic linkages within the model, particularly the feedback loops. As in the Krumbein model, the transformed "effects" of the functioning of the coastal system have a bearing on higher order elements (or Krumbein's "Process" elements). In the Ordered Response model, three levels of feedback are identified; and this recognition has functional significance.

The low-order feedback labelled F1 in Figure 4.3 takes place in a manner identical with Krumbein's model. It is the hydraulic readjustment of morphology and sediments towards an equilibrated state. The middle-order feedback labelled F2 in Figure 4.3 is a recognition that the long term consequence of the operation of the coastal system is the progressive modification of its "boundary conditions", either by erosion (by hydraulics and sediment transport) or by sediment accumulation.

The high order feedback labelled F3 in Figure 4.3 has a functional significance identified by Pethick (1984, p3): in which he noted (as above) that the coastal system continues to function even when no sediment transport is occurring. The functional role of the system continues to be to "disperse energy". The coast serves to transform energy from one state to another. However, if this function of the coastal system is identified by a feedback loop, then there is an inherent implication in the model of two other functions of the coastal system. These are identified as a morphologic transform and a sediment transform.

These alternative functions of the coastal system were hinted at by Bradley and Griggs (1976) in their investigation of shore platforms. In summarising this work, Pethick noted "the function of the shore platform [is] as a dissipator of wave-energy and as a pathway for sediment transport."

The proposition that the coastal system has in fact three functions is illustrated in Figure 4.4.

The Sediment Transform

While previous functional approaches to coasts have tended to highlight the flow of energy through the system, the sediment cascade has highlighted the flow of sediment as a characteristic of the Marlborough Sounds coast. The "sediment transform", as one function of this coastal system, could be regarded as the systematic tendency of the coast to transport and modify sediments which are delivered to it.

It is a matter for particular investigation in the following chapters, to identify the extent to which the fingerprint of a sediment transform can be interpreted from the sediment deposit signatures in the shore and offshore domains.

The Morphologic Transform

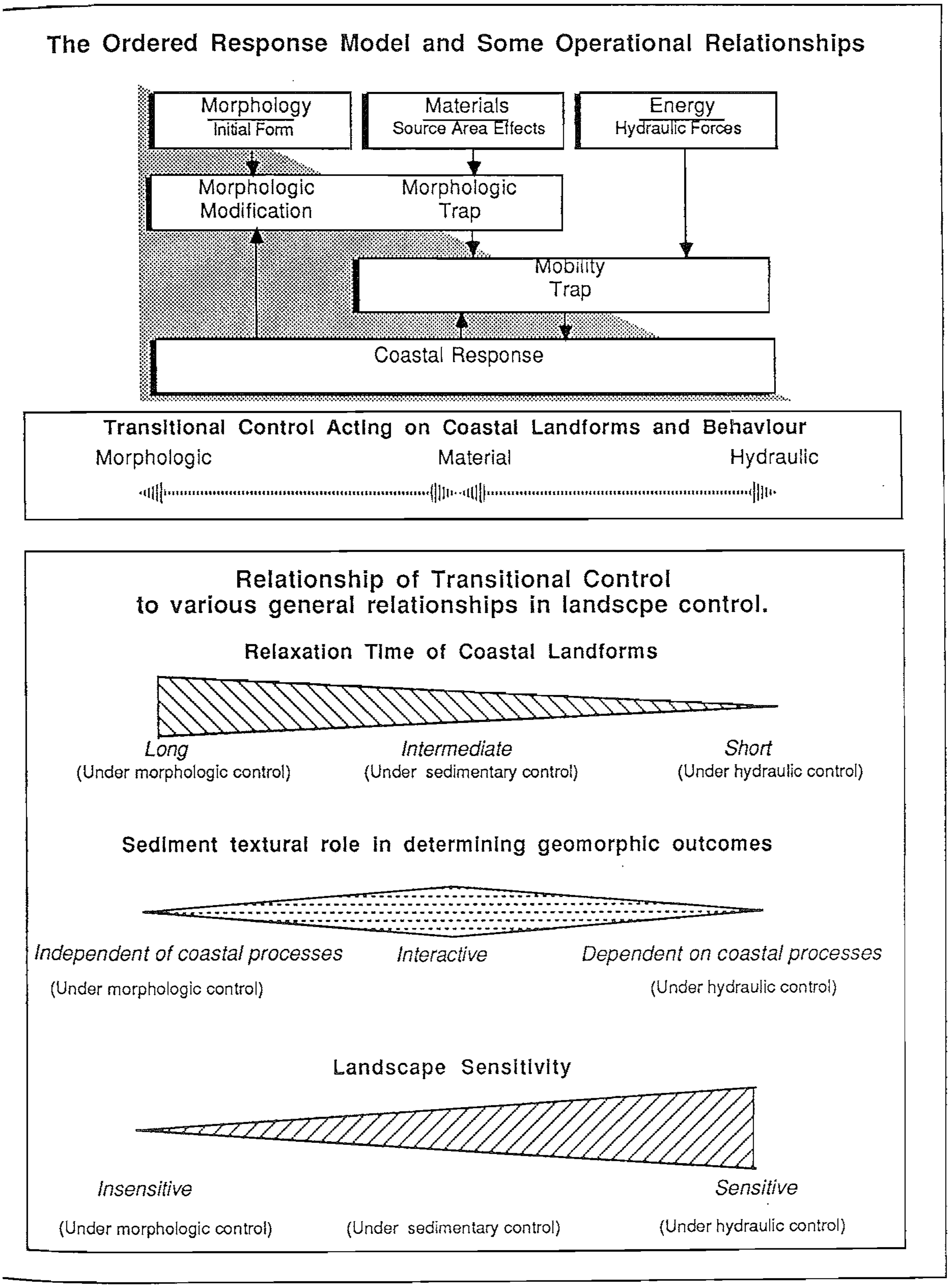
The functional approach in geomorphic investigations in general has been associated with a redirection of attention away from the larger scale to the smaller scale features in the landscape. This can largely be attributed to the difficulties of generalising about process-form relationships beyond small-scale examples.

However, the observation that there exist "characteristic forms" in the landscape, sometimes at quite large scales, testifies to the inherently stable behaviour of complex systems at a range of scales, and thus to the tendency of the mechanisms within them to produce convergence in form. It was noted earlier, that the landscape as one complex system would appear to have certain preferred states. The structure of the Ordered Response model would suggest that the reason why form convergence occurs is related to the feedback mechanisms which enable equilibrated behaviour to develop.

The transitional arrangement of the model facilitates the recognition of aspects of the temporal behaviour of forms in the landscape. Figure 4.5 illustrates a continuum of landform behaviour according to relaxation time. Landforms, and specifically coastal forms, are shown as extending from those which have a long relaxation time (i.e. they are morphologically dominated "relicts"in the landscape which have a long cycle over which they equilibrate to prevailing process conditions), to those which have a short relaxation time. The latter have little "memory", and these elements are dominated by energy (hydraulic) conditions. An intermediate group are characterised by sediment domination, and the relaxation time of these will depend on the extent to which their behaviour is mobile (energy-dominated) or immobile (morphology-dominated).

Figure 4.5

The Ordered Response Model:
and its Relationship to other Geomorphic Concepts



This latter distinction illustrates the connection between the reasoning presented here and that adopted by Brunsden and Thornes (1979) in their discussion of landscape sensitivity and change. They recognised that landforms could be ranked on a continuum according to their relative sensitivity to change, or their mobility.

By implication, coastal sites which are immobile also have the characteristic of acting in a manner largely independent of the operation of the coastal system, and will as a consequence have a long relaxation time. They are, conversely, strongly dependent on the conditions imposed by the morphologic coastal controls. Examples are the hardrock frame of the landscape, or the large terrace forms within it. At the other end of the scale are sites which are mobile or sensitive to the internal behaviour of the coastal system, and tend to have short relaxation times. These may include coastal sites in which fine sediments are easily remodelled by hydraulic conditions. In the intermediate range are coastal sites which are characterised by interaction between coastal controls. These sites can be of particular interest because they may contain a valuable key to the recognition of contemporary coastal behaviour. These are also sites in which sediments play the largest role in determining coastal character.

Summary

The Ordered Response model makes a clear distinction between coastal controls and the process-response interactions which determine the effects of these controls at individual coastal sites. As a consequence of the ordered structure of the model interactions between controls take place which give rise to the pattern which has been named here "Transitional Control". The implication of this Transitional Control becomes apparent in coastal domains which are characterised by a wide range of morphological settings, and by a wide range of relative mobility among the sedimentary materials, the latter coinciding with mixed grain size material and low coastal energies. The outcome of Transitional Control is that to regard such a coastal system as being dominated by morphology, sediment , or energy alone would be inappropriate, since coastal behaviour is seen here to depend more strongly than in any other type of coast , on the mutual coadjustment between all three of the coastal controls.

The implication of the structure of the Ordered Response model is therefore that coastal landforms can be recognised as varying according to two functional characteristics. The vertical criterion is that of Trapping behaviour, which gives rise to coastal sites which vary with respect to their abundance of sediment, and to Source Area effects. The horizontal criterion leads to a range of variable landform mobility. Both these criteria are functionally defined, and arise from the relationship which is postulated to exist between Coastal Controls and the range of forms and deposits which are their effects, and which together define the character of a coastal zone.

In some cases or conditions of energy, sediments will be largely immobile and shoreline forms will dissipate wave energy. In others some sediment will be mobile so that energy is dissipated by both form and by sediment transport leading to form change. In yet other conditions energy levels are high enough to produce transport of a wide range of sizes leading to more substantial form adjustments. This is called transitional control.

Operationalising the Ordered Response Model

The Ordered Response Model was developed in the context of the distinctive coastal landscape of the Marlborough Sounds. The purpose of the subsequent chapters is to operationalise the model in such a way as to illustrate key relationships between sediments and other variables in the shore and offshore zone, and to evaluate the Ordered Response Model (ORM) itself as a conceptual framework. The purpose of this section is to consider the bases upon which this operationalisation and evaluation can take place.

While a necessary first step in any environmental study is adequate description, the prime objective of this study is not description of the forms and sediments of the shore and offshore zones. Rather, the objective is the identification of their functional character, i.e. the manner in which the coast responds to a given and specific stimulus. The distinction has implications for the types of data and the amounts of data required.

The coastal environment functions at a wide range of scales, so no data set is sufficiently large to describe its functioning entirely. "Function" can only be investigated with reference to a model at a given scale. The model is the interim or partial description of the functioning whole, and the data serve to validate or invalidate the model. In a functional investigation, data are primarily used to evaluate models, not to describe the environment.

Validation of Models: Functional Statements

Given the above, in what manner is a model to be validated or invalidated? It is quite apparent that if the data fail to conform to the model either the model, the data, or both must be "wrong". Wrong in this sense means inappropriate to the aspect under investigation: data are "wrong" when, for example, the sampling interval is inappropriate to the process under investigation. Models will always be underconfirmed by evidence, to the extent that most evidence cannot (for the reason above) either prove or disprove a model.

An evaluation of models must therefore be conducted at two levels. First, the test of each relationship or group of relationships is conducted with reference to those "test cases" upon which hang those particular aspects of the model (see Aronson, 1984, Ch 6). The test cases are critical in respect of determining the direction of causal relationships more than any other factor. This step involves the validation of "functional statements".

Secondly, the operational framework of the model itself is evaluated. Church (1981) made a similar distinction to that made here between the model and parts of it, but suggested that the model itself is never evaluated. Only what have been called here the functional statements are evaluated (tested). This seems to be a view which would slow the progress of investigation if there are in fact no criteria of a general nature upon which a model can be evaluated against its peers. This matter is debated in the following subsection.

Before leaving the subject of the role of data, however, reference should be made to the role of numerical technique in geomorphology. A characteristic of some modern sedimentological work is the increasing use of mathematical technique and computing power. The trend began in the early 1960s, as indicated by Krumbein (1963, p2):

> "Advent of the high-speed computer has made available a variety of ways in which the complexly interlocked variables of beach processes and deposits can be analysed in greater detail than was feasible by hand calculation."

The resources available for statistical and numeric analysis continue to accelerate, and there could be an implicit assumption made that these tools assure a more confirmed model of natural processes on the coast. The observation by Winkelmolen (1982, p264) is pertinent:

> "Mathematics and statistics are powerful tools for geologists, but we should not use them to put up a smoke-screen of quasi-exactness. A computer is not a washing machine in which our data can be purified. We should rather use the time that can be saved by using it to reflect on our basic suppositions".

In view of the huge amount of effort invested in computer modelling of various aspects of the coastal system, more often for a descriptive than a quantitative outcome, the advice is valuable.

Validation of Models: Operational Framework

There are various perspectives which can be taken with regard to the use of models in geomorphic investigation. It would appear from logic and experience, that a model can be accorded either too little or too much weight. The purpose of the following is to identify some criteria by which a model can be evaluated.

As referred to in Chapter 2, Davisian explanation of landscapes placed the highest weight on the model, and secondary weight on field investigation. The purpose was "to provide a safe explanatory theory with respect to the origin of certain observed features, so that the imagined counterparts of the observed features and of many related features may be systematically deduced from the theory" (Davis, 1915, p71). The consequences of such a view are twofold.

First, evidence was to be "imagined" where it was not (yet) available. The result was short-term results, but long-term confusion where the imagination and the observation became indistinguishable. Elements of this, it was suggested, applied to material reviewed in Chapter 2. Secondly, it reflects an approach to investigation which is concerned with the application of a simple and general model, which had a demonstrated preference to cover problems, rather than to uncover them in order to solve them later. Such could be described as the worst possible science. The mechanism of progress in science is curiosity, but curiosity first and foremost about the subject matter and not the model of it.

A contrast can be drawn between two viewpoints towards science, which have been distinguished by Chorley (1978) and Richards (1982) as "functionalism" and "realism". Functionalism is defined, as a scientific stance, in terms of its seeking out of repeated instances of form, and in this manner proceeding to an identification of process. Functionalism has been found in some instances to be an inadequate base for investigation, primarily for the reason identified earlier in this chapter - that there can be more than one control acting upon system behaviour, and consequently more than one determinant of form. The identification of process from form is therefore hindered by the problem of equifinality i.e. that the endpoint could have been reached by more than one route.

Realism is an alternative approach to science, and one which has been commended in geomorphic application (Brunsden and Thornes, 1979, p463; also Chorley, 1978). Because of the manner in which theory is regarded in Realism, it is not unreasonable to substitute "model" for "theory" in the following:

> "In Realism, a theory is a means of conceptualizing a framework within which reality is apprehended".
> (Gregory, 1986)

As a consequence, reality cannot be comprehended adequately without resort to theory, because underlying "controlling" factors can be comprehended only in the theoretical, and not the empirical domain.

The significant difference between a purely empirical stance towards science, and the realist stance, is the attitude to the relationship between investigative structures (theories or models) and reality. From the empirical stance, the structures have no more substance than the hypotheses of which they are comprised. From the realist stance, the model can have substance if it gives access to "reality". A distinguishing feature of the realist view of reality, is that it includes (in fact is predicated upon) a structure of ideas. The investigator is concerned not only with effects, but with the underlying structure which controls them. There is something inherently useful in this approach, with reference to the geomorphic problem under investigation. For this reason, this study has proceeded from a realist standpoint, and the utility of such an approach will be evaluated in the conclusion of the thesis.

The immediate and practical relevance of adopting this perspective, is with regard to the criteria upon which the investigative structures (models) can be evaluated.

> "The test of a theory [model] to an actor using it is then its coherence and practical adequacy, rather than its empirical adequacy".
> (Gregory, 1986)

This approach is not a rejection of the importance of empirical confirmation of functional statements (hypotheses) which may be part of or developed from a model. The approach requires recognising the role of the model as something more than a tool of convenience, and something other than being the end of the investigation. It is an explicit recognition on coherent philosophical grounds, that the "whole is more than the sum of the parts", and that the purpose of a model is to enable the investigator to grapple with what comprises this whole.

Where the purpose of the investigation is to identify the functioning of a coastal system, the role of the model is to express the causal (control) linkages which determine the observed effects. The criteria upon which the model is validated lie in the extent to which the model succeeds in showing the linkages which exist between elements of the landscape system in a coherent manner, and in a manner that has practical adequacy.

The Ordered Response model qualifies on these criteria.

Chapter 5

Coastal Sediments of the Marlborough Sounds

The proposition has been advanced in Chapter 1, that the key to understanding coastal sedimentation in the Marlborough Sounds lies in the recognition of the fate of several sedimentary fractions. The purpose of this chapter is to identify those fractions, and to discuss the manner in which the fractionation of sediments can be used as a key to identifying environmental behaviour.

The concept of sediment fractionation denotes those processes in which components of a mixture are separated by exploiting differences in their properties. Sediments are composed of a more or less heterogeneous mix of particles, inorganic and organic. Differences between sediments are identified on the basis of differences in the relative proportion of given fractions present in the mixture i.e. the identity of a population of sedimentary particles can be recognised in its fractional composition. This composition defines its textural character (gravelly, sandy, muddy) and hence the environmental character of a coastal site. Its composition also determines the manner in which a coastal site responds to coastal processes. It is in this latter respect that sediment texture is a key component of coastal functioning.

The transport of sediment en mass may modify the gross form of a coastal site, but it is through the fractionation of the sediment population that qualitative changes in the coast take place. In this light, the differences noted in Chapter 3 in the textural character of sediments delivered to the coast are seen to be significant. The modification of the character of the coast, and of the manner in which it functions, depends fundamentally on the mix of particles delivered and on the capacity of the shore to redistribute these. For reasons identified in general terms in Chapter 4, and discussed in detail in subsequent chapters, the low energy shore has a limited capacity to redistribute sediments delivered to it. Consequently the process of fractionation is the gauge by which it becomes possible to assess coastal response.

Three sections of this chapter first identify the methods of sediment analysis employed in this investigation; secondly, report on fractions identified in coastal sediments; and thirdly, discuss the manner in which the patterns of grain-size distributions have been and could be interpreted.

Sampling and Textural Analysis of Coastal Sediments

This section describes the criteria of sampling and the methods of analysis.

Sampling Criteria

Field investigators of necessity must make sampling decisions, initially from their recognition of the patterns of sediment in an environment (Krumbein, 1961).

A primary distinction is made between three coastal domains in the Marlborough Sounds. These are the shoreline, the nearshore and the offshore. The shoreline refers to the intertidal zone, and to those contiguous areas which are actively worked by wave action. Nearshore samples were taken on the steep slope adjacent to the shore. This is referred to as the nearshore slope. Offshore samples were taken on the more gently sloping bed of the Sounds.

The recognition of pattern in the environment, and the scale at which pattern occurs, stems from the investigator's perceived models of the environment. This recognition may be derived from the literature or from field reconnaissance. A key task is to identify the scale of variation in sediments.

Data on shore and offshore sediments in the Marlborough Sounds available from previous studies was limited. Description of offshore sediments on the published sediments map (Lewis and Mitchell, 1980) uses broad textural classes to identify the inner parts of the Sounds as bedded with mud, and some outer areas with sand. Boyce (1971) completed size analysis on a suite of beach and offshore samples from sites in the inner Sounds. The offshore samples are referred to in Chapter 9. Newton (1977) did not report on formal sediment analyses in a study of changes in shore profiles in Tory Channel.

Shoreline

Detrital accumulations on the 800km of shore in the Queen Charlotte and Pelorus Sounds are found as discrete sediment bodies, rather than as a continuous beach. Much of the shore is comprised of cliff or rubble surfaces, or is paved in a gravel lag deposit. Accumulations are defined as sediment bodies several particles thick with some homogeneity in their textural composition. The nature of accumulations on the shore are discussed in detail in Chapters 6 and 7.

Field reconnaissance involved the analysis of a large number of samples (>500). Differences in methods of analysis (between settling and sieving, reported below) meant that some results were not comparable. The decision was made to reanalyse a suite of 176 shoreline samples by a standard settling method, and these are reported here.

This suite was sampled on beach and intertidal surfaces in the Grove Arm of Queen Charlotte Sound, in the northern and southern bays of Queen Charlotte Sound, and in the Mahau Sound. The distribution of samples is listed in Table 5.1. The bedrock lithology of these areas is predominantly schist. Some differences can be found in particle shape between particles derived from the schist and the greywacke terranes, which tend to produce platy and blocky grains, respectively.

Sample Recovery and Logging

Shoreline sediments were recovered by trowel from surface and subsurface deposits. Sample size varied from 500gm to 5kg, depending on the predominance of gravel. Samples were placed in self-sealing plastic bags of dimension 120mm x 180mm, (for the majority of samples less than 1kg) or in plastic bags sealed by twist-ties. The self-sealing bags had write-on panels, on which were noted in pencil or ink the date, location, sample type and sample serial. In most cases, this was accompanied by notes of adjacent coarser fractions if not sampled, of sample depth and thickness, and shoreline slope at the sample point. The latter was obtained by a modified Abney Level attached to a flange on an aluminium sheet of dimensions 150mm x 120mm. The dip direction was obtained with reference to a bulls-eye level on the plate surface.

Submarine Samples (Nearshore and Offshore)

Reconnaissance

The investigation of nearshore and offshore sediments was accomplished by direct inspection and sampling on SCUBA, and sampling by surface-actuated sampler. An initial reconnaissance of the offshore was completed in January, 1982, with the use of a 4 metre powered aluminium dinghy. At four sites: Opua Bay (Tory Channel), Grove Arm (Queen Charlotte Sound), Clova Bay (Beatrix

Basin) and Duncan Bay (Tennyson Inlet), echo soundings of bay axes and transverse profiles were taken with a Ferrograph 500D chart-recording echosounder. Samples were taken with a leaded grab sampler, the design of which gave inconsistent results. Bottom samples were recovered at each location, and analysed by the hydrometer method.

This limited reconnaissance was followed by a survey on SCUBA of the bay bottoms and nearshore of 10 bays in the Pelorus Sound, in April 1982. Four divers including the author made 21 dives to a maximum of 23m (75') in bays marginal to the Pelorus Channel, in Mahau Sound, Clova Bay and Tennyson Inlet. In total 69 samples were recovered, and 12 cores of 1.5 metres in length. A 600 m line with knots at regular intervals was laid from a 7 metre dive boat along the bay axis or extending from a bay-mouth. Samples were recovered by hammering 200mm long tubes into the bottom. These samples were analysed also by the hydrometer method. The dives were used to survey bottom micro-form, vegetation and textural character.

The most distinctive differences between submarine sites were found to relate to bottom gradient and to depth. Nearshore sites have coarser surface sediment textures including sand, while bay bottom sites are characteristically fine and silty. Nearshore slope sites can often be rocky or have granule "scree faces". At delta sites, a break in slope just below low water is juxtaposed with a steep nearshore face, often having a surface texture of granule detritus with a silt matrix. At greater depths, silt and clay dominate over the coarser components. Micro-morphological form on the flat bed stems principally from fauna, especially tube worm burrows. Shallower sites in the nearshore and offshore with higher levels of light penetration have an irregular distribution of seaweeds. In some locations in Queen Charlotte Sound (Grove Arm 18-22m, Fence Bay, Onahau, from 6m depth) there is an almost continuous distribution of seaweeds.

Nearshore Samples

The aim of nearshore sampling was to identify the transition in sediment and morphology over the submarine segment of the nearshore slope. The sampling interval reflected was determined by observed changes in slope gradient or sediment texture. Reconnaissance on SCUBA preceded sampling.

Nearshore samples were recovered by diving on SCUBA equipment. The steep nearshore gradients, extreme variability in texture over short distances, and correlation of sediment texture with gradient, made direct inspection and hand sampling necessary.

Samples were recovered by the author with one field assistant. Diving from a moored inflatable boat or from the shore, a reconnaissance was completed on the downslope leg taking note of changes in surface texture and gradient. Once a uniform slope and texture was encountered by visual inspection, the divers proceeded upslope on the same axis (with the use of a compass). Samples were taken in the centre of facies as identified on the recconnaisance. Note was taken of depth (from depth gauge), the time (for correlation to tide stage), and slope gradient, using the device referred to above. Notes were taken with pencil, writing on plasticised paper or directly on the PVC sampling device. Visibility varied from a maximum of 5 metres to a minimum of less than 0.3m.

Considerable experimentation preceded the selection of a suitable diver-operated sampling method. Initial methods involved the use of 50mm internal diameter white PVC circular pipe in 200mm lengths. These were forced or hammered into the muddy bottom. The top was sealed with a standard end cap, which had an internal taper which sealed when forced over the tube. The tube was then pulled or dug out, and capped at the other end as at the top.

The technique was clumsy to implement on the very fine textured bottom, where disturbance suspended clouds of mud which cut vision to centimetres. Considerable force was required to extract the cores from the more compacted lower layers, and the tubes were often difficult to uncap on the surface with changes in pressure. The tube samplers gave short cores of the bed but due to variable effort expended in forcing the cores in as the compaction of the bed varied there was distortion of the vertical distribution of sediments in the core sample. As the focus of the study was primarily on obtaining first an understanding of contemporary sediment dynamics, subsequent sampling was confined to surface samples.

An alternative design permitted undisturbed retention of the surface layers to a standard depth, a standard sample size, and ease of underwater operation. The sampler was comprised of four elements: a self-sealing plastic bag, a rectangular-form PVC tube of dimension 100 x 50mm in section and 100mm long, and two pipe joining sections which fitted over the outside ends of the tube. A series of samplers was prepared on the surface. A joining section was forced onto the end of the tube, locking the three elements (bag, inner section, joining section) together.

The samplers were carried in a catch-bag, and taken out singly on site. The joining section was used as a handle, to insert the internal section into the bottom to the depth of its narrowed dimension. The plastic bag was used as a liner for this inner section. The tube was then pushed along the bottom, with the top surface of the inner section along the mud surface. When the bag was full its open end was slipped off the tube and the flaps brought together. A second joining section was forced over the end of the inner PVC section, sealing the flaps of the bag together. The sampler was disassembled at the surface,and the bag cleaned and sealed.

Writing in pencil adhered to the white PVC inner tube, so details of bottom morphology, slope and depth were noted directly on the sampler. These were transcribed later. A second sampler, a small lidded tube, was used to obtain a small sample of surface muds, and was placed in the sealing bag to keep these together.

Sampling of the nearshore was conducted in July 1985 by the author and one field assistant. Fourteen dives were completed in the Queen Charlotte and Kenepuru Sounds with the recovery of 64 samples. Details of the traverse profile, depths, slope and sample locations are reported in Table 5.2. The textural character of 33 samples is reported here, all analysed by RSA and the pipette.

Offshore Samples

Offshore sampling followed reconnaissance by echo-sounding. Sampling locations were planned on the basis of 1:25,000 bathymetry. A sampling strategy was based on the location of principal stream inflows, of the form of the bottom (location of channels etc) and on location of headlands. Each suite of samples within a bay was designed to distinguish the scale of bottom sediment variability. Sites were located on the water by sighting to topographic features and compass sights. Accuracy was estimated at within 100m in smaller bays, and 200m in open areas.

Sampling of the offshore was conducted in 1985 and 1986. During the winter of 1985, samples were recovered from the northern bays of Queen Charlotte Sound by a 300mm x 300mm Ekman sampler from a 6 metre boat. In February 1986, samples were recovered from Tory Channel, Inner Queen Charlotte, Kenepuru, Inner Pelorus Sounds and the marginal bays of the Pelorus Channel using a smaller Ekman grab of similar design. A total suite of 252 samples was samples was recovered, subjected to qualitative description and logged. The distribution of samples is reported in Table 5.3.

Offshore samples reported here were all taken with a 200mm x 200mm Ekman grab. The spring-loaded jaws were primed open on the surface and the sampler lowered to the bed on 7mm line in depths ranging from 2 metres to 45 metres. The sampler was dropped to the sea bed over the last 0.5-1m. Additional lead weights gave the sampler an air-weight of 8kg. The sampler impressed into the mud bottoms between 50 and 150mm depending on softness. The release sender was then slid down the line to impact the release ring, allowing the springs to pull the twin jaws shut under the sample box. On sandy bottoms, the closing of the jaws was the action which collected the small sample.

The sampler was recovered by hauling the line aboard , lifted into a clean basin in the boat and opened, dumping the full sample into the basin. In general the box sample shape was retained. A sub-sample was taken from the surface of the box sample to a similar depth as the nearshore samples (50mm). A self-sealing plastic bag of identical dimensions to those used for the dive and shore samples was used. It was pre-labelled on the write-on panel with site, depth and sample serial information. The Ekman was swung overboard, flushed clean , then stowed. Either a 5m or a 6m fibreglass runabout was used for all offshore sampling.

Over 250 samples were taken with the Ekman grab, and note taken of sediment textural differences both while sampling and subsequently in the lab. Of these, 69 samples, grouped into suites which can serve specific interpretive purposes, are reported in Chapter 9. The selection of these was based on a preliminary analysis of all offshore samples. Some bays were not selected as case studies, and some intermediate samples were not analysed. Summary textural indices for samples are presented in this chapter.

Methods of Sediment Analysis

Samples were stored in a moist condition until analysed. Sample preparation and analysis of necessity varied between gravel-sand and silt-clay size grades, but all techniques were based on the direct assessment of settling velocities. Sample preparation was determined by the aim of obtaining comparable samples for settling.

Shoreline

Preparation

Samples were split, using a sample splitter, to obtain a sub-sample the size of which varied with grain-size. For coarse granules, up to 200gm was used, for sands, a standard of 30-50gm was used. Organic material was floated off after splitting. No chemical analysis was applied to shoreline samples. Where large shell fragments dominated, parallel samples with the shell and with the shell removed by hand were analysed. Any variations of this type are described in the text; effects on size (moment and percentile) parameters were found to be minimal.

Analysis

All samples presented here were analysed by an automatic Rapid Sediment Analyser (RSA), the technical details of which are listed in Appendix 2. The RSA device involved the introduction of the split sample to the top of a 2m water column. The sample was held below the water surface until released. Upon release, a solenoid triggered the timing operation of software on an Apple IIe computer. As sediment settled a measured distance of 1.87m, it collected on a tray suspended from a Metler 160 electronic balance with 0.01gm accuracy. The cumulative output of the balance was logged by the microcomputer at approximately one second intervals, until a selected sampling period finished. This was based on the settling rates of the finest particles, and ranged from 30 to 90 seconds for fine gravel and coarse sand, to 600 seconds for material down to the coarsest silt grade (4.25ø). The cumulative curve of weight was transformed by the software to equivalent settling diameters, and a variety of grain-size plots and parameters were calculated. A second analysis was completed on the basis of the Chi settling rate parameter (May, 1981).

The results of RSA analysis were found to deviate substantially from results obtained by sieving of parallel sub-samples. An example of the deviations is shown in Figure 5.1. The curve presents the percent-in-class weights at 0.25ø intervals. The sample is typical of inner Queen Charlotte Sound beach samples, taken from near high water. The mean size by sieving was in the granule class, but by settling classed as coarse sand. The origin of these deviations can be traced

Figure 5.1

Comparison of Sediment Analysis by Sieve and Settling

Figure 5.1

Sieve vs Settling Analysis (Phi Offset) Sample RSA 022

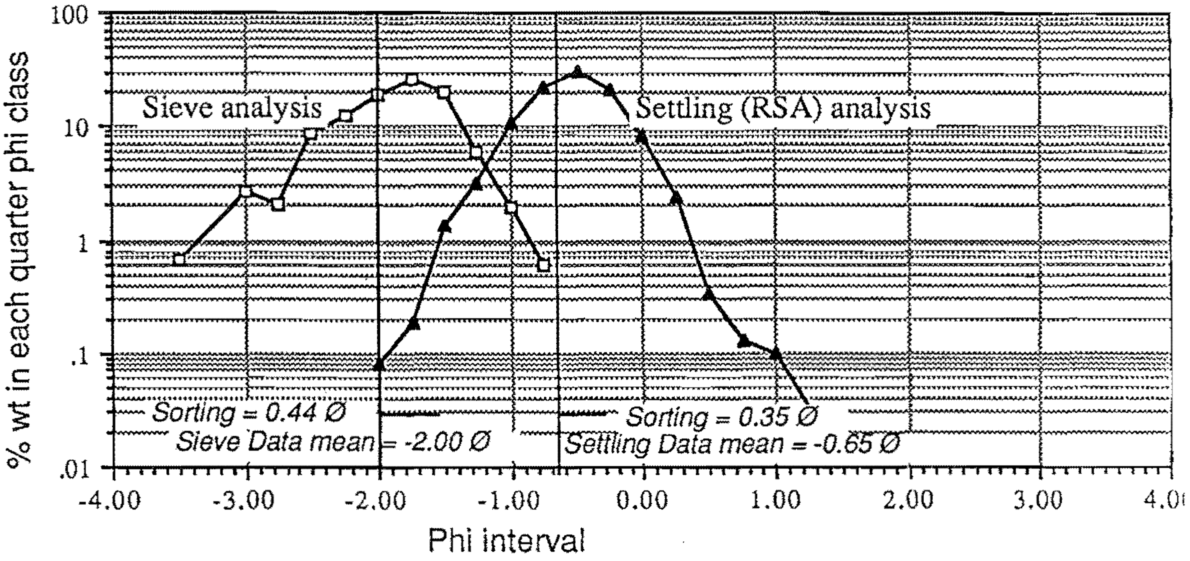
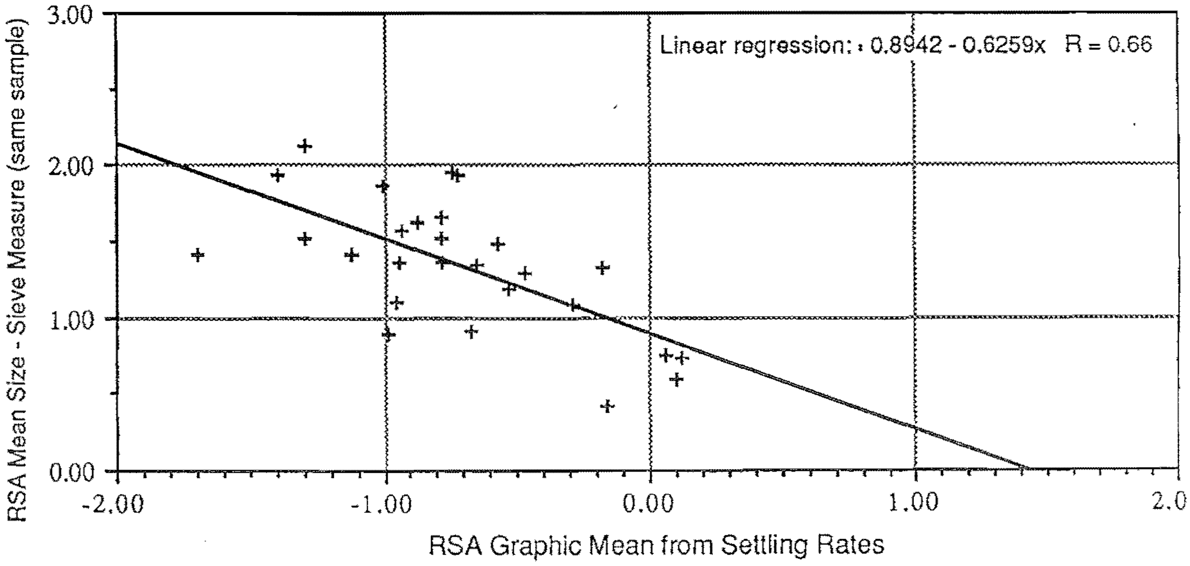


Figure 5.2

Comparison of Mean Sizes Obtained by Settling (RSA) and Sieving



Results of sediment size analysis of gravel and sand sized material by settling and sieving methods show systemmatic deviations. Figure 5.1 shows the displacement of mean grain size by nearly 1.5ø based on a parallel analysis of subsamples. Figure 5.2 shows that differences diminish with decreasing grain size. Differences stem from particle shape factors in schist materials and make sieve and settling data incomparable.

to the platy form of the schist particles, which settle in water at a rate slower than would spherical particles of the same intermediate-axis dimension.

Figure 5.2 is a scatter plot of 28 samples over a mean (RSA) size range of -1.7ø to 0.1ø. On the y axis is shown the difference in phi units between the mean size calculated by sieving and that calculated by RSA settling. Maximum deviation was 2.2ø units and the minimum deviation 0.4ø units. In all cases the sieve mean was coarser than the RSA mean for the parallel sub-samples split from the original sample. The slope of a linear regression fitted through the points indicates a decreasing difference between analytical methods with fining, with an x intercept at 1.5ø. (Slope and r value on Figure 5.2). The platy shape of schist particles is more distinct in pebble sizes than in sand.

These deviations highlight the ambiguity of sieving as an analytical method for process investigations, whenever settling velocity is the dynamic factor under consideration. Particularly in platy material, as dominates in shoreline material in the Sounds, seiving is an analytic method which is liable to lead to systematic misinterpretations in hydraulic behaviour.

Submarine Samples (Nearshore and Offshore)

Preparation

Samples were stored in a wet state, in moderately cool conditions. No problems with reducing conditions developing during storage were encountered. Preparation involved two stages: first a test sub-sample, followed by the analysis of a series of parallel sub-samples.

(a) *Test Sample*

A test sub-sample was taken, split, and half was weighed in moist state, then dried overnight and reweighed. The other half was weighed moist, wet-sieved at 63microns, and the coarse fraction retained, dried and reweighed. These gave an estimate of percent coarse and percent water content in the retained sample. Notes were also taken of appearance, macro-organics, shell content, and the retained coarse fraction was examined under a stereo microscope. Diatoms were abundant in some samples, but sand was the main coarse fraction in offshore samples. Calculations were then made as to the moist sample size required to yield 15-20gm of dry weight of the mud fraction after wet-sieving.

(b) *Parallel Sub-Sample Preparation*

For nearshore and offshore analysis, three sub-samples were taken: one for fines analysis, one for sand and shell analysis, and one for organics. For settling of sandy materials, a larger sub-sample was required than that which yielded the 15-20gm of muds for the fines analysis, hence, the separate sub-samples.

Samples subject to fines analysis were first treated with 10% (weight-by-volume) Hydrogen Peroxide to dissolve organics. In the absence of this treatment, flocculation of the clay fraction was observed, with greatly increased settling rates. The rapid settling of clays is in fact to be expected in natural salty conditions (Krank, 1981), and to treat for organics not only removes an environmentally present flocculant, but is also liable to cause the splitting apart of silt particles particularly mica-plates. The latter could be seen glinting in the treated samples. The analysis proved necessary for standardisation however, as it could not be assessed a priori to what extent organics were co-depositional or post-depositional accumulations. The apparent grain-size distributions thus give the appearance of a sample which would settle much more slowly (i.e. appear finer) than could be expected in environmental conditions.

Treated sub-samples were then raised in temperature to over 70° C to reduce the hydrogen peroxide to water and oxygen. The samples were then filtered in a Buchner funnel through standard grade filter papers. The moist sub-sample was washed using distilled water into a tray, and 50ml of Calgon (Sodium Hexametasulphate) added to aid dispersion. The sample was then wet-sieved through a 63 micron sieve, and the coarse fraction retained, dried and weighed. The fine fraction was dispersed for 10 minutes in a mechanical mixer, then poured into a 1 litre glass settling column. The column was topped up to the 1 litre mark with distilled water, and covered with a watch-glass to prevent evaporation. The columns were left for 12 hours to check for flocculation.

Analysis

Sub-samples of 15gm taken for organics were dried overnight at 90°C, allowed to equilibrate to room temperature and weighed. The samples in porcelain crucibles were then kiln dried for 12 hours at 450°C, before cooling and reweighing. Weight loss was attributed to the lost organics, and calculated as a percentage of initial dry weight.

THE LIBRARY
UNIVERSITY OF CANTERBURY
CHRISTCHURCH, N.Z.

The one litre columns containing 15-20gm of fine sediment were stirred for 50 seconds, then sampled at intervals by pipette at the standard depths to obtain weight fraction at half-phi intervals from 4ø to 6ø, then one-phi intervals to 10ø. Up to 22 analyses were run concurrently, using the schedule given in Lewis (1982). Pre-weighted sets of 9 glass beakers per column were dried and reweighed to 0.001 gm, the weight gain representing sampled sediment concentration. Weight gain times 50 minus 1 (gram) for the calgon weight yielded a weight in suspension at each time period from 20 seconds (everything finer than 4 ø) until 32 hours (finer than 10ø).

The coarse fraction in samples was weighed, and where the coarse content exceeded 15% of total sample, was also settled by RSA, with preparation as follows. Most nearshore samples contained an appreciable coarse fraction (sand and granule). Sufficient coarse material for settling was obtained by a third sub-sample, oven dried at 65° for 8 hours then weighed cool. The dried blocks were dispersed by 10% H_2O_2 (Hydrogen Peroxide) from a squeeze bottle which both dissolved the organics and split up the hardened mud nodules. The sample was wet-sieved and the coarse fraction dried and reweighed to give percent coarse. To the dried coarse fraction, 10% weight-per-volume HCl (Hydrochloric Acid) was added by squeeze bottle to dissolve the shell ($CaCO_3$, calcium carbonate) material. Following this treatment the sample was rinsed on the wet sieve, dried and reweighed.

Measurement of Particle Size

Particle size is by no means an unambiguous measure. Pettijohn (1976) identified six alternate measures, including

(1) volume (L^3)
(2) weight ($M.L.T^{-2}$)
(3) surface area (L^2)
(4) cross-sectional area (L^2)
(5) settling velocity ($L.T^{-1}$)
(6) intercepts through particles or projections (L_x,L_y,L_z).

The dimensional analysis is from Winkelmolen (1982).

The unit of measure differs according the definition used. The fundamental choice is whether to obtain and express size in a static or dynamic index. A dynamic index such as settling velocity is only nominally a size, as argued by May (1981), and consequently, in his view, should be expressed only as a velocity. The conversion of settling velocities to a standard sedimentation diameter is a convention which has the advantage of giving a metric which can be related to static measures such as are obtained by calipers or sieving. In this study all populations of grains were measured by settling through water. Time intervals taken to settle a specified distance were calculated to standard sedimentation diameters and reported as percent-weight per size interval.

In reporting a measurement, the prime distinctions are between a nominal grade scale (e.g. Wentworth, 1922), an arithmetic scale (e.g. millimetres), or a geometric scale (e.g. Phi). Grade scales have practical descriptive utility. The terminology used here derives from Folk, Andrews and Lewis (1970). An arithmetic scale is preferred by Buller and McManus (1972) on the grounds of familiarity and the dangers of misinterpretation of some geometric scales. Some reference is made here to arithmetic measures in millimetres.

The scale of phi units was devised by Krumbein (1934). The logarithmic scale of phi is defined as :

$$\phi = -\log_2 (d / d_o),$$

where d represents grain diameter and d_o represents a standard grain size of 1mm.

As noted by Buller and McManus (1972), this converts the geometric Wentworth scale into an arithmetic scale of positive and negative integers. In the range from -2ϕ (coarse endpoint of granules) to 8ϕ (boundary from silt to clay), each phi unit represents one grade on the Wentworth scale. However, the empirical reason why a logarithmic transformation has usually been applied is that many particle size distributions have been observed to be skewed towards finer sizes. The adoption of a log transform has been observed to tend to normalise these distributions towards a Gaussian distribution, giving access to a wide range of standard statistical tools. Providing adequate attention is given to statistical usage and physical interpretation, the phi scale has practical value.

The phi-fraction percent-by-weight data are presented in two main forms: as a cumulative curve of the percent coarser than a given phi value, and as line-histograms of a percent weight per quarter phi interval. The latter are used only for the sand-gravel range. Such curve plots were recommended by Bagnold and Barndorf-Neilsen (1980). All methods of presentation become incompatible if data in one form are compared with data in another (Lewis, 1982). These problems are resolved by an internally standard presentation.

Statistical Presentation of Data

Indices

A range of indices have descriptive value with regard to distinguishing one sediment sample from another. A measure of central tendency, the median or the mean value, provides the simplest summary of the grain-size distribution. The notion of sediment sorting expresses the range of sediment sizes in a deposit. A beach which contains a wide range of sediment sizes is described as poorly sorted. Conversely, if the grains are measurably similar in size, the sediment is well sorted.

Higher moments of the mathematical distribution curve constructed from grain-size data have been used to describe the shape of the curve. Skewness and kurtosis identify deviations from a Gaussian normal curve. The first describes the extent to which the mathematical distribution obtained from size data is symmetrical about the mean. It is found empirically that many hydraulically sorted samples have an essentially normal (Gaussian) distribution, and hence a skewed distribution may be used as an index of departure from that form. Likewise, kurtosis is a measure of departure from the statistically normal curve shape. Leptokurtosis indicates a peaked curve, platykurtosis a flattened curve. Kurtosis is therefore a measure of the relative sorting near the mean as against the tails of the distribution. Its physical interpretation is not as apparent as are other moments, but as an index it has descriptive value.

For shoreline samples, values of mean grain-size, sorting, skewness and kurtosis were calculated using the formulae for inclusive graphic parameters specified in Folk (1974). Data were logged by the micro computer direct from the RSA balance, and converted into phi percentile data. Interpolation from the cumulative curve yielded values which were inserted into the formulas given in Appendix 2.

The median was used as the measure of central tendency for fine samples. Results of analyses were found to be reproducible, but pre-treatment was known to modify the fine materials. This diminished the interpretable significance of the fine limb. The analysis of small sub-samples is imprecise and errors can arise in matching the curves from coarse and fine analysis where the sample extends across the size boundary from sand to silt at 4ø.

The index of sorting used is the Phi Quartile Deviation (Krumbein,1936). This value (notated as QDø) is defined as half the range in phi units from the 25th to the 75th percentiles, or the equivalent of one standard quartile range in ø units. The formula is given as:-

$$QD_{\phi} = (\phi 75 - \phi 25)/2$$

The measure is inferior to sorting calculated by reference to the ø16 and ø84 values (Folk, 1974) but was a more robust measure in samples which contained higher sand or clay contents, where the estimation of limb values was less reliable.

Initial Description of Sediments

Summary Grain Size Statistics

Samples reported here were obtained from the three domains discussed in the previous sections.

Shoreline Domain

Shoreline samples were taken of what were termed "accumulations". These were distinguished from the lag surfaces of gravels on which they lay by textural and morphological criteria, that are discussed in the following chapters. These samples represent the sediments which comprise beaches and intertidal accumulations. Average values for the indices of mean, median, sorting, skewness and kurtosis are listed in Table 5.4. Mean grain-size of these samples was -0.49ø, or coarse sand. Average sand content was 71%; the remaining 29% was gravel. The mean value for sorting in the 176 samples was 0.67ø, or moderately well sorted. The samples were on average values near symmetrical (skewness = 0.02) and mesokurtic (kurtosis = 1.07).

Table 5.1

Shoreline Sediment Sampling Locations

Sub-region	Grid Ref NZMS 260 P 27
Queen Charlotte	
Grove Arm	
Outer shore	
Wedge Point	945 937
Ngakuta	906 923
Bythells	938 927
Momorangi	886 927
Aussie	878 923
Umungata	887 943
Iwirua	935 936
Grove	872 931
Northern Bays	
Lochmara	GS 34953 and GS 9496
Southern Shore	
Kahikatea	034 953
Outer Shore	025 955
Pelorus	
Mahakipawa	
Moenui	769 918
Belvue	793 909
Okahoka	798 932
Mahau	
Double Bay	825 942
Moutapu	817 836
Ohingaroa	845 952
Willow	857 962
Kenepuru	
Broughton	900 986
Te Mahia	914 984
Puketea	948 998
Black Rock	001 008
Sandy Bay	021 017
Waitaria	975 972

Grain Size parameters reported in Appendix 3.

Table 5.2

Nearshore Sediments Summary

Sub-region	Samples	Grid Ref	Details
Queen Charlotte			
Grove Arm			
Whenuanui	9	918 927	Prodelta slope
Momorangi	4	889 967	Prodelta slope
Umungata	3	888 943	Prodelta slope
Okiwa	5	869 921	Prodelta slope
Northern Queen Charlotte			
Onahau: Fence Bay	5	921 991	Prodelta slope
Pelorus			
Kenepuru			
Puketea	5	943 995	Prodelta slope

Grain size parameters reported in Appendix 4.

Table 5.3

Offshore Sediments Summary

Sub-region	Samples Reported here
Queen Charlotte	
Grove Arm	13
Northern Bays	5
Tory Channel	
Maraetai	8
Hitaua	5
Opua	5
Deep	5
Pelorus	
Mahakipawa	1
Mahau	4
Maori	4
Four Fathom	11
Nydia	4
Kenepuru	
Kenepuru	4

Table 5.4
Shoreline Sediments Grain Size Moment Values

n=165	Mean	Median	Sorting	Skewness	Kurtosis
Mean Value	-0.40ø	-0.52ø	0.67ø	0.02	1.07
Standard Deviation	0.61ø	0.59ø	0.20ø	0.17	0.16

Table 5.5
Submarine Sediments Grain Size

Offshore Samples	n=	Sand %	Silt %	Clay %	25% ø	Median ø	75% ø	QDø ø
All samples	69	19.7	52.0	28.3	4.6	6.0	8.2	1.8
Sub-regions								
Pelorus	27	8.7	49.1	42.2	5.4	6.9	9.5	2.1
Queen Charlotte	19	26.1	47.5	26.4	4.1	5.9	8.1	2.0
Tory Channel	23	24.2	57.8	18.0	4.2	5.2	6.9	1.3
Nearshore Samples								
All samples	33	54.4	22.5	32.1	2.6	4.2	6.9	2.2

Table 5.6
Submarine Sediments Non-lithic Contents

	Shell Content		Organic Content	
	Mean %	Std Dev %	Mean %	Std Dev %
Offshore Samples				
All samples	22.5	17.1	5.3	2.8
Sub-regions				
Pelorus	20.6	17.0	6.4	2.4
Queen Charlotte	24.8	21.7	6.3	3.1
Tory Channel	20.2	14.1	2.9	0.9
Nearshore Samples				
All samples	10.2	9.4	4.1	2.0

The distribution of samples within mean size grades and sorting, skewness and kurtosis classes is shown in Figure 5.3. The largest proportion was very coarse sand (65%), while a further 14% had mean sizes in the granule range. Only 21% were sands finer than very coarse grade.

Over one third (36%) of the samples were well sorted or very well sorted. 18% were poorly sorted and a further 19% moderately sorted. The remaining 26% were moderately well sorted. Figure 5.3 also shows the proportions of samples in each skewness and kurtosis class. The largest proportion in each case were near symmetrical or mesokurtic. More were fine-skewed than coarse, and leptokurtic than platykurtic.

Submarine Domains

Summary values of the average median grain-size, sorting index (Phi Quartile Deviation), and sand-silt-clay percentages are given in Table 5.5, for the offshore and the nearshore domains. The offshore domain data are also broken down by three subregions, Pelorus, Queen Charlotte, and Tory Channel, from which samples were recovered.

The average median grain-size of offshore samples was 6.0ø, between medium and fine silt. Pelorus samples were on average finer (6.9ø), Queen Charlotte fractionally coarser (5.9ø) and Tory Channel coarser again (5.2ø) but still within the range of medium silt. Sand content was on average 20%, silt 52% and clay 28%.

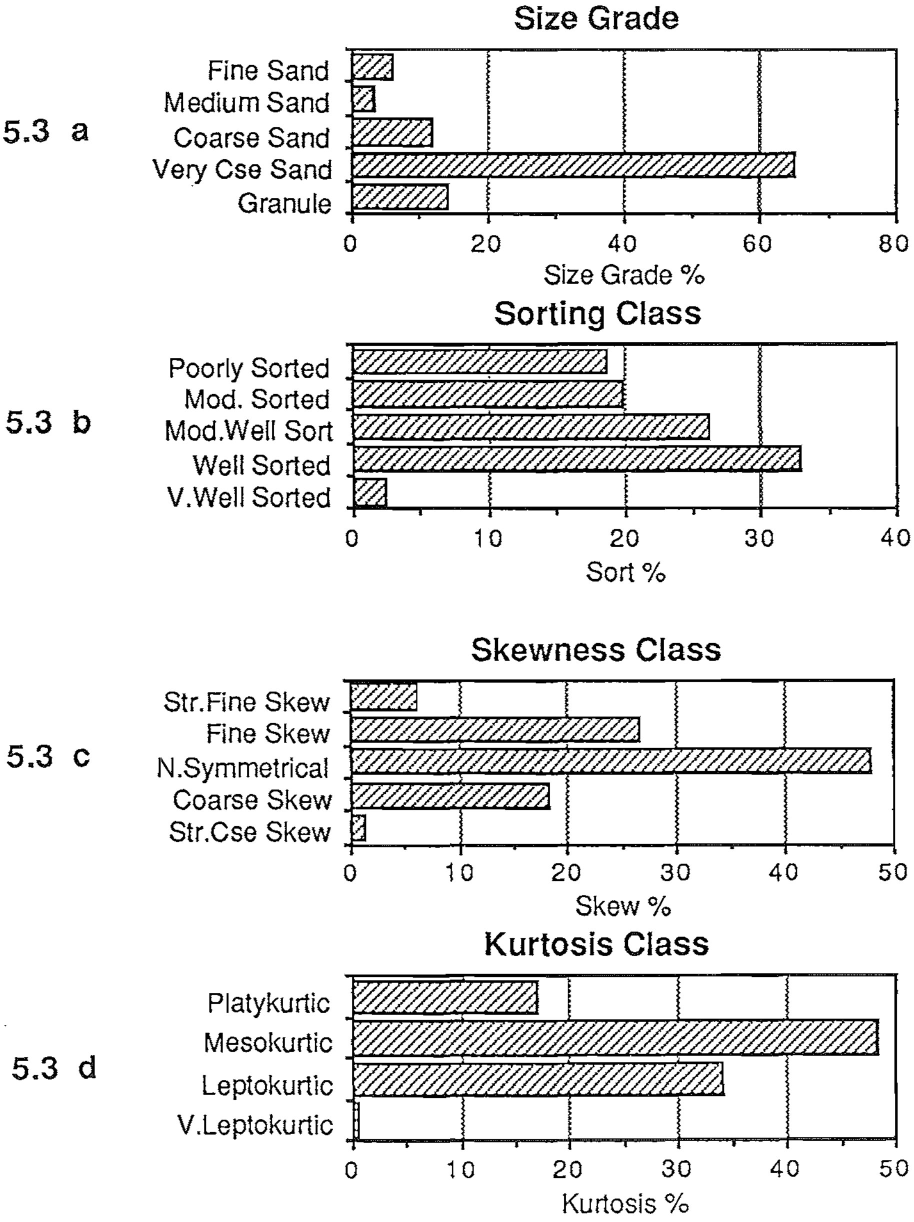
Nearshore samples had an average median size of 4.2ø, or coarse silt. This value reflects the high sand content in these samples (54%).

A plot of textural classes for offshore samples is shown in Figure 5.4, using the terminology of Folk, Andrews and Lewis (1970). The Pelorus Sound offshore samples have a higher clay content and less sand, and plot predominantly in the mud category. Queen Charlotte samples were more variable, predominantly sandy mud, while Tory Channel samples were mainly sandy silt or silt.

Figure 5.3

Shoreline Sediments
Frequency per Class in Moments of Size Distribution

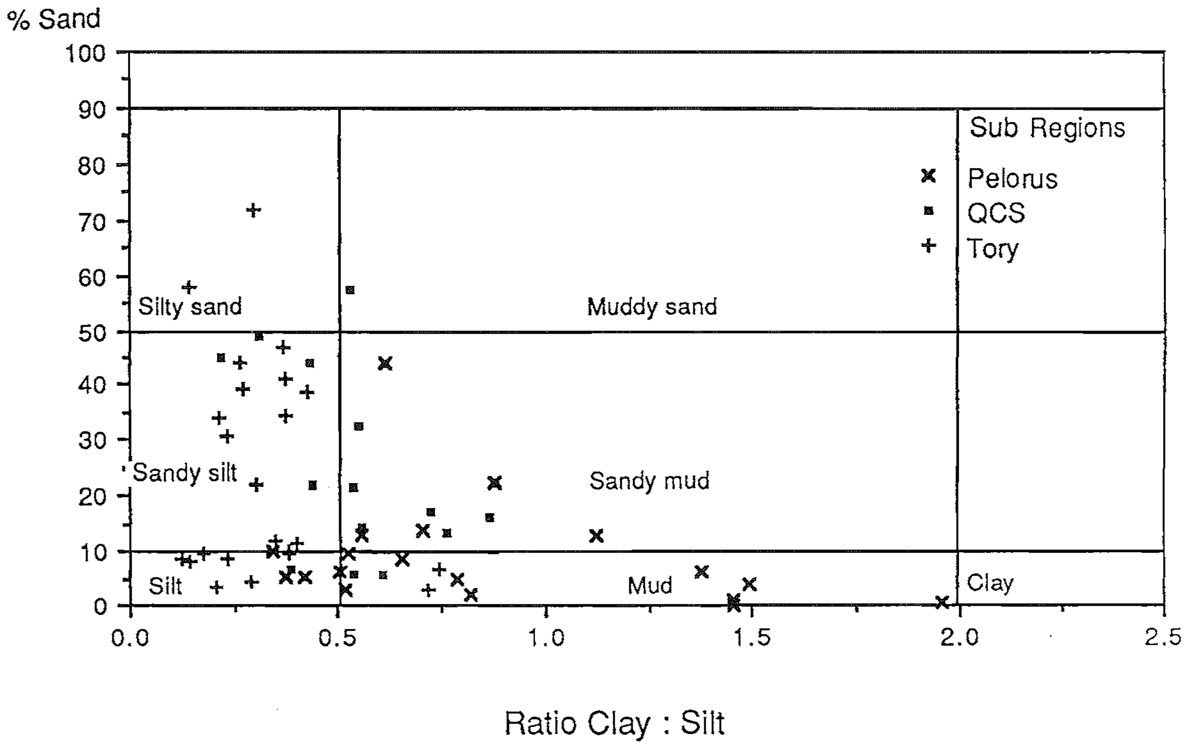
Figures 5.3 a to d



Mean grain-size and moments of size distribution curves for all shoreline samples.

Figure 5.4

Offshore Sediment Textural Class
by Sub-region of sampling



Nomenclature according to Folk, Andrews, and Lewis (1970

Summary textural plot of all offshore samples by sub-region of sampling as labelled.

Grain Size: Discussion

There is a clear differentiation between shoreline and offshore deposits, while the nearshore represents a zone of transition in which there is a mixing of the mud and sand fractions. This points to a fractionation of sediments taking place at or near the shore.

The predominance of the very coarse sand and granule classes in the values for mean grain-size of shoreline sediments points to a distinctive feature of Marlborough Sounds shore deposits.

Folk (1974) and many others including Sundborg (1956) have observed a relative scarcity in nature of granule-coarse sand (0 to -2ø) particles. Folk (1974, p5) assumed that sediments with mean sizes in this range must be a mixture of pebbles with sand.

However, a plot of 25 beach samples shown in Figure 5.5 shows that the mean values of these shoreline sediments are attributable not to a mixing of two flanking populations, but to modal values coincident with the mean size.

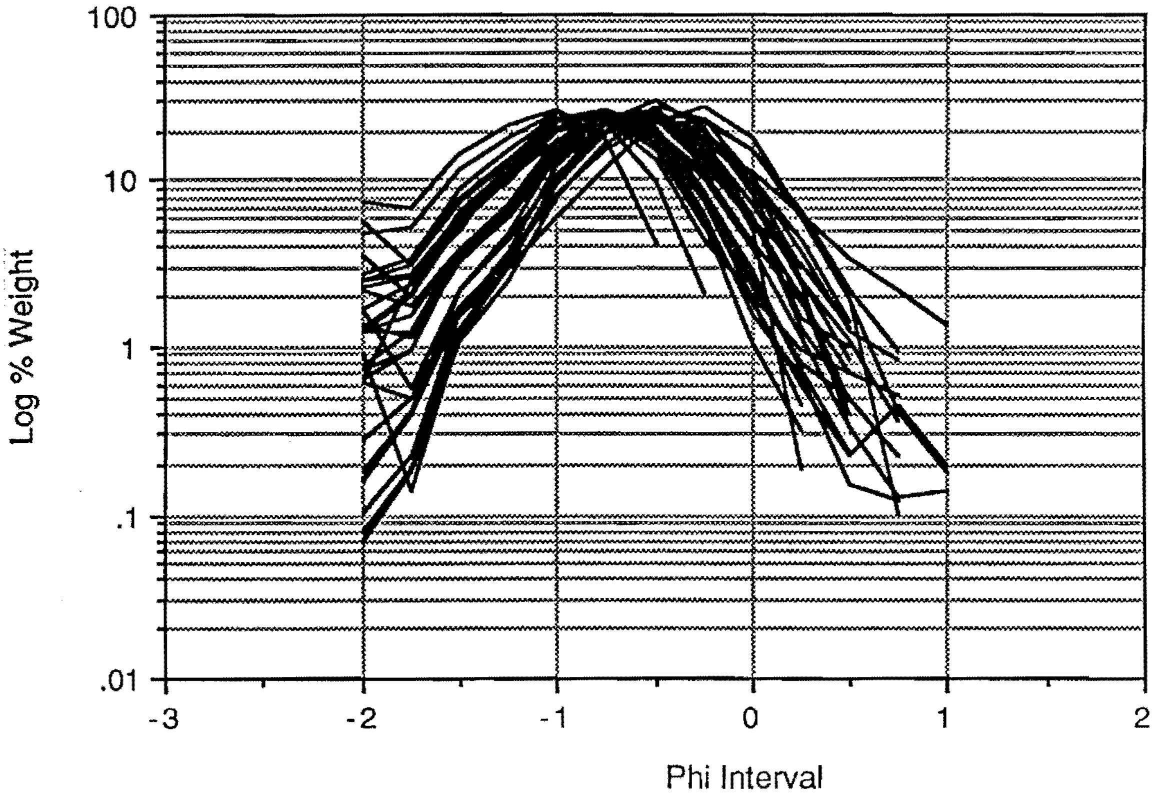
Shea (1972) rejected the grain-size deficit proposition, suggesting that it reflected local factors in the environments in which sampling had been conducted. The similarity in grain-size distributions in the beach samples in Figure 5.5 which were sampled from the upper foreshore of 25 different beaches in the Grove Arm and inner bays of Queen Charlotte Sound, suggests that there are distinctive factors within the environment which determine grain-size. These could stem from either the availability of particles from the source (Folk, 1974) or from the manner in which local hydraulic processes sort shoreline materials.

Grain Size and Sorting

Folk (1974) noted that in every environment sorting is strongly dependent on grain-size. In Figure 5.6 a scatter plot of mean grain-size of shoreline samples against their sorting values is presented. An association of best sorting with the coarsest particles present relates to the very narrow range of particle sizes in the beach sample curves shown in Figure 5.5. With diminishing mean size away from the granule-very coarse sand mode, sorting decreases.

Figure 5.5

Grain-Size Curves for 25 Beach Samples showing Modal Uniformity



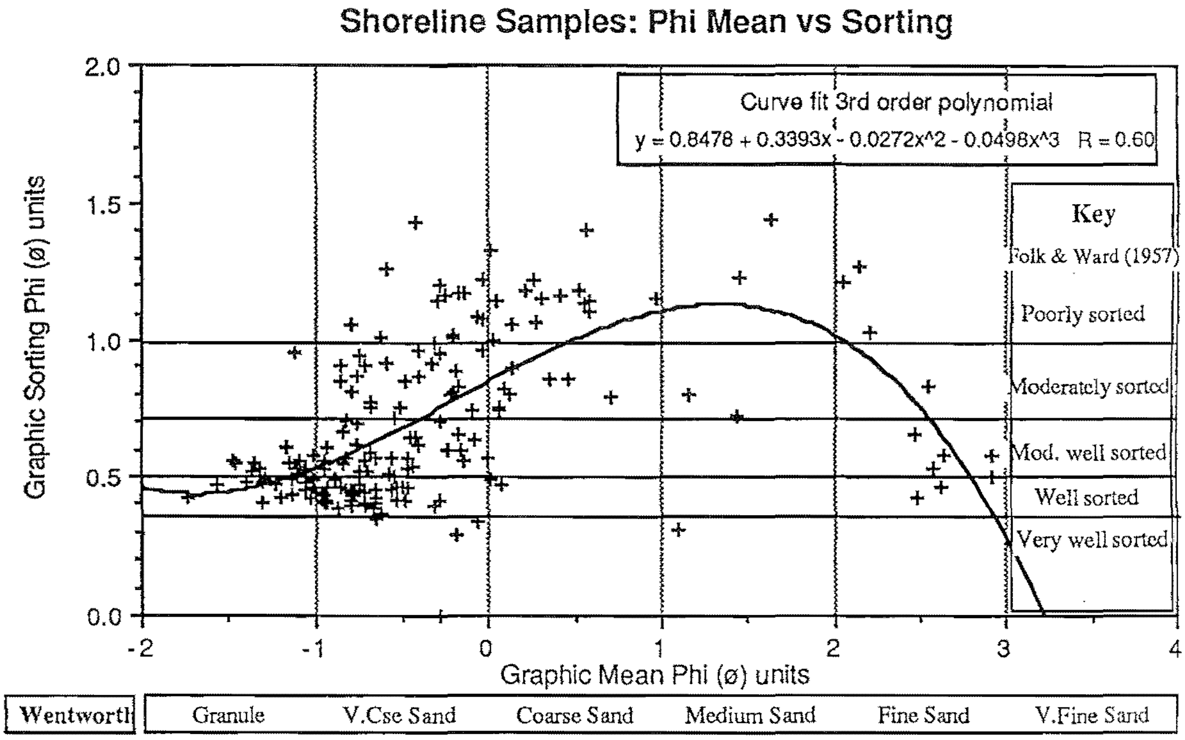
Overlay plot of 25 beach samples

(RSA 006 007 016 017 019-023 040 046 092 094 106 120 121 125 126 141 142 143 187)

defines an envelope showing unimodal distributions and modal sizes in the very coarse sand grade. This modal size is reported as "deficient" in many environments (Folk, 1974)

Figure 5.6

Size-Sorting Relationship in Shoreline Sediments



Mean grain-size plotted against graphic sorting for shoreline samples. Best sorting coincides with very-coarse sand/ granule and fine sand grades. Good sorting in fine sands is widely reported, but good sorting in the granule grades is more rare (Folk, 1974). Folk and Ward (1957) proposed that the "modified sine curve" pattern widely reported in the size-sorting trend, and observed here, was attributable to the mixing of two end member populations. This interpretation accords with the data here, as the trend towards poor sorting in samples with a mean size in the coarse/medium sand grades reflects the mixing of a gravelly population with a sand population. Contrary to the observations of Folk and Ward (1957) and others, the gravel mode here is not in the -3ø range, but around -1ø.

This trend is reflected in the third order polynomial curve, fitted by computer. The Pearsons "r" value is 0.60. The curve shows a sinusoidal trend, which identifies a trend to better sorting again in samples with a fine sand mean. This suite of samples was drawn from near low water. A characteristic pattern in the Sounds beaches is for a zone of fine sands to be found extending from below to just above low water level.

Figures 5.7a and 5.7b present plots of median grain-size of offshore and nearshore samples, plotted against their Phi Quartile Deviations. As an index of sorting, this cannot be compared directly to Graphic Sorting.

Quartile deviations on offshore samples range from 1.7ø to 2.8ø, and show no trend of systematic variation with median grain size. Nearshore samples show higher values of Quartile Deviation, up to 5.6ø. A linear regression of nearshore values gives an r value of 0.76, and identifies a general trend for Quartile Deviation to increase with decreasing median grain size.

Size-Sorting Trends: Discussion

The cyclic pattern in size-sorting found in the shoreline sediments has been identified in other environments. However, well sorted sediments are rarely found in samples with mean sizes around -1ø. Folk (1974) suggested that best sorting will be found in a gravel mode at -3ø to -5ø, and the poorest sorting to coincide with mean sizes of 0 to -1ø.

Folk's (1974) anticipation of poor sorting in the 0 to -1ø range stemmed from the asumption referred to above that there was a "natural" gravel mode at -3ø to -5ø. Such a predominant mode is not found in shoreline accumulations in the Marlborough Sounds, despite the very wide range of particulate sizes available in the shoreline environment. One key factor in the accumulation of finer rather than coarser gravels is identified in following chapters as the low levels of shoreline energy on the sheltered coast.

The trend towards better sorting in the fine sand sizes (2 to 3ø) found in these shore samples is a pattern matched in most fluvial and coastal environments. This is usually attributed to the hydraulic characteristics of particles in this size range, in that they are the most easily transported at the smallest velocities (Inman, 1949).

Figure 5.7

Submarine Sediments
Ranges of Grain-Sizes

Figure 5.7 a

Offshore Samples: Median vs Phi Quartile Deviation

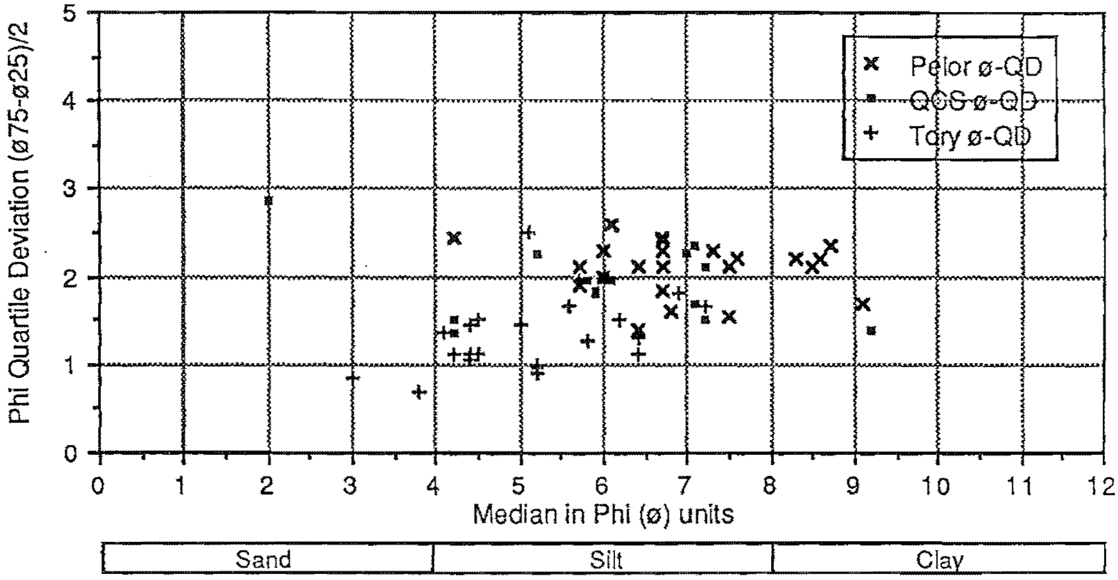
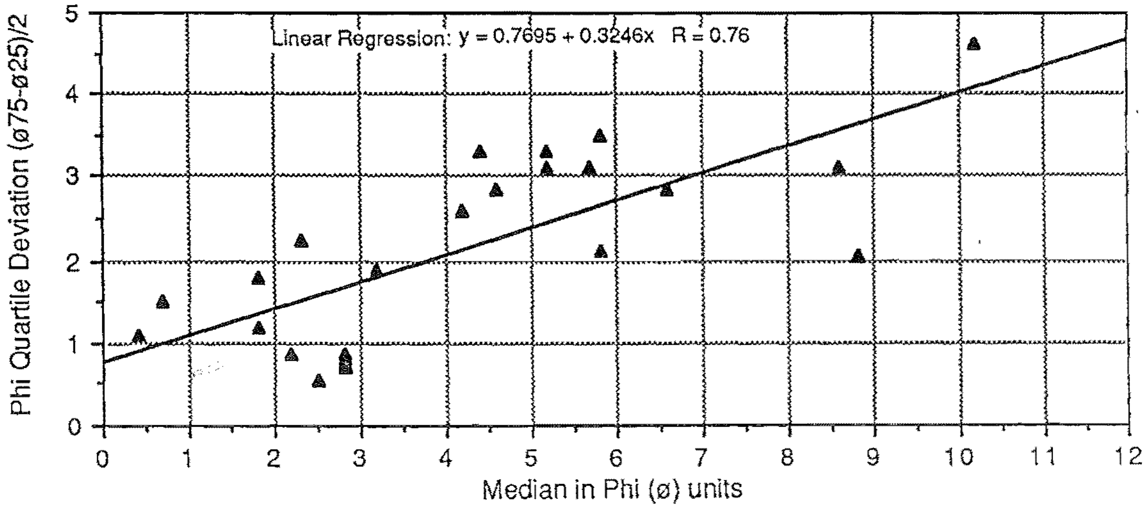


Figure 5.7 b

Nearshore Samples: Median vs Phi Quartile Deviation



Median grain-size plotted against sorting index for offshore and nearshore samples. Predominantly silt-sized offshore samples show no trend in sorting varying with median size. Sorting decreases with fining in nearshore samples.

The relative uniformity in sorting found in offshore samples over the median size range from 4 to 9ø suggests that fractionation of the sediment body is a less useful index of this environment. This is discussed in Chapter 9. This can in part be traced to a relative insensitivity of grain-size to hydraulic processes in this range.

Finer grain-sizes, falling in the silt (4.0ø to 8.0ø) or clay (>8.0ø) range were shown by Hjulstrom (1935, p299) to have quite different resistances to erosion. In these cohesive materials, not only friction between grains but also electro-chemical cohesion and the effects of surface forces cause them to resist erosion. The contrast between the erosional and the depositional behaviour of fine materials was a key finding of Hjulström's investigation. Sundborg (1956,p169) noted that:

> "although there is some connection between grain size and erosibility even for cohesive [material], it seems appropriate to make use of some other property than grain size to characterise the erodibility of such [materials]".

Nearshore samples contain sediments with a mean grain-size of 0ø to 4ø, as well as finer sediments. In these intermediate grain-sizes, Sundborg (1956, p168) noted that both frictional and cohesive forces may be of significance: "sometimes the frictional forces predominate, sometimes the cohesive, depending on porosity, water content, the mineralogical composition etc". He suggests that the prime cause of differential behaviours between sites including cohesive sediments lies in the porosity of the total sediment.

Sand Fraction in Submarine Samples

The sand content in submarine samples has been referred to above. In nearshore samples, the content ranged from 7% to 97%, while in offshore samples the range was from 1% to 72%. The sand content in each sample is plotted against the depth of water at the sampling site in Figure 5.8. It can be seen that sand contents were highest in shallower water (<10m) where nearshore sampling took place. In the samples, sand content shows no clear correlation with depth.

The sand fraction was analysed separately from the mud fraction, and the mean size and sorting values from this analysis are shown in Figure 5.9. As well as nearshore and offshore samples, also plotted are a suite of sandy samples taken from just below MLWS. Overall, the samples were moderately well to very well sorted. The very well sorted samples are found in the range of 2ø to 3ø. These sorting values are unrealistic of environmental sorting, because they have been subject to truncation in the fine limb. While nearshore samples are coarser than the others, the most significant overall pattern is that in the submarine domains are found the finer sand fractions which are largely absent from the shore.

Organic and Shell Content of Submarine Samples

Grain-size analyses in this investigation are based only on the inorganic fraction. An estimate of organic content was made on parallel sub-samples by weight loss after combustion at 475°C for 6 hours. Shell content in the coarse fraction (<4ø) was measured by weight change after HCl treatment.

Mean organic and shell contents are reported for offshore and nearshore samples in Table 5.6. Mean organic content in offshore samples was 5.3%, and in nearshore samples 4.1%. Pelorus Sound samples had the highest mean content of 6.4%; Tory Channel the lowest at 2.9%. Queen Charlotte offshore along with nearshore samples had the largest coefficient of variation at 0.49; Tory Channel the least variation at CV=0.31.

Mean shell content in the coarse fraction of offshore samples was 22% - a little higher in Queen Charlotte at nearly 25% and lower (20%) in Tory and Pelorus. Nearshore shell content was yet lower (mean 10.7%) but had a higher coefficient of variation (standard deviation/mean, at 0.92 as against 0.77 for offshore samples).

No correlation was found in these parameters with depth of water.

Variation of Organic Content with Grain Size

Figure 5.10a shows the variation of organic content in both offshore and nearshore samples with median grain-size.

The highest organic contents in offshore samples were found in samples with a median grain-size near 7ø. While a higher level of organics is associated with Pelorus Sound, Figure 5.10a shows that the highest organic contents were found in samples from Four Fathom Bay (O1, O2 are bayhead samples in Pelorus Sound) and the Grove Arm of Queen Charlotte (50, 90 and 110 lie along the axis of the Grove Arm, inner Queen Charlotte). This suggests that organic content relates more to the type of depositional site, rather than the Sound from which the sample was recovered.

Figures 5.8 and 5.9

Sand Content of Submarine Samples: Grain Sizes and Variation with Depth

---

Figure 5.8 Offshore and Nearshore Samples: Sand Content by Depth

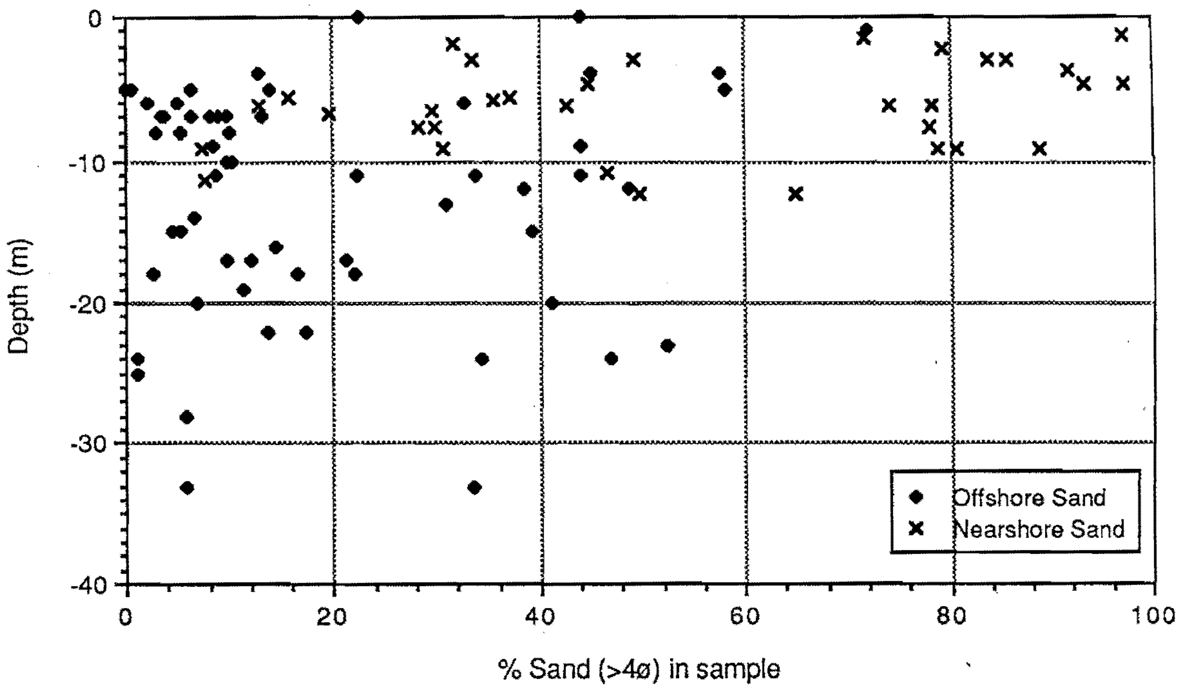
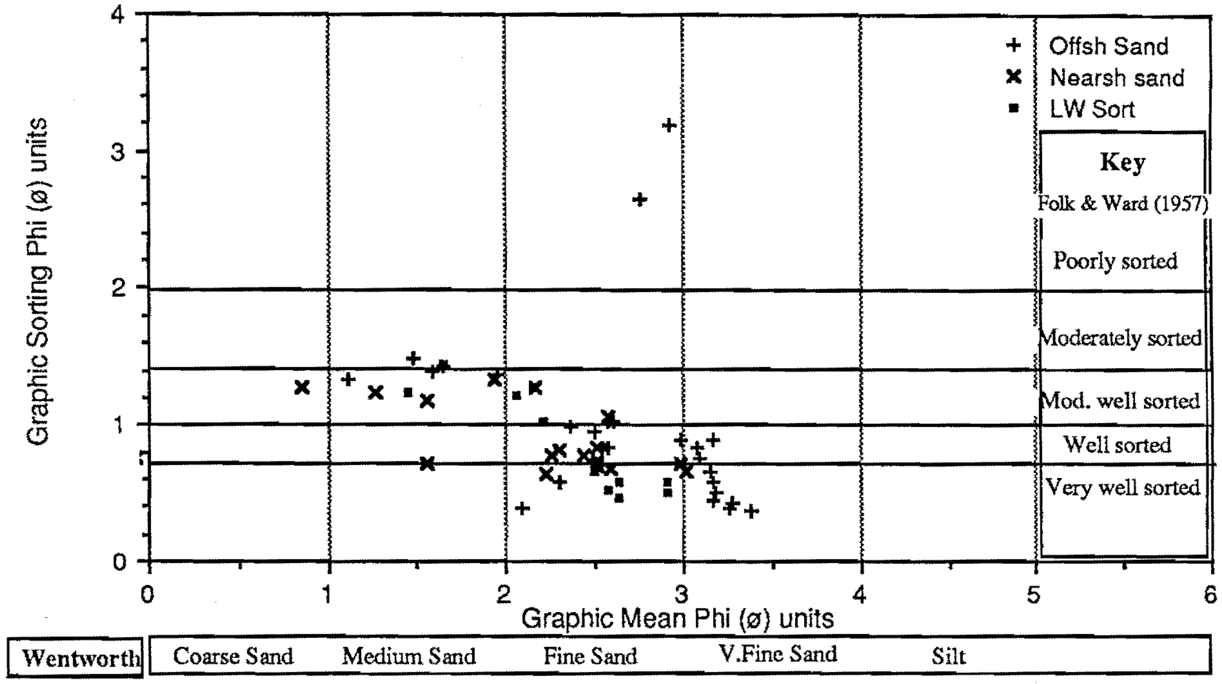


Figure 5.9 Sand Fraction : Phi Mean and Sorting



Top: Sand content (%) in submarine samples plotted against depth of sampling. Sandiest samples are in shallow nearshore. Offshore sand content does not vary systemmatically with depth.

Bottom: Sand fraction (<4ø) analysed separately from the mud fraction gives values predominantly in the fine sand classes.

Figure 5.10

Submarine Sediments
Organic Contents

Figure 5.10 a

Organic Content of Nearshore and Offshore Samples

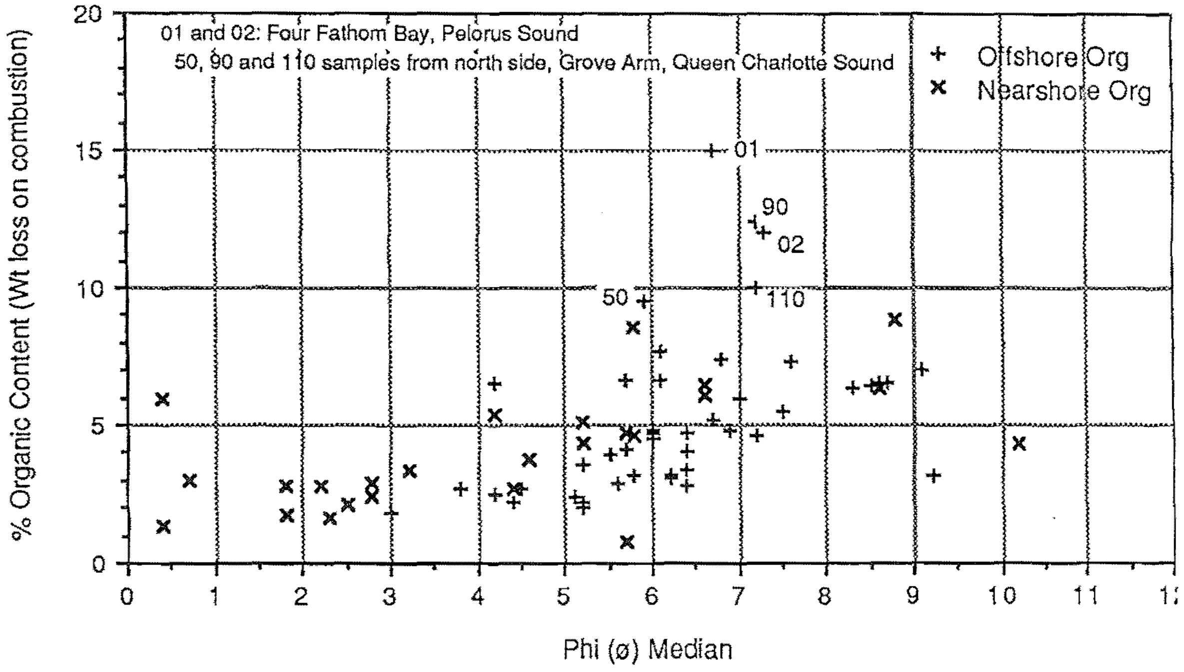
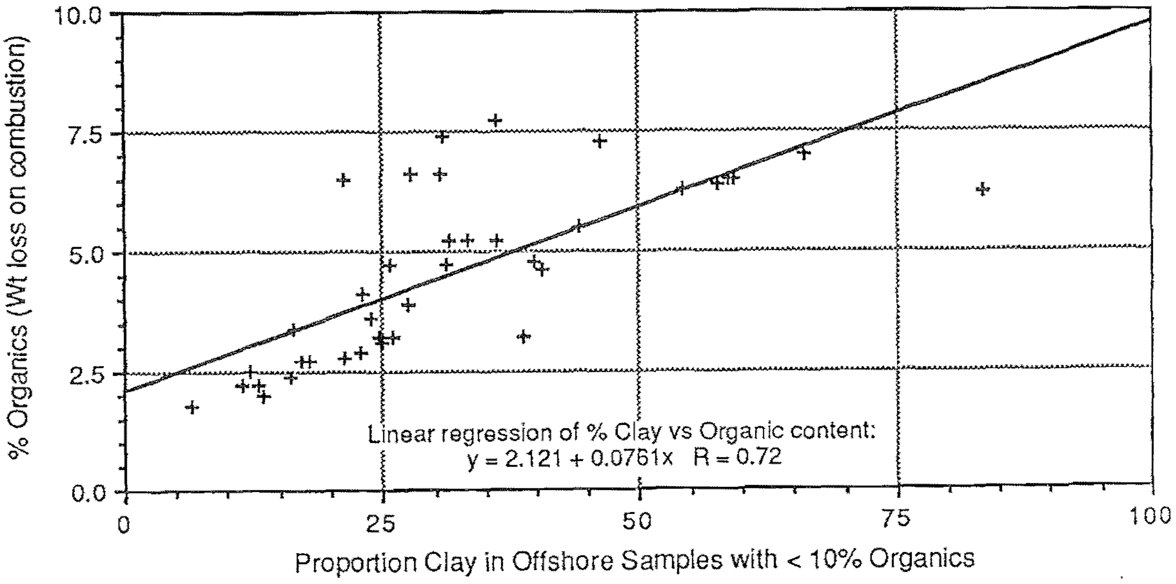


Figure 5.10 b

Offshore Samples: Organic Content vs % Clay



Some variation in organic content with grain-size is apparent in the Figure. This is more apparent in Figure 5.10b, which shows a scatter plot of organic content against clay content. Samples plotted are the offshore samples in Figure 5.9a, with the exclusion of the four samples with organic contents over 10% in order to make the trend in the less strongly organic samples apparent. A linear regression shows an increasing trend of organic content with clay content, with a Pearsons r value of 0.72.

The correlation would suggest that offshore environments prone to retention of clays are also liable to be associated with higher organic contents in their sediments. An element of this relationship is probably attributable to the elimination from the clays of water which had not been removed in the initial drying process.

Origin and Modification of Grain Size Distributions: Discussion

This study is concerned primarily with the fate of sediments derived from catchment sources. Therefore, the issue in the analysis of coastal sediments involves more than the interpretation of the grain-size patterns within given coastal sediment deposits. It extends to the consideration of why certain sediment fractions are redistributed to given coastal sites.

The preceding section has given an overview of the grain-size fractions which were sampled in the coastal environment of the Marlborough Sounds.

Sediment Fractions in the Coastal Domains

In the offshore domain, sediments were found to have mean grain-sizes mainly in the silt size range (4ø to 8ø). Sand content was rarely over 50%, with a mean content of 19%. Clay content ranged up to 60%, with a mean of 28%. There was no overall correlation between the range of particle sizes in a given sample (i.e. the Quartile Deviation) and mean size.

In the nearshore samples, sediments were found to be of more variable size and had a mean sand content of 54%.

The sand fraction in submarine samples, and sandy samples from near low water, was shown to be fine and well sorted.

In shoreline samples, a range of mean sizes from -2ø to 3ø was found. The fine sands were those referred to above. At the other end of the size spectrum was a dominant granule and very coarse sand population which included a group of well sorted samples. These mean sizes correlated with modal sizes in the same range, which is a range of particle size not commonly found in sedimentary studies.

As well as these well sorted samples, there was a population with mean sizes in the coarser sand ranges, which were more poorly sorted. These were samples with a higher medium sand content than the well sorted granules.

In addition to these sampled grain-size populations, the shore is comprised of sediments of much coarser grain-sizes. The relationship between these coarse populations and shoreline accumulations of finer gravel and sand is discussed in the following chapter.

The Interpretation of Grain Size Patterns

Textural analysis, and especially size analysis, has been a central part of "descriptive art" in sedimentology since before 1940 (Winkelmolen, 1982). For this descriptive art, Winkelmolen identifies two purposes. Descriptive terms are required to define the properties of lithofacies and to classify lithostratigraphic units. The second purpose is to "describe sediments in parameters in order to understand genetic differences between sediments, e.g. to relate sediments to their mode of emplacement" (Winkelmolen, 1982, p225). Parameters well suited for the purposes of facies description may well not serve as effectively for the additional purpose of physical interpretation.

A wide variety of methods for the physical interpretation of sediments has been developed. Not all have been greeted by universal acceptance (Ehrlich,1983; Reading, 1987). Dissonance between alternative approaches is a hallmark of the literature (see Middleton,1976; Bridge,1981). Winkelmolen (1982, p225) concluded:

> "it should be admitted that it is easy to identify fields in sedimentology where the input-output ratio is more favourable than in size analysis."

The descriptive value of sediment textural parameters was demonstrated in the previous section. This section considers the manner in which these can be interpreted to identify the sedimentary dynamics of the environment.

Folk(1974) considered the problem of interpretation to stem largely from a shortage of data about grain-size:

> "The significance of mean grain size is not yet well enough known to make any positive statements; volumes of data on recent sediments must be collected before we can say anything really meaningful."
> (Folk, 1974, p3)

The abiding problem in most sedimentary investigations, however, is not the shortage of data, but the difficulty in deciphering the meaning of the available data. The meaning of sedimentary data is found in the fingerprint which the sediment might be expected to contain about the history of processes which have acted upon that sediment, and about the other controls which determine its granular composition and its location.

The proposition put in Chapter 4 was that a primarily empirical approach to the investigation of coastal sedimentary behaviour was inherently inadequate, because the underlying controls which determine observed effects were accessible only by reference to theoretical constructs.

What is needed therefore is a coherent framework within which the patterning of sediments can be interpreted. The construct which is under investigation in this, and subsequent chapters is the Ordered Response Model. The following material is a review of the concepts which underpin the model.

Elements of the Interpretation Problem

Reference was made in Chapter 4 to the conflict in approaches, identified by McLean and Kirk (1969), which appeared to exist between the interpretations given to sediments by Inman (1949) and by Folk and Ward (1957). A brief review of these viewpoints is given here.

Hydraulic Sorting

Inman (1949) observed a physical relationship between sorting, skewness, and median diameters of sediment samples. By reference to the principles of fluid mechanics, he identified three primary controlling factors: the degree of bottom roughness, the settling velocity, and the threshold velocity. Sediment grain-sizes were to be investigated in order to obtain a clue to the conditions under which sediment was transported and deposited.

A central observation of the paper was that

> "the degree of sorting would be a function of the ability of a fluid to sort out one grain from another".
> (Inman, 1949, p61)

As well as the fluid mechanics theory of the problem which was derived mathematically, Inman cited the empirical observation of Hjulström (1936). The distinction which could apparently be made between three modes of sediment transport-suspension, saltation, and traction - was highlighted. This distinction came to be a key to the manner in which sediment grain-size distributions were interpreted.

As an outcome of the relationship between these three primary controlling factors, Inman anticipated that fine sand (2ø to 3ø, or about 0.18mm) would be among the best sorted materials. Grain-size data in this study, and many others, bear this out. In lower shore and low water deposits, fine sands were found to be the predominant sediment. Fine sands are apparently the most easily winnowed from intertidal surfaces by local wave conditions, and are transported by waves on the receding tide to the foot of the shore.

An equally well sorted population of grains was found in the granule-very coarse sand range. These are wave worked, and hydraulically sorted. There are also, however, shoreline sediments which are wave worked but range from moderate to poorly sorted. This poor sorting stems from the abundance of sand in these deposits. It is not the medium sand fraction which develops beach accumulations at high water, but the granules and very coarse sand.

These patterns in the distribution of sediments within shore deposits must reflect the effects of hydraulic sorting to greater or lesser degrees. Various models have been proposed by which hydraulic control of sediments can be recognised.

The adoption of the method of plotting grain-size distribututions as cumulative curves on log-probability paper is described by Bagnold and Barndorf-Nielsen (1980). The plot of a normal Gaussian distribution on such paper will yield a straight line, and the observation of relatively straight lines on sediment size curves was therefore evidence of relatively normal distributions of grain-size.

However, there were systematic departures from straight lines noted on most curves, especially in the limbs. Visher (1969) proposed that these could be interpreted as further lognormal populations. Straight-line segments on such plots were then correlated with the modes of sediment transport discussed by Inman (1949: traction, saltation, suspension), and by authors including Visher (1969), Moss (1972), Middleton (1976) and Bridge (1981). There are differences in the nuances placed on interpretations between different authors, but all accept the general proposition that geometric features of a log-probability plot of cumulative grain-size curves are indicative of hydraulic processes.

The interpretation of straight-line segments as sub-populations is challenged by a range of authors who found on empirical grounds that the assumptions of Gaussian normality were inapplicable. Kennedy, Ehrlich and Kana (1981) failed to find "normal" populations in suspension under waves, challenging an assumption of the supposed "normality" of each independently mobile population in transport.

Bagnold and Barndorf-Nielsen (1980) showed that the log-hyperbolic function may be a distribution which better approximates the pattern of natural grain-size populations- a pattern which would not plot as a straight line on Gaussian probability paper. Similar observations were made by Barndorf-Nielsen (1977) and by Wyrwoll and Smith (1985). Fieller, Gilbertson and Olbricht (1984) made reference to curve-fitting with yet another distribution, the "skew-log Laplace" distribution, for the analysis of the grain-sizes of natural sediments.

Despite variations in interpretations, however, these authors have a similar approach to grain-size analysis. Specifically, it is an approach which seeks out an expected distribution of grain-size, against which a given sample can be compared. The authors of what could be called the hydraulic school, attribute hydraulic properties to these distributions.

Reference was made earlier in this chapter to the observation of Sundborg (1956) that grain-size is a poor index of finer, cohesive sediments, and an inconsistent index of sediments in the intermediate size ranges where samples contain clay, silt and sand. To some extent, the variable sorting which was found in offshore samples, and the lack of correlation to grain-size, can be attributed to this lack of sensitivity of fine grain-sizes to hydraulic sorting.

Inman (1949, p61) recognised a significant distinction between local sorting involving the assortment of particles at a particular locality or site of deposition, and progressive sorting consisting of an assortment in the direction of transportation. The spatial scale over which hydraulic sorting is expected to occur is one of the more debated aspects of sedimentary interpretation. The difference between the views of Inman and his hydraulic interpretation and Folk(1974) and others lies in the extent to which progressive hydraulic sorting is accepted as a significant control on the grain-size distribution.

Source Area Effects

Folk (1974) rejected the mechanism of progressive sorting as a significant means by which grain-size distributions are altered:

> "Many studies of individual environments show sediments getting finer away from the source but these changes are so varied that they can be deciphered only by extensive field and laboratory work... Grain size depends largely on current strength of the local environment (together with size of available particles), not on distance"
> (Folk, 1974, p3).

The interpretation of grain-size modification given by Folk and Ward (1957, p9), in a situation where there was a bimodal population of sand and gravel, was :

> "The stream only affects the relative proportions of the two modes, not their sorting or grain size... if sediments get finer downstream, it is chiefly because the amount of gravel becomes less, rather than that its size is changing."
> (Folk and Ward, 1957, p11).

The interpretations obtained by this reasoning reflect in part the assumptions relating to the "natural abundance" of certain modes (notably gravel, fine sand, silt) referred to in the last section.

While the granule-very coarse sand population found to predominate in the sampled Marlborough shore deposits was not one of the three "naturally abundant" modes identified by Folk and Ward(1957), Folk(1974) acknowledged that there may be circumstances in which lithological factors in the catchment give rise to an abundance of grains in different size ranges. It is reasonable to interpret some component of the dominance of these modal beach grain-sizes to catchment lithological factors - particularly in the parts of the schist terrane where quartz veins are a dominant element of the lithology.

The apparent deficiencies in certain size grades was refuted by Shea (1974). However, that author also challenged the hydraulic interpretation of "straight-line" (log-normal) components. He showed that straight-line components could be identified in 11,212 grain size analyses, but that the pattern was found also in a composite curve based on the grain-size curves of samples drawn from a wide range of hydraulic environments. On this basis, Shea found it unacceptable to interpret the individual curves as reflecting primarily hydraulic control, but attributed the breaks in slope of the cumulative curve to attrition and the nature of the parent materials (i.e. to source area effects).

One of the most debated aspects of grain-size interpretation, therefore, relates to what determines the shape of the grain-size curve. From an hydraulic interpretation, the log-normal curves are recognised as the expected distribution. From a source area viewpoint, such a control cannot be accepted as primary.

The question of what determines source area effects was discussed from the source area viewpoint by Ibbeken (1983). He argued the merits of interpreting initial source area populations derived from rock breakage in terms of a Rosin distribution, one used in the coal industry. He interpreted progressive modification in a river channel as reflecting a transition from a Rosin towards a Gaussian distribution. In some respects, this approach bears an analogy to the hydraulic approach of Visher (1969) and others, in seeking for a "natural distribution" against which samples are to be compared. However, the expected distribution is initially determined by non-hydraulic factors.

Resolving Conflicts of Interpretation

From similar data, different investigators have demonstrated an ability to derive quite different conclusions. Rather than seeing these approaches as contradictory, however, McLean and Kirk (1969) identified a manner in which a coherence could be recognised between them. The apparently different approaches were seen by these authors to stem from views taken of the problem of sediment interpretation at two different levels. These were distinguished, in the model presented in Figure 4.2, as different orders of control.

In a study of grain-size variations on mixed sand and gravel beaches, McLean and Kirk found it useful to distinguish the control of both source area materials, and hydraulic modification. Because the source area effects determine the initial particle availablility, it was logical to regard the source area control as acting at a higher order of control. In sediments reported in the previous section it is also possible to recognise aspects of grain-size attributable to source area contributions as well as components attributable to hydraulic modification. If the view is taken that there are two controls which operate at different orders, then the operational question to consider would appear to be the appropriate scale at which these controls are expressed.

Schumm and Lichty (1965) also explored concepts of hierarchic relationships and their influence on the interpretation of causality.

> "the distinctions between cause and effects in the moulding of landforms depend on the span of time involved and on the size of the geomorphic system under consideration. Indeed, as the dimensions of time and space change, cause-effect relationships may be obscured or even reversed, and the system itself may be described differently."

Schumm and Lichty (1965, p112) continued later, with regard to resolving conflicts between competing views of control on landform change:

> "To resolve the controversy resulting from ... two viewpoints it may be necessary to think only in terms of large and small areas or short and long spans of time. A choice must be made whether only components of a landscape are to be considered or whether the system is to be considered as a whole."

To obtain a coherence between alternative interpretations of pattern is desirable in science, not only because it helps to resolve apparent contradiction, but also because it leads towards the development of more general models.

These observations are pertinent to the present investigation, because of the scale at which the coastal system is to be regarded.

Sedimentary Fractionation Viewed as Ordered Response

When sediment dynamics are considered at the scale of the system as a whole there are analytical demands distinct from those most pertinent to an investigation confined to the consideration of sediment character at one site, or to its modification along an axis of transport.

Sediment Fractionation in the Trapping Environment

The first demand in the Marlborough Sounds coastal setting stems from the essentially closed nature of the system. In an enclosed or *trapping* coastal environment, all sediments which are delivered to the coast must be redistributed somewhere. Consequently, the problem of understanding coastal sedimentation in such an environment lies in recognising where specific fractions are retained, and what controls their redistribution. Seen in this light, the individual grain-size distributions in a trapping environment might be expected to bear a certain complementarity to one another.

Complementarity and the Deposit-Repository Concept

A distinctive approach to sedimentary fractionation was proposed by Kuenen (1964). In the concept of "deposit-repository", Kuenen focussed not on individual sediment samples in isolation, but on the differentiation between them. Winkelmolen (1971) quoted Kuenen:

> "A deposit of sorted material requires that the matter which has been left out has accumulated elsewhere, or that the matter which has become relatively concentrated is more diluted elsewhere. This twin accumulation with opposite characteristics constitutes the repository".
> "A repository can lie either up-current or down-current, below, above or beside the deposit under consideration."

An outcome of viewing a range of coastal sites or of samples within sites in this light, is to recognise a complementarity between samples, such that no sample can be analysed in isolation, if the intention is to obtain a process interpretation.

Developing the deposit-repository concept to its application to sediment sorting, Winkelmolen(1971, p707) writes:

> "Each sorting process during transport and deposition involves the splitting of the original source material into two populations with different and complementary characteristics. One or both may be situated in a new environment or one may have remained behind in the original site."

The deposit-repository concept resolves the problem of *signal recognition* identified above, with regard to the distinction between populations in transport, versus those not eroded (lag) or those just deposited. In view of the fact that in the environment as a whole one is liable to sample any one of these three groupings of populations, it is not surprising that some populations are not "log normal", as the complement of a log-normal population need not be so itself.

There are a number of challenges in the operationalisation of the deposit-repository concept. One stems from the measure of size. Winkelmolen (1971, p707) noted that the distinctions between deposits may be found in size distributions, density or shape. The problem with size, he notes, is that:

> "the two new populations, which may be regarded as a deposit and its repository, usually have a certain size range in common. Their character as twin deposits may not be very evident therefore."

Winkelmolen procedes to identify a measure of shape which is shown to be less ambiguous a means to evaluate what is referred to here as fractionation. The technique advocated by Winkelmolen (1971, 1980) of rollability has not however yet been extended to include the full range of clastic particles which are encountered in the coastal environment in this study. The pragmatic position adopted here, therefore, is to accept the limitations of size as an inherently ambiguous measure of sedimentary fractionation, and to procede with an analysis of coastal sediments from a conceptual base of deposit-repository.

Broader-scale analysis and sediment distributions

At the broader scale of investigation, it would not seem useful to begin the description of the coastal sediment problem from a theoretical presupposition of an expected distribution of either the sediment grain-sizes supplied or the distribution towards which they are tending.

Chapter 3 showed that the sediments delivered to the coast from catchments are mixtures of grain sizes, and in some cases these mixtures could be expected to be comprised of a wide range of sizes. There are no established grounds on which to presume that over a specified period of time the catchment will deliver a log-normally distributed sediment population. Depending on the timespan, on catchment conditions, and on driving forces, the supply of materials might be expected to be skewed fine or coarse.

Furthermore, the Marlborough Sounds are characterised by low levels of shoreline energy, and generally low velocities of tidal currents in the marginal embayments. Consequently, the hydraulic energies available to redistribute material are typically low. Although sediments may tend towards developing a texture which is hydraulically determined, it might be assumed that such a pattern will be developed at only specific types of coastal sites.

On this basis, the conclusion is reached that the most useful stance from which to investigate sediments at the broader scale within the coastal system is to begin with the recognition of various traps which exist within the system.

The Ordered Response Model as a Framework for the Trapping Environment

Within the construct of the Ordered Response Model, a framework is proposed in which hydraulic factors, source area factors, and the trapping form of a coastal landscape can be considered in a coherent manner. These relationships are now discussed with reference to the three domains in Figure 5.11 labelled H (hydraulics), S.A. (source area), and M.T. (trapping morphology).

Hydraulic Effects

The hydraulic modification of sediment takes place as a response of mobile sediments to hydraulic forcing (H). Where the coastal system is under hydraulic control, then all the material within a given domain will be capable of being moved by the available environmental velocities. Finer material will tend to be rejected. Coarser material may be buried or left behind as a lag. This is the essence of the concept of hydraulic sorting.

However, in a trapping environment, such sorting may not take place. There may develop what can be visualised as a feedback relationship, such that the hydraulic sorting which would take place given the available hydraulic energy, cannot take place because of the topographic relations of the materials in motion to their boundary conditions. Norrman (1964) made the following observations, which hightlight this relationship:

> "In the nearshore zone, affected by waves, suspended material is whirled up, but is not necessarily transported out of the environment, but may settle when the wave motion ceases. As in fluvial conditions, the finest material can be expected to be sorted out in the updrift area of longshore drift and be transported to the downdrift area, but there the energy level may be as high or higher than in the updrift area. Then we have the possible combination of large amounts of rather fine material and high-energy conditions" (p116)

In a range of coastal settings, there are sites at which high energy and fine materials are found in combination - in tidal mudflats, for example (Pethick, 1984). One of the most distinctive features of the shore in the Marlborough Sounds, is the juxtaposition within some shores of fine and coarse deposits.

This behaviour is referred to as mobility trapping, and is conceptualised in the Ordered Response Model as a recirculatory control and response occurring at the lowest order, by way of the feedback loop F1.

Source Area Effects

Source areas effects are seen to act within the ordered response framework in the central column of the model, in what was identified in Figure 4.5 as the "sediment transform". Source area effects determine the available sediments, but as labelled as S.A. in Figure 5.11, there are not one but three ways in which source area effects can be determined.

At the lowest order, the source area effect is determined by mobility trapping (S.A.3), acting in the manner specified by Norrman, above.

At the highest order, there are source area effects determined by the local lithological factors, labeled as S.A.1. This is the source area contribution as identified by Folk (1974), and is the conventional way in which source area effects are regarded.

At the middle order, S.A.2, it can be seen that a third determinant of source area factors is what has been described as the morphologic trap, and is the expression of trapping which defines the range of particles made available within the domain labeled M.T. The morphologic trap stems from the enclosed form of the coastal site to which material is delivered.

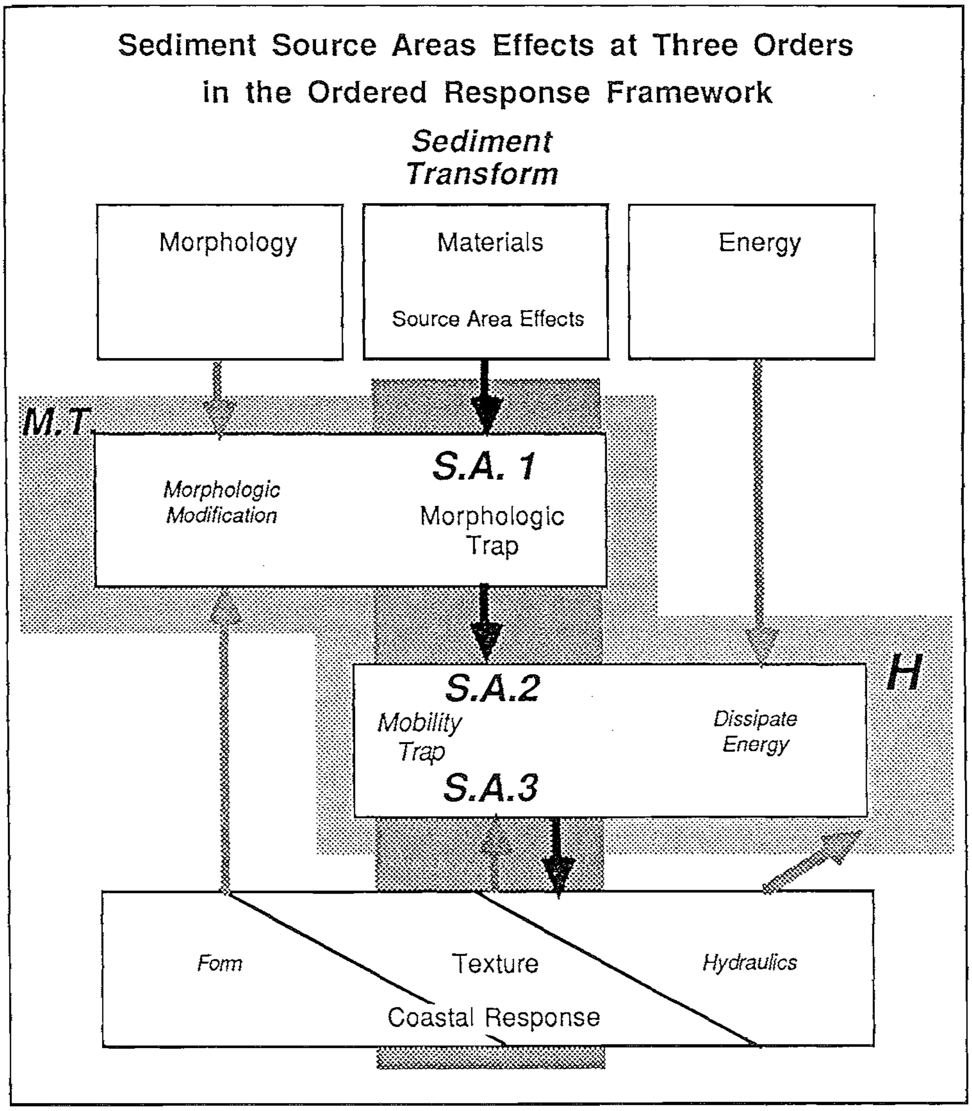
Feedback Loops and Trapping Behaviour

It would seem that the most elegant way in which trapping can be schematised is as a feedback loop within a conceptual model. The retention of material at a given site modifies site character and this modification is reflected in the cycle of coastal change by an upward transfer in the model. Control is exercised in the downward direction, and response in the upward direction. Trapping is recognised in terms of the cycling of control with a feedback loop; and the physical expression of this conceptual trapping can be seen in the retention of sedimentary materials within a bounded domain.

The prime distinction between the two feedback loops in the Ordered Response Model lies in the subsequent behaviour of the material involved. If the

Figure 5.11

Identifying Controls on Source Area Effects in the Ordered Response Framework



Sediment sampled at a site reflect their retention at that site. Trapping is identified in two control domains: one morphologic (M.T) and the other hydraulic (H).

Viewing the coastal function as a sediment transform reveals source area effects to be determined in three ways-

SA 1 or catchment lithology factors,

SA 2, the material trapped at a given site by an enclosed morphology, and

SA 3, material trapped by interactions between sediment and hydraulics.

material which has been retained remains mobile in the site of trapping, then the behaviour is characterised as mobility trapping. If the material becomes static, then the modification of the site is to its morphologic form, hence the behaviour is characterised as morphologic trapping. Morphologic trapping involves a modification to the boundary conditions within which sediment mobility occurs; hence it warrants placement at a higher order than the mobility trap.

These observations of feedback behaviour lead to one of the most interesting outcomes of looking at the coastal system from the viewpoint of ordered response. This is that while an hydraulic equilibrium established between sediments and hydraulic energies in the coastal domain is one possible end-point in the functioning of a coastal system, it need not be the only end-point. Rather, equilibrium conditions are an outcome of the balancing of controls and responses within the coastal system.

An hydraulic equilibrium might be one of the characteristic behaviours of the mobility trap, stemming from the dominance of hydraulic factors. This could be visualised as a coastal response located (conceptually) on the right-hand side of the spectrum of coastal responses, which exist at the lowest level of the model.

Conversely, there may be types of mobility trapping which reflect a domination by materials (or source areas effects). Such a coastal behaviour would lie more centrally in the range of coastal responses, and could be described as a sediment dominated response. The ability to recognise a range of coastal behaviours in this manner was described in Chapter 4 as being an outcome of "transitional control". At this point, the existence of such behaviour is recognised deductively: its expression is a matter for investigation in subsequent chapters.

Extending this consideration of feedback behaviour to the morphologic trapping region of the model, it can be seen that characteristic form in a landscape, referred to in Chapter 4, is an equivalent expression of stable feedback behaviour. In terms of coastal sedimentary dynamics, the more significant relationship is that between the morphologic trap and the mobility trap. Given that it is the morphologic trap that determines at a first order the source area factors in sediments, it is concluded that an investigation of sediment textures must make reference to coastal morphology, as well as to the hydraulic redistribution of the supplied material.

In summary, the most important outcome of the perspective taken on coastal behaviour through the Ordered Response Model is the interpretation of sediment dynamics in terms of trapping behaviours.

Because the first of these trapping behaviours is identified as morphologic, the first step in further investigation is to identify the expression of morphologic traps in the coastal system. The second step is to identify the expressions of mobility trapping. These two steps are respectively the focus of Chapters 6 and 7, for the shoreline domain, and Chapters 8 and 9, for the submarine domains.

These chapters are intended to explore not only the empirical features of these domains, but also the extent to which they can be seen to express the functional relationships proposed in the Ordered Response Model.

Two aspects in particular are the focus. The first is the scale at which trapping behaviour can be recognised. The second is the extent to which sites are seen to be dominated by morphologic or mobility trapping. The practical relevance of the former is that, in identifying the scale at which the coastal system functions, it becomes possible to recognise the spatial extent over which materials derived from catchments are liable to be dispersed. The practical relevance of the latter is in terms of assessing the sensitivity of a site to change, and of identifying the factors which will determine the extent to which, and the relaxation time over which, a site will return to an equilibrium after modification.

Chapter 6

Shoreline Form and Function

The focus of this chapter and the one which follows is on the function of the shoreline domain within the framework of landscape development and functioning. From the perspective of the catchment-coast relationship which is under investigation, the role of the shoreline is that of a filter or trap for certain sedimentary fractions. This chapter considers the controls which act to determine shoreline sediment trapping and by-passing, while Chapter 7 examines the implications of these controls for sediment fractionation.

Two features are distinctive of shores in the Marlborough Sounds. The first is their intricate and varied form and surface texture. Within small longshore distances, the shore form can vary from cliff, to a ramp cut out of backshore colluvium, to a shore underlain by materials of alluvial origin. The second feature is the mixed grain-size composition of shoreline deposits. These include mixed sand and gravel beaches, sandy surfaces and mud flats of widely varying extent.

Reference was made in Chapter 2 to shoreline classifications of the Marlborough Sounds shore developed by Boyce (1971) and Newton (1977). Four major longshore classes were identified: hard-rock shores, pocket beaches, linear deposits and bayhead or delta beaches. The definition of each was given in Chapter 2. These classifications had a practical utility within the context of each study.

Classification is valid only to the extent that it leads to a recognition of those factors which control coastal form and texture, and therefore gives an insight into the shore's functional character. This chapter begins by identifying elements of form on shorelines of the inner Marlborough Sounds. This leads to an analysis of the controls which act to determine form and function on these shores.

The first section is a description of the range of shore forms. In the second section, three independent controls on shoreline character are discussed: morphology, sediments and hydraulics. The third section shows the manner in which interaction between these controls determines shoreline behaviour. A consideration of the ordered response framework in the shoreline domain leads to the development of a framework which focusses on sediment mobility. The utility of the framework lies in defining five sediment behaviours to which materials delivered to the shore may be subjected.

Shoreline Description

Sources

The investigation of shoreline form entailed the survey of 169 shoreline sites in the inner Queen Charlotte, Kenepuru and Pelorus Sounds.

Surveys were conducted with a Hilger Watts Quickset Level, tripod and staff; and with a Wild TO compass-card theodolite. This was supplemented by over 200 individual measurements of shoreline slope at a wide range of locations, taken with a modified Abney Level mounted on an aluminium plate with dimensions 200 by 150mm.

Over the period January 1982 to February 1986, every bay in Queen Charlotte Sound as far east as Snake Point, in Tory Channel, in Kenepuru Sound, and in Pelorus Sound as far north as Tawhitinui Island, was visited by boat. Every beach in the Queen Charlotte Sound from Okiwa to Torea Bay, in Mahau Sound, and Kenepuru Sound was inspected on foot, as well as most sites in Tory Channel, Tennyson Inlet and bayhead locations in Pelorus Sound. Field notes were taken of all sites.

This was supplemented by reference to oblique and aerial photographs identified in Appendix 1. The prime source of topographic evidence on hillslope morphology is the NZMS 260 sheets identified in Chapter 2, at a scale of 1:50,000; and the 1:25,000 base-maps on which the topographic sheets are based.

Criteria for Initial Description

Two key factors which influence shoreline form in the Marlborough Sounds are low wave energy and tidal range. On a high energy beach wave processes are a dominant shoreline control. The effect of a lower level of energy is to permit the expression of other controlling factors. One of the most important of these is the initial morphology of the site against which the shore is emplaced.

An initial distinction can be drawn between shores which are backed by steep (gradient >1:2.5), intermediate (1:5 to 1:2.5) and shallow (<1:5) hillslopes. Steep slopes are found along the sides of most bays and outside their mouths, while shallow slopes are generally restricted to bayhead locations. The effect of a broad intertidal surface is that material eroded from the backshore or abraded from the intertidal surface is largely retained within the shore zone.

A second distinction can be drawn between shorelines sites which have deep water (>10m) near shore, and those where waters within 150m of the shore are shallow. Because the origins of coastal form can be traced to the antecedent river systems there is a general trend from shallow drowned to deep drowned sites from the inner to the outer Sounds, and from inner bay to outer bay locations. In shallow drowned locations there can be onshore transfers of sediment, principally muds, from offshore. Onshore transfer of coarser material (sands, gravel) from the nearshore onto the shore by waves is uncharacteristic of sites other than the most shallow on a low energy shore due to the limited wave base of short wavelength waves, discussed in more detail below.

The effect of tides on a low energy shore is to displace a narrow zone of wave working across the shore. In Table 6.1 tidal parameters are given for a range of locations in the Marlborough Sounds. Tides are semi-diurnal. The key distinction is between sites in the Queen Charlotte Sound, with a micro-tidal spring tidal range of 1.5m, and sites in the Pelorus Sound. The Pelorus is part of a different tidal system, and has a spring tidal range of 2.4m. This falls in the meso-tidal (2-4m) class.

In Table 6.2, the implications of this displacement are shown in terms of the width of the intertidal surface for each tidal range. Five shoreline gradient classes are given. The steepest shores have gradients from vertical to 1:6. In Queen Charlotte Sound this translates to an intertidal surface narrower than 10m wide, and in Pelorus Sound to a surface less than 16.5m. The most gentle shoreline gradients found in the inner Sounds are associated with intertidal surfaces of up to 1000m (Mahakipawa Arm, Pelorus Sound).

Shoreline sediments range in size from boulders to clay. Mixed sand and gravel beaches have been shown to present a wide range of particle sizes to reworking by waves, and as a consequence are morphologically distinctive and dynamically complex (Kirk, 1980, p189). The addition of material finer than sand to shore sediments adds even further complexity to beach form and process.

Table 6.1

Tidal Ranges, Marlborough Sounds

Port and Secondary Locations	Mean Spring and Neap Tides (m)					Time Differences	
	M.H. W.S.	M.H. W.N	M.L. W.N.	M.L. W.S.	M.S.L	M.H.W hrs mins	M.L.W hrs mins
Queen Charlotte							
PICTON	1.5	1.0	0.5	0.0	0.7		
Okiwa Bay (Inner Q.C.)	1.5	1.0	0.5	0.0	0.7	-0003	-0006
Long Island (Outer Q.C.)	1.5	1.0	0.4	0.0	0.7	-0012	-0019
Te Iro Bay (Tory Channel)	1.3	0.9	0.4	0.0	0.7	-0019	-0010
NELSON	3.7	2.9	1.1	0.3	2.0		
Pelorus Sound							
Havelock	2.6	2.0	0.9	0.2	1.4	+0006	+0006
Pelorus Sound Entrance	2.5	1.9	0.8	0.2	1.3	-1000	-0120

From N.Z. Nautical Almanac (1982)

Table 6.2

Ranges of Shoreline Gradients

Slope Class	Gradient	Intertidal Width Tidal Range 1.5m Queen Charlotte	 Tidal Range 2.4m Pelorus Sound
Morphologic Frame			
Rock (cliff) or rubble shore	>1:6.5	<10m	<16.5m
Shoreline ramps	1:20 - 1:65	10 -30m	16.5 - 50m
Bayhead shores	1:100 - 1:20	30 - 150m	50 - 250m
Middle order bayheads	1:200 to 1:100	150 - 300m	250 - 500m
e.g. Whatamango Bay, Queen Charlotte Sound			
Kaiuma Bay, Nydia Bay, Clova Bay Pelorus Sound			
Tidal "flats"	<1:200	>300m	>500m
e.g. Okiwa Bay, Mahakipawa Arm, Kenepuru Head			
Shoreline Accumulations		*Slope limits in degrees (observed)*	
Pocket beach	1:20 - 1:3.3	3° - 17°	
Intertidal sand-gravel	0 - 1:6.6	only locally over 8°	
Intertidal fine sand	0 - 1: 0.66	up to 1°	
Intertidal mud deposit	0 - 1:125	less than 0.5°	

Compiled from field measurements, and topographic sheets

Shoreline Morphological Zones

Figure 6.1 shows a number of morphological zones which are found on the low energy tidal shore with a mixed composition of mud, sand and gravel. Principal distinctions are between high water, intertidal, and low water zones. A number of morphologies characterise each zone.

Morphologies can be either *abrasional* or *accumulational* (Zenkovich, 1967). High water abrasional morphologies include cliffs and rubble abutting a high water scarp. Accumulational forms are referred to as beaches. The term beach is restricted to wave worked accumulations of gravel or sand. A *high water beach* as the term implies is limited in extent to the upper portion of the profile. Where the beach deposit extends to low water, the shore type is referred to as a *pocket beach.* Gradients of pocket beaches are shown in Table 6.2. Where the beach crest stands clear from the backshore scarp, the crest region is referred to as a berm.

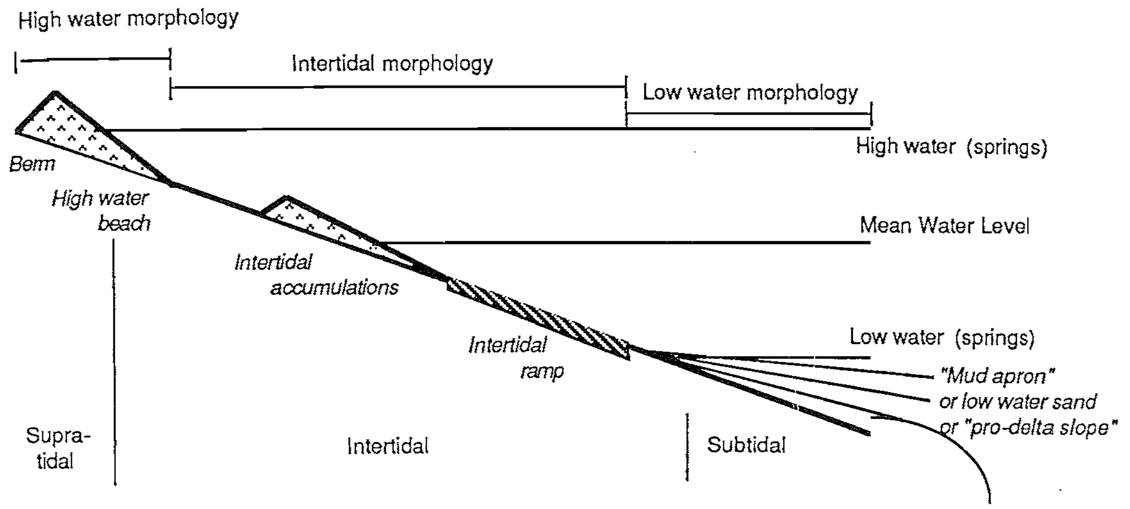
Intertidal morphologies can also be abrasional or accumulational. Abrasional intertidal surfaces include what are referred to here as rubble shores and ramp shores. *Rubble shores* are those which are comprised of material of boulder or cobble size, and may include finer materials. Rubble shores have uneven profiles related to the backshore supply of coarse material and are compartmentalised between rocky outcrops. These are distinguished from *ramp shores* which have a more even gradient from high to low water. Ramps tend to develop along longer stretches of shore and in cases where their extent exceeds 100m are referred to as *linear ramps.* Gradient ranges for each class are given in Table 6.2.

Reference has been made to the pocket beach where a continuous accumulation extends at an even gradient across the intertidal surface. More limited accumulations of mixed sand and gravel occur on the intertidal surface of many intermediate to shallow gradient shores, the distribution and dynamics of which are discussed later. Foreslope gradients (i.e. on the seaward side) of these accumulations are specified in Table 6.2 as ranging up to 1:6. These deposits are generally the more poorly sorted of the mixed sand and gravel shoreline sediments described in Chapter 5. Locally, where they are better sorted, gradients closer to those of the steeper beach accumulations can be achieved (1:5-1:3).

Other intertidal accumulations are referred to as intertidal sand deposits. These lie at gradients less than 1:66.6 (1°), and are the well sorted fine sand

Figure 6.1

Morphological Shoreline Zones: Nomenclature of Marlborough Sounds Shores



Morphological Zones on the Low Energy, Tidal Shore

High, mid and low water zones show variations in morphology and sediments.
High water forms include cliffs, scarps and rubble shores, and beaches.Beaches are often confined in extent to the upper shore.
Intertidal forms include paved gravel ramps, and diffuse gravel sheets which may be wave-reworked into intertidal accumulations.
Extent and form of intertidal surface depends on local coastal gradient.
Low water forms depend on nearshore gradient, and range from steep prodelta slopes to surfaces of gently sloping fine sand, to a mud apron in shallow settings.

population identified in Chapter 5. These sandy surfaces are found predominantly near the foot of beach deposits, or near low water.

Mud accumulations are found almost exclusively in areas at a gradient less than 1:125 (0.5°). Such locations are found only on the most gentle intertidal surfaces, in intertidal depressions, and at low water.

Low water morphologies depend on the nearshore slope below low water level. In deep water locations with a steep nearshore slope (gradients >0.1) the low water zone is generally gravelly, with a convex morphology identified in Figure 6.1. Where the gradient is more gentle, a sand deposit is found. In the most shallow drowned locations, a low water *apron* of mud drapes the lower shore areas.

Examples of Shoreline Morphologies

A range of examples is shown in Plates 6.1 to 6.3. Figures 6.2 to 6.4 accompany these plates. These are grouped by the initial criteria identified above.

Bayhead Locations and Shallow Drowned Shores

Photographs of shores found in the shallow drowned inner Sounds, and on shores with broad intertidal extent, are shown in Plate 6.1. The first and second plates show sites in the Mahakipawa Arm, a shallow drowned embayment of the Pelorus Sound; the third plate is of a site in Bythells Bay at the head of a small embayment in Queen Charlotte Sound. The significant element in all three photographs is the extent of the intertidal surface.

The broadest intertidal surfaces are found at the heads of the Sounds. In small bayheads the intertidal surface may be of more limited extent due to a steeper shore gradient. In general, shores with an intertidal surface of 30m or more in the Queen Charlotte Sound and 50m in the Pelorus Sound have a different morphologic character to those with narrower surfaces.

Plate 6.1
Low Gradient and Inner Sounds Locations

Plate 6.1a

Rubble ramp shore and prograding stream delta
at Mahakipawa Arm, Pelorus Sound.

Shoreline forms on a sheltered shallow gradient shore.

See Figure 6.2a: profile of rubble ramp, axis parallel to boat ramp.

Looking east from
NZMS 260 P 27 GR 776 907

Jan 1986

Plate 6.1b

Intertidal surface near stream delta above.

Note gravel surface at low water, and intertidal sand and gravel accumulations which pond water upslope.

Zostera grass outcrops develop on sandy facies.

See Figure 6.2b, axis top right of photograph to bottom left.

NZMS 260 P 27 GR 776 907

Looking northeast

Jan1986

Plate 6.1c

Intertidal surface, Bythells Bay, Queen Charlotte Sound.

Looking west from
NZMS 260 P 27 GR 897 927

Note gravel ramp in foreground, mixed sand and gravel beach at high water.
Sandy accumulations at foot of beach are colonised by *Zostera.*

Taken at low water springs

Oct 1983

Figure 6.2 a

Low energy ramp shore profile on sheltered shore, inner Pelorus Sound
(See Plate 6.1a)
Prominent features are high water scarp, a poorly sorted, steep (1:8) intertidal ramp of gravel, and a low water "apron" of muds resulting from shallow nearshore gradients and nearshore sediment source.

Figure 6.2 b

Gently graded intertidal surface adjacent to stream, inner Pelorus Sound.
(See Plate 6.1b).
Poorly sorted mixed sand and gravel beach at high water, intertidal boulders and cobbles protrude from a muddy- sand and gravel sheet.
Intertidal mixed sand and gravel accumulations have relief of 0.1 to 0.4m.
Ponding upslope of the accumulations results in intertidal mud patches
Zostera grass grows on sandy patches.
Spartina townsendii is an aggressive colonising rush species which is rapidly spreading across intertidal accumulations in the inner Pelorus.
Lower intertidal surfaces may include gravel lag surfaces, periodically mud-draped.

Figure 6.2 c

Shore profile of small bayhead, Queen Charlotte Sound.
(See Plate 6.1c).
High water beach overlies alluvial gravels with fine weathered matrix.
Sandy intertidal accumulations are colonised by *Zostera* grass.
Lower intertidal surface is a lag ramp of alluvial gravels cut from the antecedent fan surface or delivered by the bayhead stream.

Figure 6.2

Shore Profiles: Low Gradient and Inner Sounds Locations

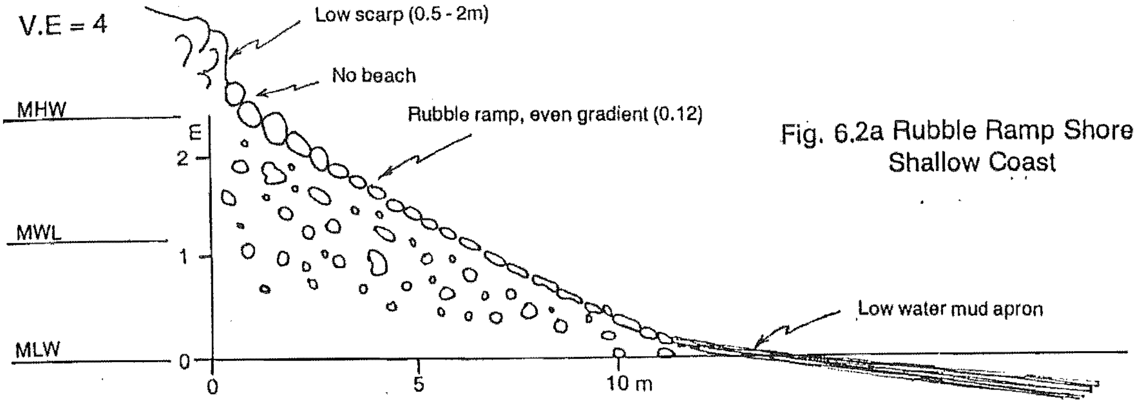


Fig. 6.2a Rubble Ramp Shore, Shallow Coast

ellvue Bay, Mahakipawa Arm. Plate 6.1a)

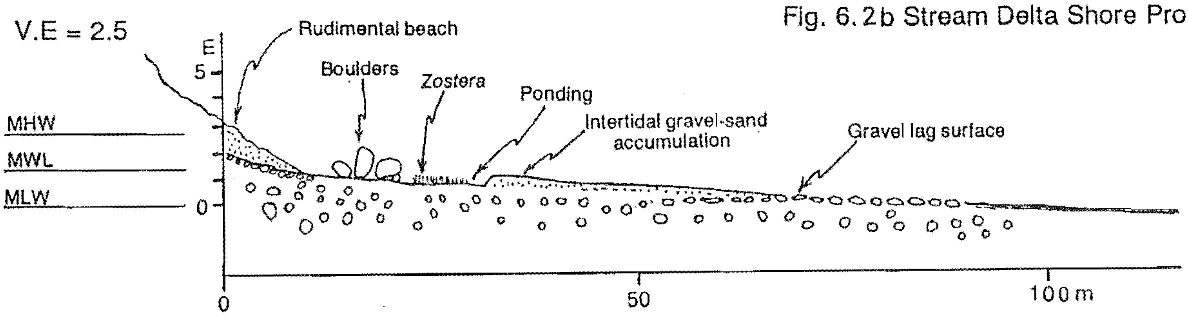


Fig. 6.2b Stream Delta Shore Profile

}ellvue Bay, Mahakipawa Arm. Plate 6.1b)

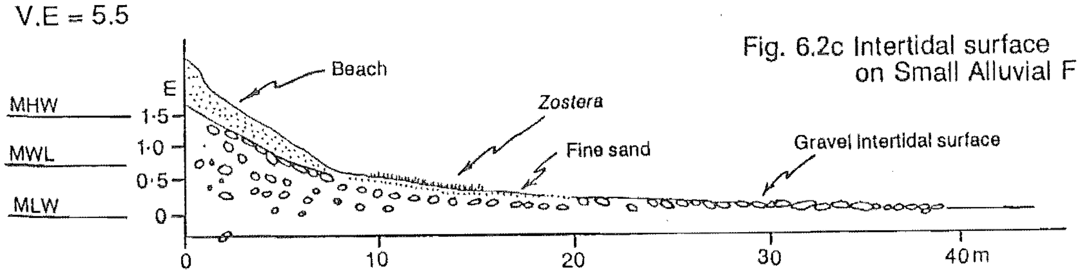


Fig. 6.2c Intertidal surface on Small Alluvial Fan

hells Bay, Grove Arm, Queen Charlotte Sound. Plate 6.1c)

In the Mahakipawa Arm, the intertidal surface is over 1000m in extent between high and low tide levels, and comprises a broad delta of gravels and sand in the upper tidal area, with finer materials in the mid to lower tide areas. Characteristic of shallow drowned sites in the inner Pelorus Sound is a low tide apron of muds draping the lower shore deposits. The same pattern of shallow drowning is found in the Havelock Estuary, along the shores of the Mahau Sound, in some bayheads of Kenepuru Sound, and at the head of the latter. At Okiwa Bay in the Queen Charlotte Sound, the deeper nearshore waters and a lower mud content at low water mean that the intertidal surface of over 700m in width is largely sandy. Mud drapes this sand to a depth of 100 to 300mm in the southern area near the Grove (see Map 4), where a a low gradient underlying surface, a stream source, and sheltering from the easterly fetch occur. Across the central portion of the flat, moderate to well sorted fine sands predominate, coarsening seawards.

On the bay side of shallow drowned areas, a range of shoreline types develop which may be found also on more deeply drowned shores. The most common of these is the ramp shore. Typical gradients are from 1:20 to 1:6.

In Plate 6.1a, wave erosion of a coarse gravelly colluvial backshore has developed a broad intertidal ramp from low to high water. Extensive high water accumulations are rare on such abrasional shores. A profile of this shore is shown in Figure 6.2a. Key elements of the profile are the high, mid, and low tide morphologies. The alignment of platy gravels with the slope of the shore surface is a distinguishing feature of ramp shores. Surficial deposits form a one particle thick paved surface typically underlain by a clast or matrix supported, well weathered colluvium.

In the middle distance of Plate 6.1a the sun is reflecting off surficial water on a muddy-sand and fine gravel stream delta. The darker surface texture is due to Zostera grass growing on sandy deposits. The gradient of this sandy accumulation is 1:66.6. Stream inflows on shallow shores have prominent sandy surfaces. Low intertidal gradients are the main factor in permitting this accumulation to occur. The bottom is within 2 metres of the water surface over the extent of this photograph.

Plate 6.1b shows the intertidal surface near a stream delta in the vicinity of Plate 6.1a. Significant elements of this shore are the gravels at low water and the boulders at mid to high water, reflecting the abrasional origin of the intertidal surface. Superimposed on the abrasional surface are muddy sand and gravel accumulations, with a peak vertical extent of 0.45m, extending from low water over 20m towards high water. This can be seen in Figure 6.2b. Muddy deposits pond upslope of the accumulations. The offshore is a source of intertidal mud on most shores of the inner Pelorus Sound. The initial source of this mud is principally from streams. However, its arrival at the shore in shallow drowned areas is mainly by resuspension from the nearshore by waves with the rising tide. A significant feature of the profile in Figure 6.2b is the gravel lag surface underlying the shore. Like intertidal lag surfaces on most shores, this is one particle deep. The intertidal gravel-sand accumulations overlie this lag ramp and are discussed in detail in Chapter 7. The material underlying the beach deposit comprises deeply weathered clasts and matrix, with a surface rarely more than 0.2m below the beach surface.

On shallow gradient shore sites dominant sources of shoreline sediments derive from streams and the nearshore.

Bayhead shores are found in smaller bays, and typically comprise a number of shoreline morphologies. Plate 6.1c shows the intertidal surface in a small Queen Charlotte bayhead. The gravelly ramp in the foreground has been developed by the erosion of underlying materials. The high tide zone is occupied by a beach 300m long. The beach aligns towards the direction of longest fetch and is bisected by a stream mouth directly above the centre of the Zostera patch. These can be seen on Figure 6.2c. The shallow beach deposit is underlain by a wave-worked surface of alluvial gravels, within 0.3m of the surface. The presence of Zostera is diagnostic of a fine sand deposit. Seaward of the Zostera , muddy sand in a shallow deposit overlies the gravel-rich intertidal surface. Platy schist pebbles with dimensions up to 150mm are aligned parallel to the shoreline slope to yield a paved intertidal surface.

Bay side Locations with Backshore Supply on Intermediate Gradients

A narrower intertidal surface is associated with steeper bayside shores. In Plate 6.2a, the bayside of Ngakuta Bay in Queen Charlotte Sound is pictured. Three shoreline types can be identified - a cliff, a pocket beach and a rubble shore.

The schist bedrock outcrops form a cliff at high water, with a low water ramp strewn with gravels. A pocket beach 30m in extent is associated with the backshore stream gully. Pocket beaches are characteristically of steep gradient

Plate 6.2
Intermediate Gradient or Bay Side Locations

Plate 6.2a

Bayside shore, Ngakuta Bay, Queen Charlotte Sound.

Note schist bedrock cliff, pocket beach backed by stream gully, and rubble shore.

Pocket beach profile shown in Figure 6.3a

NZMS 260 P 27 GR 903 925

Dec 1985

Plate 6.2b

Rubble shore, Ngakuta Bay, vicinity of above.

Active erosion of backshore colluvium of gravel and cobbles in a fine matrix. Only coarse material on shore bench surface.

Hillslope stability upslope relates to side-casting of material from road construction.

Profile in Figure 6.3b

NZMS 260 P 27 GR 903 925

Dec ,1985

Plate 6.2c

Broad intertidal ramp surface cut from alluvial/ colluvial cliff

Mills Bay, northern Kenepuru Sound.

Profile in Figure 6.3c seawards from cliff in foreground.

NZMS 260 P 27 GR 935 024

Low water

Feb 1986

Figure 6.3 a

Profile of pocket beach, bay-side position Queen Charlotte Sound.

(See Plate 6.2a)

Pocket beaches are comprised of well sorted mixed sand and fine gravel, and extend to below low water . Sub-tidal form comprises coarser materials draped in silts.

Figure 6.3 b

Rubble shore profile, bayside location..

(See Plate 6.2b).

Shores cut into poorly sorted colluvium in sheltered locations develop poorly sorted rubble surfaces .

Figure 6.3 c

Ramp shore profile abutting terrace remnant.

(See Plate 6.2c).

Undercutting of alluvial/ colluvial cliff develops arched caves 1-3m wide and 1-2 deep in softer materials. Collapse of slope supplies material to shore.

Figure 6.3

Shore Profiles: Intermediate Gradient or Bayside Locations

V.E = 10

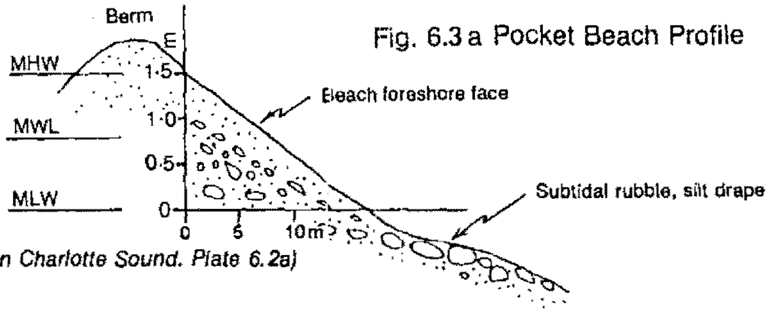


Fig. 6.3 a Pocket Beach Profile

(Ngakuta Bay, Queen Charlotte Sound. Plate 6.2a)

V.E = 2.5

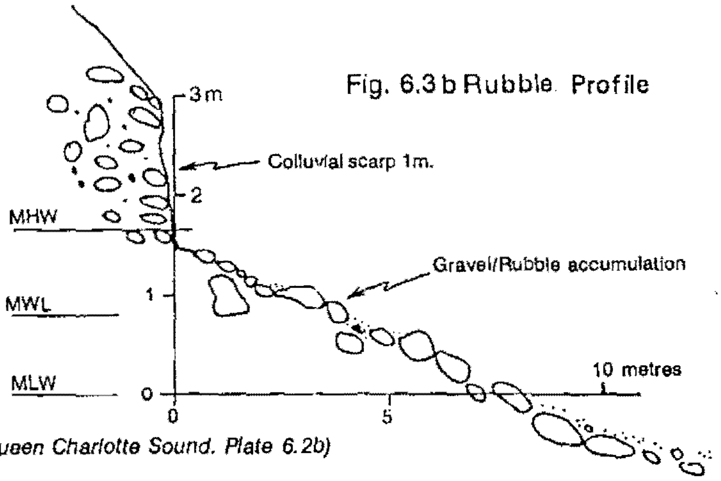


Fig. 6.3 b Rubble Profile

(Ngakuta Bay, Queen Charlotte Sound. Plate 6.2b)

V.E = 3.0

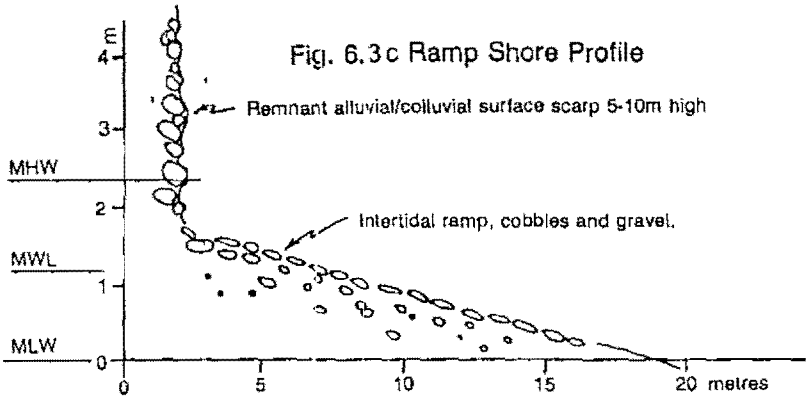


Fig. 6.3 c Ramp Shore Profile

(Mills Bay, Kenepuru Sound. Plate 6.2c)

(generally 1:12 to 1:6, and up to 1:3), and extend from within 0.5m above high water to low water. A profile of a pocket beach shore is shown in Figure 6.3a. Again, the beach is underlain by coarser alluvial deposits. The beach extends to below low water and at its foot a gravel or cobble nearshore is mantled with silt.

The third shore type evident in Plate 6.2a is a rubble shore. A close-up can be seen in Plate 6.2b. Rubble shores are derived from local backshore erosion and comprise two main morphological elements - a backshore scarp and a steep intertidal bench developed from the eroded detritus. The term rubble is used to refer to boulder, cobble and coarse gravel material, where the material is distributed in a chaotic manner, lacking orderly alignment. In this case, high water aligns with the foot of the scarp. This site has an easterly aspect across a fetch of 600m. In more exposed locations a rubble shore will develop into a shoreline ramp. Ramps are broader, and extend above high water. A factor contributing to ongoing erosion at this site is downslope movement related to the sidecasting of road debris onto the hillslope above the beach. A profile of the rubble shore is shown in Figure 6.3b.

A broad intertidal ramp shore is shown in Plate 6.2c, situated at Mills Bay, northern Kenepuru Sound. The ramp slopes at 1:8 comprising coarse gravel of dimensions up to 200mm lying aligned with the surface. The material was derived from the erosion of the alluvial/colluvial backshore cliffs, which extend to a height of up to 10m. High water line is apparent as the tonal break from light to dark. These are located on Figure 6.3c. These terrace shores are one of the two shore types on intermediate gradient hillslopes. Terrace shores are rare in Queen Charlotte Sound, but found extensively on the northern Kenepuru, in Mahau Sound, Nydia Bay, and Tennyson Inlet. Other intermediate gradient shore ramps develop against colluvial fans.

Shoreline erosion of terrace and colluvial deposits is commonly uniform over appreciable longshore distances (100-1000m), leading to the development of a linear ramp shore.

Steep Shore Locations

Shores emplaced against steep hillslopes are comprised of either alternating cliff and rubble shores or a narrow linear ramp backed by a scarp. Surface materials are variable and reflect backshore supply and the redistribution of material by waves. Plate 6.3a and Figure 6.4a show a linear ramp on the southern shore of Queen Charlotte Sound, to the east of Whatamango

Bay. Low and mid tide segments of the profile comprise a coarse gravel ramp and the high water shore includes discontinuous accumulations of finer gravel developing rudimental beach forms. A closeup of a steep shore ramp is shown in Plate 2 of the Frontispiece. The even gradient of the intertidal surface is apparent.

Plate 6.3b shows hillslope material slipping onto a narrow shore platform in the Mahau Sound. On steep shores, a dominant source of shoreline material is derived from the erosion of the backshore supplemented by the addition of material from upslope. Figure 6.4b identifies the plan form of a slump lobe. Finer materials are winnowed from the nose of the slump and moved to the flanks. Short ramps develop on the flanks and beach accumulations at the distal end of each. The persistent effects of slumping depend on the characteristics of the material delivered, and conditions at the receiving site. Coarse material (cobbles, boulders) is rarely reworked but comprises a permanent modification on a narrow, low energy shore. The shoreline recovery rate from delivery of finer materials is proportional to the rate of reworking and the form of the shore. On steep shores the effects of slips may persist for 2-10 years; on shallow shores for an indefinite period.

Plate 6.3c shows a shore platform developed on a schist ridge-end at Ngakuta Bay, Queen Charlotte Sound. Shore platforms are found on exposed rocky ridge ends on many points along the axis of Queen Charlotte Sound. They have a widespread distribution along the southern flank of Mahau Sound, and also in Kenepuru Sound east of Portage, and on the southern shore. Distribution is unknown in the outer portions of Queen Charlotte and Pelorus Sounds. The known distribution shows a systematic association with exposed locations, with fetches of over 1km to the northwest quarter or, in the case of the points on the north of Queen Charlotte Sound, a wide range of fetch directions from the south and east quadrants, often over 2km in extent. Shore platforms show strong dependence on schistosity in detailed form. Most show the high-water step form apparent in Plate 6.3c. The widest platforms which have been observed are in upper Kenepuru Sound where they are over 5m in width in an area with a 4km fetch to the northwest.

Plate 6.3
Steep Gradient or Outer Bay Locations

Plate 6.3a

Steep linear ramp shore, Queen Charlotte Sound.
Southern shore, vicinity of Whatamango Bay

Exposed to a fetch over 4km to the northwest.

Profile in Figure 6.4a

NZMS 260 P 27 GR 001 943

Jan 1986

Plate 6.3b

Hillslope processes on steep slope backshore, Mahau Sound

Side casting of road debris has slipped onto narow shore platfom.

Material has been reworked into ramp shores on the flanks, and the finest material is found in pocket beaches downdrift or in nearshore. Coarse material remains immobile.

Plan view in Figure 6.4b

NZMS 260 P 27 GR 851 964

High water

Feb, 1986

Plate 6.3c

Shore platform on schist rock point, Ngakuta Bay, Queen Charlotte Sound.

Charcteristic "high water" platform form.

Profile in Figure 6.4c

NZMS 260 P 27 GR 908932

Feb 1986

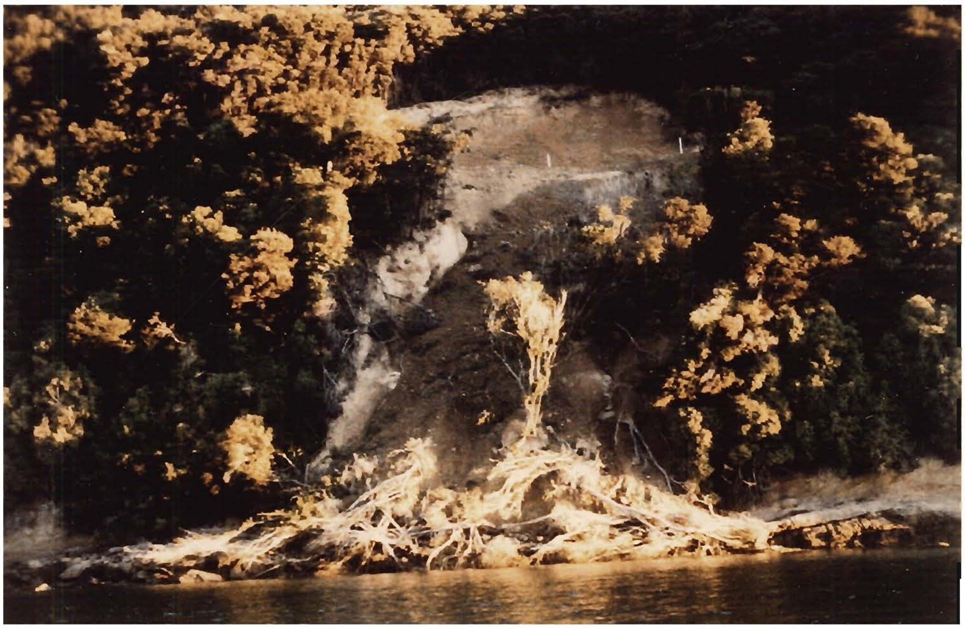


Figure 6.4 a

Profile of linear ramp shore, in exposed location, Queen Charlotte Sound.
(See Plate 6.3a)
Intertidal bench consists of a coarse gravel ramp, with discontinuous beach accumulations at high water. .

Figure 6.4 b

Plan view of shore after slump of backshore materials onto shore..
(See Plate 6.3b).
Wave reworking of lobe nose removes finer materials into nearshore and alongshore.
Lobe nose develops a rubble texture, while shoreson either flank develop ramp deposits of the intermediate size material.
Finer gravels may be worked into pocket beach accumulations at the end of these flows.

Figure 6.4 c

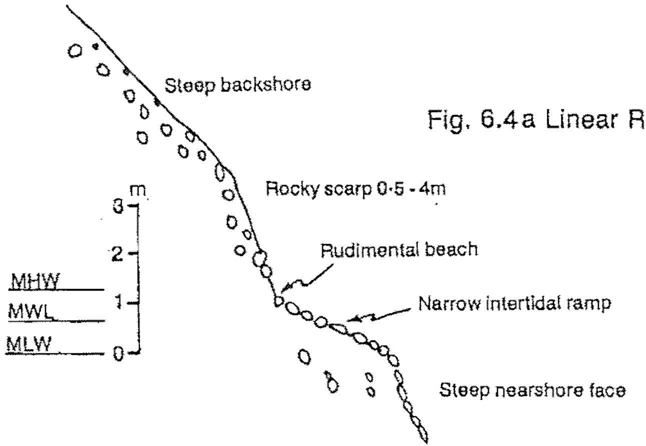
Shore platform, Queen Charlotte Sound.
(See Plate 6.3c).
Shore platforms develop in schist bedrock shores., especially on exposed ridge-ends.
Platform develops at high water, with a steep intertidal step, and a more rudimental platform at low water.

Figure 6.4

Shore Profiles:
Steep Gradient or Outer Bay Locations

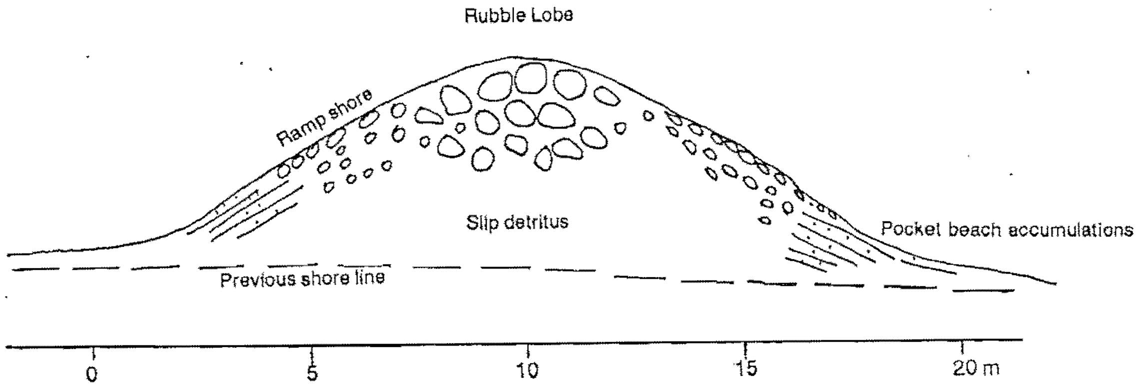
V.E = 4

Fig. 6.4a Linear Ramp, Steep Shore Profile



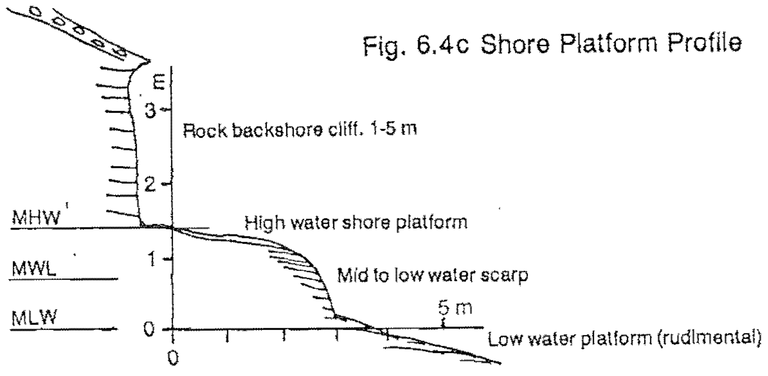
(Exposed Shore, Queen Charlotte Sound. Plate 6.3a)

Fig. 6.4 b Plan view of shore after Slump



V.E = 1.5

Fig. 6.4c Shore Platform Profile



(See Plate 6.3c)

Discussion

Shoreline classification on a low energy, tidal, mixed material shore is a three-dimensional problem, both literally and conceptually. Differences in shoreline character from high to low water across the intertidal surface and alongshore are such that the number of classes required in a purely empirical classification would be unwieldy. Conceptually, it is possible to recognise the tripartite controls of morphology, sediments and energy acting on the shore and a consideration of the variations in these factors gives a more useful approach to shoreline analysis.

Independent Shoreline Controls

Morphology

The landscape factor is addressed first in plan. The principal question is, At what scales does the morphologic frame of the shore compartmentalise shoreline processes? The next aspect addressed is the extent to which shoreline gradient reflects backshore gradients. An initial distinction has been made in the previous section. The question addressed below in more detail is the relationship between hillslope morphological types and shoreline types.

The Scale of Shoreline Form in Plan View

Of all the altitude contour lines in the Marlborough Sounds landscape, the shoreline contour (defined as MHWM) is the most distinct. The following discussion of shoreline irregularity is made with reference to maps drawn to a scale of 1:50,000 (Maps 2, 3 and 4). Shore lengths were measured by Numonics digitiser with an accuracy of 0.25mm on sheets of map series NZMS 260.

The shoreline length of the Queen Charlotte Sound and Pelorus Sound is 792km. The analysis of coastal form on maps gives a simplified perspective of an intricate landform. In the field, the analysis of form tends to proceed from a limited perspective. To achieve coherence between large scale and small scale observations it is useful to develop a scheme in which several orders of scale can be recognised.

Three orders of shoreline irregularity can be recognised in the Marlborough Sounds, which are referred to as sub-regions, embayments, and indentations.

Sub-regions

At the first order, the coast can be divided into a series of sub-regions which correlate with the principal river drainage routes in the antecedent landscape. These include the inner Queen Charlotte (from Okiwa to Dieffenbach Point), outer Queen Charlotte (from Dieffenbach Point to White Rocks), and Tory Channel. The Pelorus Sound system is divided into the inner Pelorus (to Putanui Point), the Pelorus Channel (to Tawero Point), Kenepuru Sound, Tennyson Inlet, and the Beatrix Bays, including Clova and Crail bays. No systematic reference is made here to the outer reaches (Tawhitinui and Waitaria Reaches) of the Pelorus Sound.

Summary morphometric data for these sub-regions are presented in Table 6.3. Listed are the length of the inlets, the range in channel width, and the shoreline length. The Pelorus Sound with a length of 51.5km is slightly longer than the Queen Charlotte Sound (45km). The Kenepuru Sound, a major branch of the Pelorus, has a length of 22.5km. Branching off the Queen Charlotte Sound is Tory Channel, with a length of 17km. The most open stretches of water are found in the outer reaches of Queen Charlotte Sound or in the Tawhitinui and Waitaria Reaches of Pelorus Sound. These are set apart from the more enclosed inner sounds which are the principal focus here.

Embayments

Second order shoreline irregularities occur at what is referred to here as the embayment scale. Embayments are dominant features of the coastal landscape interpreted from the 1:50,000 maps.

The term embayment is used here to refer to those larger bays which have more than one stream inflow. The bayhead stream is usually the predominant inflow but drainage on most hillslopes is linear from ridge to shore, so there are many points at which catchment inflows reach the shore.

Table 6.3

Shoreline Form in Plan
Sub-regional Morphometry

Sub-region	Axial Length (km)	Channel Width (km)	Shoreline Length (km)
Queen Charlotte (Total)	45.0	0.9-11.1	**329.6**
Queen Charlotte Outer	25.0	5-11.1	149.0
Queen Charlotte Inner	20.5	0.9-2.3	132.2
Tory Channel	17.0	0.8-1.3	48.4
Pelorus Sound (Total)	51.5		**462.7**
Inner Pelorus	10.2	1.0-7.5	55.9
Kenepuru Sound	19.8	1.3-2.6	84.8
Pelorus Channel	21.3	1.1-2.2	83.8
Beatrix Bays	15.3		66.3
Tawhitinui and Waitaria Reaches	21.5	4.5-12.0	130.8
Tennyson Inlet	8.5	0.6-2.8	41.1
Total Queen Charlotte and Pelorus Sounds			**792.3**

Measured on N.Z.M.S. 260 1:50,000
by digitiser with accuracy to 0.25 mm

Table 6.4

Shoreline Form in Plan
Embayment Morphometry
(Selected Examples)

Sub-region	Number of bays	Bay length	Embayment Index	
		(Mean, km)	(Mean)	(Standard Dev.)
Northern Queen Charlotte	8	1.77	2.10	1.19
Tory Channel	9	1.55	2.74	1.98
Pelorus Channel	8	1.95	1.36	0.79
Kenepuru	10	0.84	1.31	0.74
Tennyson Inlet	6	1.14	1.98	1.34

The axes of the embayments coincide with stream channels of the antecedent drainage pattern which had confluences upstream of second or third stream order. Examples are the Mahakipawa Arm, Four Fathom Bay and Onahau Bay, on Maps 2, 3 and 4 respectively. Also included in this category are the major bays of Tory Channel, such as Onepua (Opua) Bay.

In Table 6.4 statistics of embayment length and of the ratio of bay length to bay-mouth width are given for five of the sub-regions. The sub-regions are those which include more than 5 embayments. The index of bay length to bay-mouth width is referred to as the embayment index. Mean and standard deviations of the index are given for each sub-region.

The most deeply embayed sub-regions are Tory Channel and the bays of northern Queen Charlotte Sound. These have mean values over 2, or a bay length that is twice the bay-mouth width. The index gives an initial measure of the enclosure of the water bodies, which has implications for sheltering from waves and trapping of fine sediments.

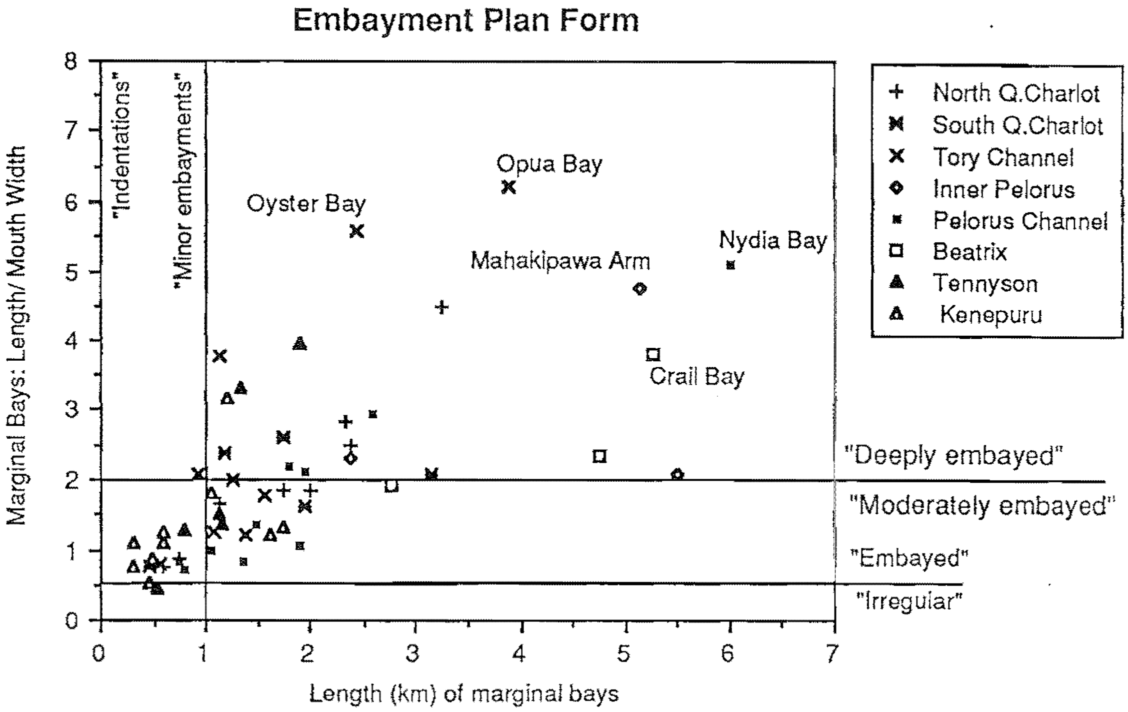
In Figure 6.5 a scatter plot can be seen of plan-form values from 65 bays from 8 sub-regions. This grouping includes all the embayments in Queen Charlotte Sound and Pelorus Sound, excluding the outer sub-regions of each. The sub-regions are distinguished in the key. Values of the embayment index are plotted against values of bay-length in km.

A distinction is drawn between bays which are deeply embayed, with a length more than twice the bay-mouth width, and those which are less deeply embayed. Six of the most deeply embayed sites are identified by name. One is the Mahakipawa Arm, a shallow-drowned embayment in the inner Pelorus. Two others are from Pelorus Sound: Nydia Bay, in the Pelorus Channel, and Crail Bay, in the Beatrix bays sub-region. Oyster Bay and Opua Bay are located in Tory Channel.

Less deeply embayed shoreline irregularities are classed as either moderately embayed, or irregular (Zenkovich, 1967). The latter category refers to shores on which embayment widths are more than twice their length.

Figure 6.5

Embayment Morphometry
Scatterplot of "Embayment Index"



Embayment Index is defined as the ratio of the embayment length to its width at baymouth. The Embayment Index is a gauge of the enclosure of a bay.

A number of bays from the sub-regions specified are plotted on the graph. Specifically identified are those deeply embayed sites with dimensions longer than 2.5km.

Shoreline irregularities in which the width of the bay is more than twice its length (depth) are classed as indentations rather than embayments.

Minor embayments are defined as those with a length less than 1km.

Indentations

Figure 6.5 distinguishes shoreline irregularities with a length of less than 1km as minor embayments. The smallest irregularities are referred to as indentations.

Indentations are distinguished here from embayments on the grounds of having only one stream inflow. These correlate with first or low-order stream gullies, with a longshore scale of 10^1 to 10^2 m. Not all indentations are apparent on the 1:50,000 map. Examples of indentations are Moutapu Bay, Mud Bay and Whenuanui (Becks) Bay on Maps 2, 3 and 4 respectively.

Discussion: Plan Form and Shoreline Functioning

The view of shoreline processes on embayed coasts developed in classical coastal literature (Johnson, 1919) and reiterated to some extent in Zenkovich (1967) and Davies (1980), is of material being swept from outer shore positions and swept into bayhead locations. The mechanism was seen by Johnson (1919) as the key to the process of shoreline evolution, or "coastal simplification". Such a pattern of change is not generally observed on the inner Sounds and the principal reasons are low levels of wave energy, a deficit in shoreline materials and the intricate compartmentalisation of the shore. The scale at which the inner Sounds shore functions, therefore, is primarily at the scale of indentations.

In Chapters 8 and 9 further reference is made to the embayment index as a gauge of the trapping behaviour of marginal bays with respect to fine sediment.

Shoreline Form in Profile: The Coastal Gradient and Offshore Gradient

The hillslope gradient which abuts the shore generally extends at a similar gradient below the water until it reaches a more gentle gradient which characterises the major part of the bed of the sounds. Echo-sounding transects reproduced in Chapter 8 show that the submarine form comprises two principal slope elements. The steeper component adjacent to the shore is referred to as the coastal gradient. The shallower gradient which abuts it at its foot is referred to as the offshore gradient.

Values of the coastal gradient range from over 1:2.5 (20°) to less than 1:50 (1°), depending largely on the backshore geomorphology. The offshore gradient only rarely exceeds 1:100, and values of less than 1:1000 are typical for the bottom of Queen Charlotte Sound.

Taxonomy of Coastal Gradients

Analysis of hillslope gradients conducted from topographic and bathymetric maps at a scale of 1:25,000 has shown that groupings of coastal gradient can be identified. These groupings correlate largely to the terrestrial landform types identified in Chapter 2. A classification of these, with gradients, is given in Table 6.5.

Slopes of the schist or greywacke bedrock frame of the landscape are consistently steep despite variations in structural orientation. The *steep slope* class of coastal gradient refers to the range of slopes over 1:2.5 (22°).

Coastal gradients of between 1:5 and 1:2.5 are identified with the *intermediate* gradient class. These gradients are found on two hillslope types. The first are hillslopes with a fan form and are associated with the landform identified in Chapter 2 as a colluvial fan. In part the origin of these forms can be traced to Quaternary conditions. A second group of intermediate gradient shores are found on shores backed by remnant alluvial/colluvial terraces.

Lower coastal gradients of between 1:200 (0.3°) and 1:5 (11°) are found in locations where the backshore topography is dominated by alluvial forms. Such forms are found at the heads of most shoreline indentations. Gully forms have a gradient of between 0.1 and 1:5. Bayhead fan gradients range from 1:100 to 1:20, while the largest indentations have at their heads alluvial flats with gradients less than 1:1000.

Coastal Gradient and Plan Form

Steep shores are characteristically intricate with indentations defining shore components with a longshore extent of 10^1 m. Intermediate gradients are associated with hillslopes of a fan form which produces a shore of arcuate forms at a longshore extent of 10^2m. Gully shores may be 10m across or less. Bayhead alluvial fans are confined by steep slopes that control their linear extent, but in the larger bays are typically 100-300m wide. Large alluvial flats develop mildly arcuate shoreline forms due to stream progradation and have a longshore extent of more than 500m.

Table 6.5

Taxonomy of Coastal Gradients

Slope Class	Gradient	Slope (Degrees)	Width of 20m contour (1:50,000 map)
Steep (Hillslope)	>1:2.5	>22°	1mm
Intermediate (Colluvial)	1:5 - 1:2.5	11° - 22°	1mm to 2mm
Low (Alluvial)			
Gully	1:10 - 1:5	6° - 12°	2mm to 4 mm
Bayhead fan	1:100 - 1:20	0.06° - 6°	4mm to 20mm
Alluvial flat	<1:100	<0.06°	> 40 mm

Table 6.6

Distribution of Coastal Gradients

Sub-region	Steep (% length)	Intermediate (% length)	Shallow (% length)	Total length (km)
Queen Charlotte				
Grove Arm	78 %		22 %	21.9 km
Whatamango Bay	74%		26%	6.8 km
Pelorus				
Clova and Crail bays	76 %	17 %	7 %	32.7 km
Nydia bay	63 %	29 %	8 %	18.9 km
Tennyson Inlet	79 %	13 %	8.5 %	34.1 km
Kenepuru Sound	85 %	5 %	10 %	84.8 km

Distribution of Coastal Gradients.

Examples of each gradient class can be found in most sub-regions. The coastal gradient can be estimated on the 1:50,000 scale maps enclosed as Maps 2 to 4. In Table 6.5 the millimetric width of the distance from the shoreline to the first (20m) contour on these topographic sheets is given as a means to identify the distribution of coastal gradients.

Prime examples of the steep-shore forms are found in the Grove Arm, inner Queen Charlotte Sound. The intricacy of the shore reflects the oblique orientation of the coast to the grain of the schistosity of the bedrock. Steepshores have less than a millimetre between the 20m contour and the shore at 1:50,000.

Intermediate gradients are often apparent on the 1:50,000 sheets as having a contour-line spacing of between 1 and 2mm, with up to 4mm on lower slopes. Intermediate gradient shores on colluvial fans predominate in the Hikapu Reach of Pelorus Sound (Map 3) from Whatanihi to Maori Bay. Terrace shores are distinguished by relatively high cliffing (often >5m) in unconsolidated and fluvially worked detrital material. These are not distinguishable on maps from colluvial (and sometimes from steep slope or alluvial) gradients.

Gully forms can be identified on the 1:50,000 sheet by a contour width of between 2mm and 4mm along stream channels. Bayhead alluvial fans have spacings of between 4mm and 20mm, while what are referred to as alluvial flats have spacings wider than 20mm between the shoreline and the 20m contour at 1:50,000.

Bayhead alluvial shores can be found in Nydia Bay and minor forms in bayheads throughout Queen Charlotte Sound. Major alluvial flats are found at the heads of Queen Charlotte and Pelorus Sounds, as well as on the northern shores and at the head of the Kenepuru Sound.

The proportion of each coastal gradient class for six sub-regions is given in Table 6.6. Steep shores comprise between 63% and 85% of shoreline length in these examples. A range of 60% and 95% is a typical proportion for most sub-regions.

Colluvial shores are more common in the inner and mid Pelorus Sound. It is possible that this reflects the diminishing rainfall gradient from west to east across the region, as well as the more shallow drowning of these sub-regions. Colluvial fans predominate in the east of Clova Bay. A high proportion of the Nydia bay shoreline (29%) is classed as intermediate gradient. This reflects both the sub-regional distribution of colluvial fans and the local distribution of remnant terraces along this shore. The same applies to Tennyson Inlet.

Alluvial shores are significant in the Kenepuru Sound (10%), and form a large proportion in some inlets such as the Grove Arm (22%). The total proportion of alluvial shoreline is of the order of 2% to 5%.

The Relationship between the Coastal Gradient and the Shoreline Gradient

There is a good correlation between shoreline gradient and coastal gradient. On steep coastal gradients, rock (cliff) and rubble shores are most frequent. On hillslopes of intermediate gradient, ramp shores predominate. Bayhead shores and tidal flats correlate with bayhead alluvial fans and with alluvial flats respectively. In terms of the broad classes defined, shoreline gradients are typically half the adjacent coastal gradient.

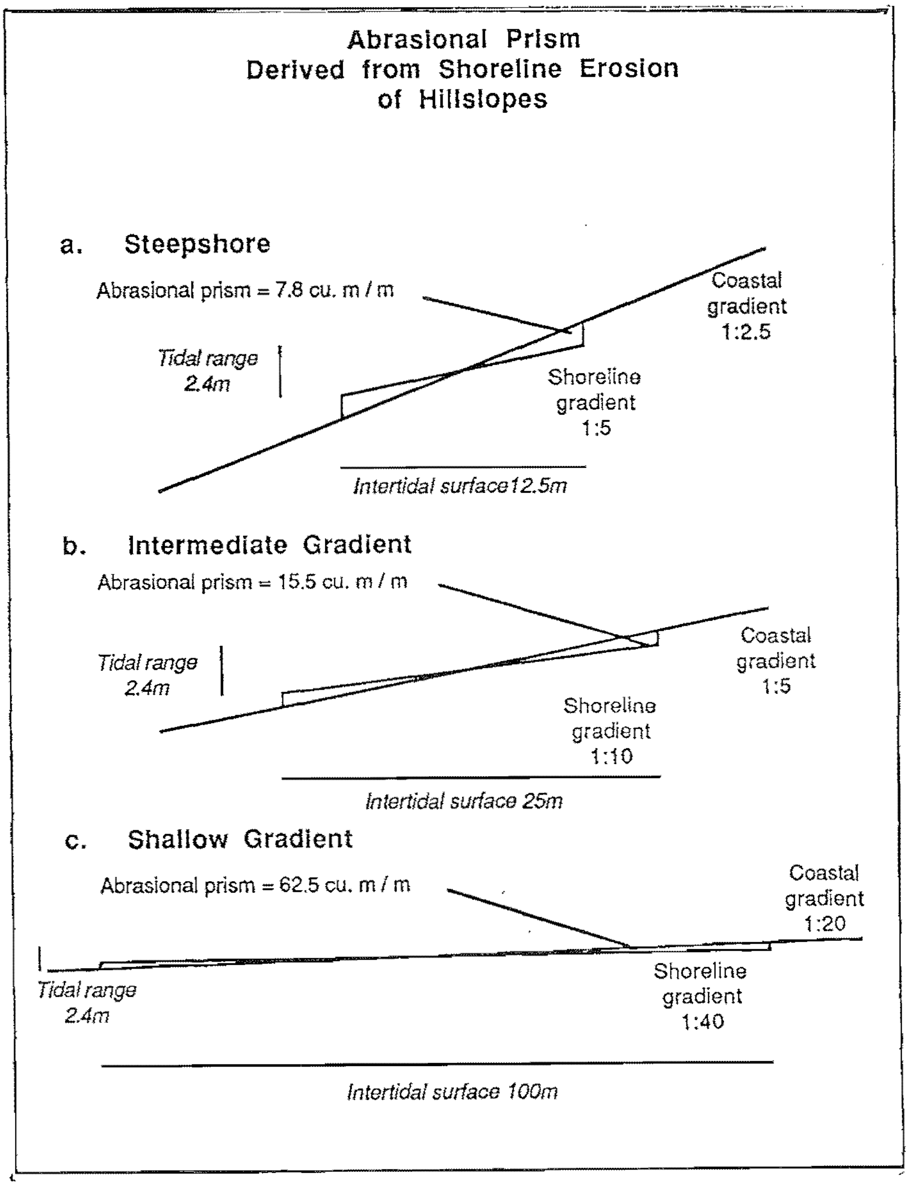
At the first order, therefore, initial morphological factors are a prime determinant of shoreline form.

The implications of the superimposition of these shoreline and coastal gradients are shown in Figure 6.6. In the absence of the accumulation of sediment materials from upslope or from stream sources the shoreline will develop by erosion of the hillslope against which it is emplaced. The abrasional prism labelled on the Figure is plotted such that all the material eroded from the shore above mean water will be deposited on the intertidal surface or immediately below low water. The extent to which this is valid depends on particle mobility of the material cut from the hillslope. Estimates of the minimum volume of material eroded to create a given shoreline gradient from the adjacent coastal gradient are given for each of four steepness classes.

The proportion of material retained at the shore could be expected to vary according to the coastal gradient a larger proportion being retained on shallow gradients. The total volume of material eroded from shores can be calculated within an order of magnitude by reference to geometry alone. As an example, the shoreline length of the Grove Arm is 22km. Of this length 78% is classed as steep (Table 6.7) and 22% shallow. If an arbitrary estimate of 60% of material eroded from a steep shore is dispersed offshore and 20% of material is dispersed from a

Figure 6.6

Relationship Between Coastal and Shoreline Gradient: The "Abrasional Prism"



Shore gradients bear a relation to coastal gradients of typically half.
Figure shows the resulting prisms of material required to be moved to obtain these differences of gradient.
Calculations are based on 100% retention of hillslope materials within the shore zone, with the transfer of material derived by erosion from above mean water onto a shoreline "bench" (Zenkovich, 1967).
Values as calculated for an intertidal surface with a vertical elevation of 2.5m. The value of the abrasional prism given for each of three slope classes represents the volume per linear metre of shore that would be transferred from the the upper to the lower profile position.

shallow shore then from Figure 6.3 an estimate of 4.68m^3/m for steepshores and 12.5m^3/m for shallow gradient shores is obtained. The total volume of material derived from shore erosion is estimated on these figures at 140,810m^3. The water area of the Grove Arm is 7.2km^2, which calculates to a uniformly distributed sediment thickness of 20mm. A similar calculation for the Queen Charlotte Sound to Tory Channel, calculated on 90% steepshore and 10% alluvial shore, with a shoreline length of 132km and an area of 68.2km^2 gives a value of 10.5mm.

Three factors determine the shoreline gradient: the initial coastal gradient, the materials of which the shore is comprised, and the levels of wave energy. In large part because of the limited capacity of shoreline processes to redistribute coarse sediments on a sheltered shore, and also the limited supply of materials to the shore by streams immediately adjacent to them, the primary controls on shoreline gradient are the coastal gradient and the backshore materials.

Shoreline Sediments

The focus of the sediment analysis reported in Chapter 5, was on materials sampled from shoreline *accumulations*. These were defined as sediment bodies of several particles in depth, with some homogeneity in grain character. Sediment accumulations, by definition, develop by the aggregation of sediment particles which implies a particle mobility. On the shoreline, a range of sediment surfaces can be identified with varying degrees of immobility.

A distinction can be made between sediments which can be intermittently moved by wave action and those which are dominated by gravity. *Wave field* material (Zenkovich, 1967, p75) refers to shoreline material that can be moved in suspension or bedload by waves. In bedload, particles move by rolling or brief suspension (for less than half the wave period). In suspension, the settling rate of particles is of prime importance. Material finer than about 0.05mm (arbitrarily taken as 0.063mm, the sand-silt boundary on the Wentworth Scale) settles so slowly in water, especially under turbulent conditions, that it tends to be held in suspension and transported out of the wave-worked zone.

Wave field material is not under the control of the morphologic trap, but of the mobility trap. However, a component of the sediment derived in situ or delivered from catchment sources is unable to be redistributed by shoreline processes and is referred to as immobile or *passive* material (Zenkovich, 1967, p75). An intermediate category of material is referred to as *semi-mobile*. These particles may move by a combination of gravity and water movement when their position on the bed permits it. Semi-mobile particles tend to become aligned to lie parallel to the shore surface, and form a *paved* surface (Parker and Klingeman, 1982; Parker et al. 1982).

A key factor in terms of the development of shores in response to sediments made available from backshore or catchment sources is the relative mobility of material in the shore zone.

Classification of Sediment Sources

A summary of sediment sources is given in Table 6.7. Two sources of shoreline sediments are distinguished: an abrasional source and an accumulational source.

Abrasional Source of Shoreline Sediments

Erosion of the initial hillslope or alluvial surface and ongoing erosion of the shoreface and backshore give rise to an abrasional supply of material. The nature of the abrasional supply depends entirely on local shore and backshore materials.

The columns in Table 6.7 identify backshore types and the type of detrital material associated with each. The fourth column identifies the persistence of supply which might be expected from a given source. Initial sources are those derived principally after the shoreline stabilised and in which relatively little continued supply took place. Intermittent supply can take place, for example, with extreme wave events eroding backshore scarps. Ongoing erosion is found on many terrace remnants mainly because the retreat of the shoreline scarp or cliff is slow and waves continue to undercut the scarps. The slow retreat can be attributed to the height of the cliffs.

Backshore hillslope instabilities contribute material to the shore on most steep slopes by debris avalanches to the shore. The most consistent locations for such avalanches are in gullies. Mass movement supply from slips is more intermittent than stream supply. The size range of materials (because it is colluvial) is akin to that of the initial abrasional supply. This includes coarse material (cobbles and coarser gravels).

Table 6.7

Sources of Shoreline Sediments

	Source		*Detrital Material Type*	*Periodicity of supply*	*Control on Grain-size*	*Population behaviour*
Abrasional	Cliff erosion		Angular rubble	Initial	Backshore Source area	Passive
	Colluvial erosion	Steepslope detrital	Cobbles to clay	Initial		
		Colluvial fan	Cobbles to clay	Initial / intermittent		Predom. passive
	Terrace remnants		Cobbles gravel and fine matrix	Initial / on-going		
	Alluvial fan		Gravel and sand	Initial / intermittent		Wave field
Intermediate	Large scale slumping		Backshore materials	Intermittent / on-going		Passive and wave field
	Gully avalanching		Upslope materials	Intermittent		
Accumulational	Stream additions		Gravel and sand	Persistent	Hydraulic (fluvial)	Wave field
	Longshore transport		Gravel and sand	Persistent / supply dependent	Hydraulic (littoral)	Wave field
	Offshore/ adjacent river		Silts and clays	Persistent	Hydraulic (tidal)	Suspension

Major hillslope instabilities can lead to the displacement of the entire backshore cliff in a seawards direction. The net effect is the rejuvenation of backshore scarp erosion as the intertidal surface is shortened and waves at high tide undermine the scarp toe. The feed of materials is confined to the rear of the profile, a situation distinct from that associated with slumping or avalanching of material across the foreshore. Major instability is registered on the north-facing slope of the ridge from Mt Cawte (Map 1 GR 579 993) to the head of the Kenepuru; specifically at The Rock (GR 580 994), Double Bay (GR 580 994) and above Sheehans (GR 595 999). Further sites have been recognised by R. Sutherland (Marlborough Catchment Board, Pers. comm. 1984).

The Accumulational Source of Shoreline Sediment

Material which is derived from in situ sources contains particles derived from one source area. Therefore, the proportion of the source feedstock which is in the size grades of passive, wave field or finer material, is externally determined. Sites on shorelines which do not have a longshore, offshore or stream sediment source comprise a particle population which contains only a local source area population.

The three sources of accumulational sediment are specified in Table 6.7. Addition of sediment from streams is a primary source and its effects can be observed on both shallow gradient (Plate 6.1a) and steep shores. The most significant features of stream supply are the selective addition of wave field material, and the permanent location of streams which are stable over time leading to the persistence of them as sources of sediments at given sites. Backshore slumping, by contrast (Plate 6.3b), is generally an intermittent supply with a more random distribution.

The distinguishing feature between materials which are derived from abrasional sources and those derived from accumulational sources is the nature of control which is seen to determine textural character. Table 6.7 identifies abrasional sources with external source area control and accumulational sources with a hydraulic control. Three types of hydraulic process are identified in Table 6.7 - fluvial, littoral, and tidal. The role of energy factors in shoreline form is discussed in the following.

Shoreline Hydrodynamics

Wave Parameters

Low energy is a relative term. Tanner (1974) identified shores with significant wave heights less than 2m as "low energy shores". The growth of waves in restricted bodies of water is limited by the length of the exposed fetch over which the wind blows, and the strength, duration, and variability of the wind (U.S. Army, 1962).

Wind roses from Picton (Rail ferry jetty) giving wind speed and direction for annual mean values, and for four seasons are given in Figure 6.7. A significant feature of the wind field is the strong north-south orientation. This reflects the characteristic funnelling of winds along valley axes. In the open Sound, a larger proportion of this wind component is from a northwesterly quarter. Calm conditions prevail for 32.7% of the whole year, and 43.6% in winter. Mean wind-speeds over 10 knots were recorded 21% of the time.

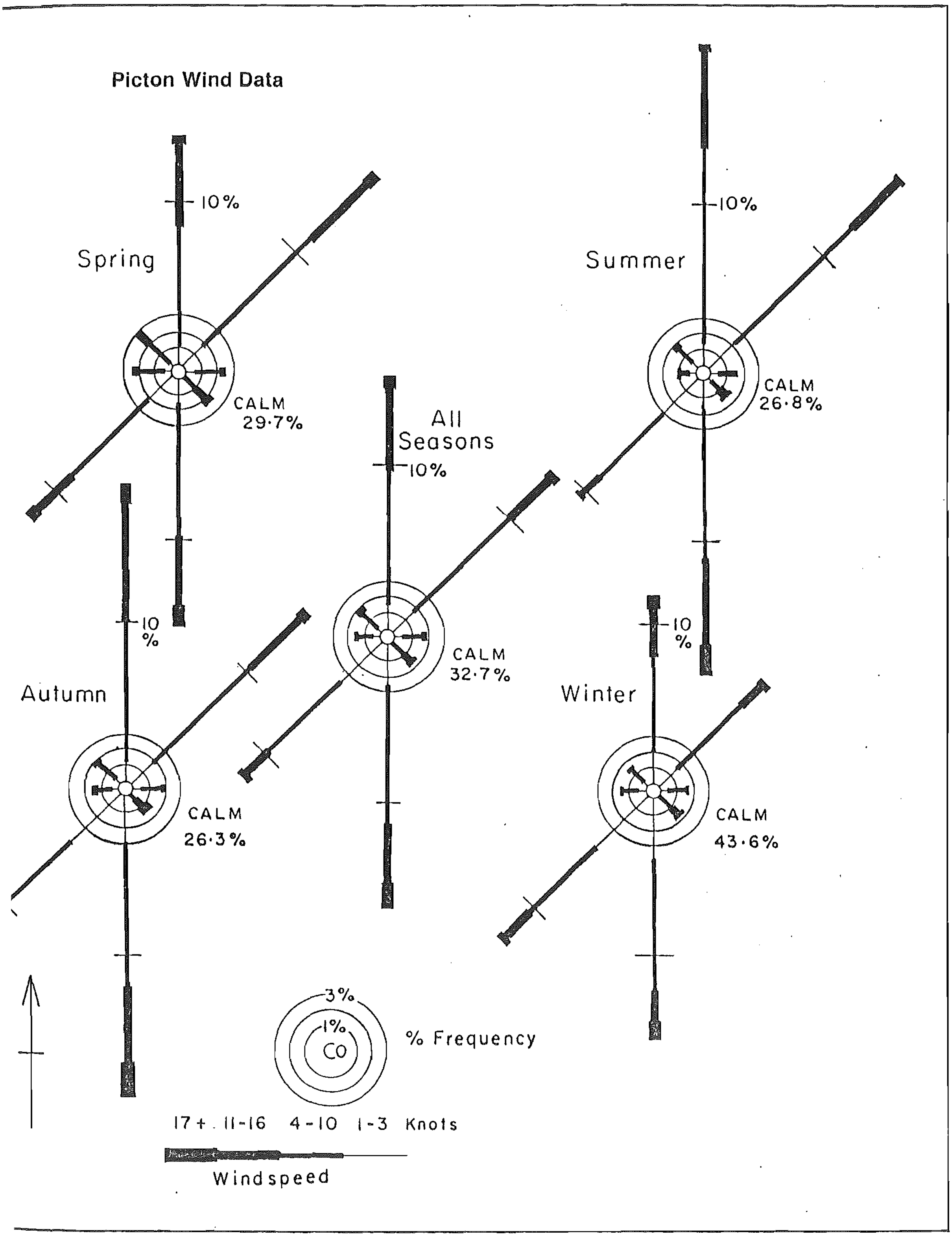
The diurnal pattern of windspeed at Picton is shown in Figure 6.8 for six one monthly intervals. Notable patterns are the calm night and morning conditions. Winds reach a daily peak in mid-afternoon (1400hrs). Winds in March and November are shown to be the strongest with calm conditions in the winter months.

Wave forecasting techniques have been developed for the prediction of waves developed in reservoirs (U.S. Army, 1962, 1974), and are described as being applicable in some cases to sheltered coastal settings and lakes.

Norrman (1964) distinguished between fetches where the wind was able to flow freely over essentially flat topography before passing over water from topographically constrained fetches with steepland either up-wind or down-wind. Topographic form in the Marlborough Sounds affects wave development by restricting overall maximum fetch distances, and by the comtrol of fetch width associated with funnelling of wind along the axes of valleys and bays. Ranges of fetch lengths measured on only one bearing (north-south, or east-west, depending on principal shore orientation) are shown for a range of sub-regions in Table 6.8.

Figure 6.7

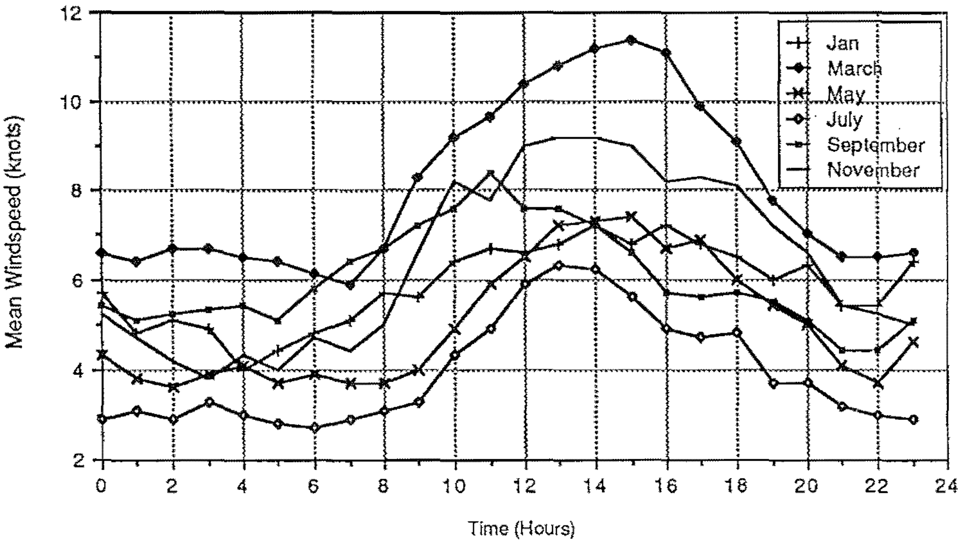
Picton Wind Data
Seasonal Velocities



Source: New Zealand Meteorological Service
Data 18 months July 1974 to August 1976

Figure 6.8

Picton Wind Data, Diurnal Variations



Diurnal values averaged over one month sampling intervals, values hourly.

Source: New Zealand Meteorological Service
Data 18 months July 1974 to August 1976

Table 6.8

Ranges of Fetch Lengths

Sub-region	Mean fetch* (km)	Maximum fetch (km)	Direction (as measured)
Queen Charlotte			
Northern bays	1.2	2.6	N, S
Grove Arm (outer shore)	1.2	2.8	E, W
Tory Channel (outer shore)	2.5	3.4	N, S
Tory Channel (bays)	0.7	1.3	E, W
Outer Queen Charlotte	4.9	7.0	N, S
Pelorus Sound			
Inner Pelorus	1.7	3.2	N, S
Kenepuru	2.3	4.3	N, S
Pelorus Channel bays	1.2	2.4	N, S
Beatrix bays	4.2	7.2	N, S
Tawhitinui Reach	4.5	6.2	N, S
Tennyson Inlet	1.6	4.6	N, S

** measured in direction of fetch as speciffied*

Pickrill (1976, p149) found on a study of lakeshore processes in southern New Zealand that wind-generated wave heights recorded were smaller by a factor of 2.33 than predicted by U.S Army (1962), and wave periods by 1.23. A series of values extracted from replotted tables to allow for this overestimation (Pickrill, 1976, p152) are plotted in Table 6.9. Values are given for four fetch lengths, ranging from 0.5km to 4km. Windspeeds at 5, 10, 15 and 20 km/hr are given for each. Wave forecast parameters are wave period (T_z) and significant wave height ($H_{1/3}$, ie. the height of the highest one third of waves, U.S. Army, 1962). Wave lengths are calculated on the basis of two wave steepness values, 1:100 and 1:12, which were the bounds of lakeshore waves found by Pickrill (1976).

Periods of 2.4 seconds and wave heights of 35cm are predicted for 20km/hr winds blowing over a fetch of 4km. Newton (1978) recorded largest significant wave heights in Tory Channel of 25cm to 35cm corresponding to wave periods of 2 to 2.2 seconds for wind generated waves. Fetch lengths and windspeeds match approximately those used for the prediction so for an approximation of mean wave conditions the values in Table 6.9 are an adequate working estimate. There is a need for further investigation of wave action acting on shores with short-fetches.

Waves developed over restricted fetches are characteristically steep and of shorter wavelengths than waves of equivalent height on the open coast (U.S. Army, 1976). This has two important implications for shore profile development.

The first implication for shore profile development on the sheltered shore is the limited sub-tidal effect of wave oscillatory flows. The depth to which waves can work sediment is proportional to their wave length. Significant sediment disturbance does not take place below L/4, or a quarter of wave length (Pethick, 1984). For even the largest steep waves in Table 6.9, this would amount to sediment being disturbed in water depths of 1.1m. This value increases with wave length.

The second implication of limited wave dimensions is the restriction on total wave energy. The amount of wave uprush above the mean water level depends on both wave energy and shore slope. Low energy shore profiles have a small supra-tidal extent. Berm height above high water in the inner Queen Charlotte rarely exceeds 0.5m. In the southern Kenepuru, and in other more exposed locations such as Clova Bay and the northern shores of Arapawa Island, berms of overl.5m above high water are rare.

Table 6.9

Wave Forecast Parameters

Fetch (km)	Windspeed (km / hr)	Wave Period Tz* (sec)	Significant Wave height H 1/3* (cm)	Wave Length Lo (m) For given steepness (H/L)**	
				0.01	0.08
0.5	5	0.65	3	3.0	0.4
	10	0.85	5	5.0	0.6
	15	1.05	8.5	8.5	1.1
	20	1.30	14	14.0	1.8
1	5	0.95	4.5	4.5	0.6
	10	1.20	9	9.0	1.1
	15	1.45	13	13.0	1.6
	20	1.65	18	18.0	2.3
2	5	1.15	6	6.0	0.8
	10	1.40	12	12.0	1.5
	15	1.70	17	17.0	2.1
	20	1.90	24	24.0	3.0
4	5	1.35	8	8.0	1.0
	10	1.75	17	17.0	2.1
	15	2.05	23	23.0	2.9
	20	2.40	35	35.0	4.4

*Wave forecast data derived from U.S. Army (1962), and recalibrated by Pickrill (1976) on the basis of observed overestimation of wave parameters.
T_Z is not the same as $T_{1/3}$, (or significant wave period) but the zero-crossing wave period as derived from charts.

Data calibrated against recorded wave maxima by Newton (1977) indicate that maximum vales of 35cm waves of 2.2 sec period in winds of 10 knots over fetches of 4km are reasonable estimates for wind waves in the enclosed Sounds.

**Values of wave steepness for waves on short, steep land fetches from Pickrill (1976).

Tidal Range

Tidal low energy shores can be morphologically distinct from non-tidal shores. Tidal ranges for a number of locations within the Sounds were shown in Table 6.1. The peak tidal range is 1.5m in the Queen Charlotte, and 2.4m in the Pelorus Sounds (N.Z. Nautical Almanac, 1984). In translocating the zone of wave work across the shore profile twice in each semi-diurnal cycle, the effect of tidal range on a coast on which wave heights are small is to disperse the effects of wave energy across the profile.

Interactive Shoreline Controls

The range of independent conditions which control shoreline form and behaviour accounts for the variability of form observed at the shore. However, not only variability, but a repeatable and orderly pattern of shore forms can be recognised at a range of scales. The observation of "characteristic form" (Brunsden and Thornes, 1979) shows that the functional control of the shore is exercised by the *interactions* of independent controls and by mutual coadjustments between them.

This section examines the nature of these interactions and their consequences for shoreline functioning.

Descriptive Analysis of Interactions

If description is restricted to sedimentary shorelines (ie: excluding hard rock shores), then it is the sedimentary component which most clearly defines the nature of the shore. Shoreline form is an artefact of sediment redistribution and shoreline energy acts through sediments.

Taking sedimentary behaviour as the central functional characteristic of the shore leads to the perspective of shoreline function as a Sedimentary Transform (Figure 4.4). The Ordered Response Model suggests that the sediment transform involves two intermediate stages: a morphologic trap, and a mobility trap. A consideration of the variation in shore types suggests two continua of interactive controls operating at different scales. The first continuum differentiates shoreline site from site. The second is of primary relevance within sites.

Morphologic Interactions

The first continuum relates to the form of the shore and the behaviour of material within it. At one end of the range can be recognised the shallow gradient shore. Regardless of the material delivered to such a shore these sites are behaviourally *retentive*. At the other end of the range are found steep-shores. At such sites finer grades of sediment are liable to be *dispersed* by a number of mechanisms. However, such sites are retentive of some sediment fractions, notably the coarsest and most immobile. Therefore, what is defined as the morphologic continuum stems from the interaction of morphology and materials in the shore zone.

Mobility Interactions

The second continuum relates to the behaviour of individual sediment particles within the shore. In some sites of moderate to high energy finer sediment particles are seen to be dispersed from shoreline sites. On a range of shoreline sites reviewed in the first section, gravel ramps were a component of the shore profile, both as linear ramp shores and on intertidal surfaces. On these ramps, finer materials tend to be dispersed, migrating as individual particles. At the other end of this continuum lies the pocket beach which is an example of an agglomerative sedimentary behaviour. The significance of agglomerative behaviour lies in the interparticle interactions. The determining factor in this set of behaviours is seen to be the interaction between shoreline materials and shoreline hydraulics. The range in behaviours between dispersion and agglomeration is referred to as the mobility continuum.

These two continua are plotted as forming the axes of an *X-Y* plane in Figure 6.9a. Within this *X-Y* plane a set of interactions between the three independent coastal controls is incorporated: and it should therefore be possible to locate all shoreline sites on this plane. These are plotted on Figure 6.8a. The *X-Y* plane is referred to as the shoreline trapping space.

In the retentive domain (R) the bayhead delta is located and the rubble shore, the former at the accumulative side of the domain, and the latter on the abrasional. At the dispersive apex (D) high mobility and a rejective morphology are plotted as defining the conditions of a shoreline ramp. At the agglomerative

Figure 6.9
Caption: Shoreline Trapping Space

While morphologic trapping defines the variability between sites (i.e. it is a higher order control), mobility trapping results in the differentiation between deposits within a shoreline site.

In Figure 6.9a, the schematic plot of morphologic with mobility trapping on an X-Y plane defines a "shoreline trapping space" on which can be located a number of shore types according to the extent to which morphologic or mobility trapping defines their textural and behavioural character.

In Figure 6.9b, the manner in which intra-site variability diminishes in a retentive environment is pictured schematically. The implication of this relationship is that sites with a low relative mobility have less differentiation between sediment deposits at the site i.e. less distinct fractionation.

Figure 6.9

Interactive Shoreline Controls and Shoreline Variability

Figure 6.9a

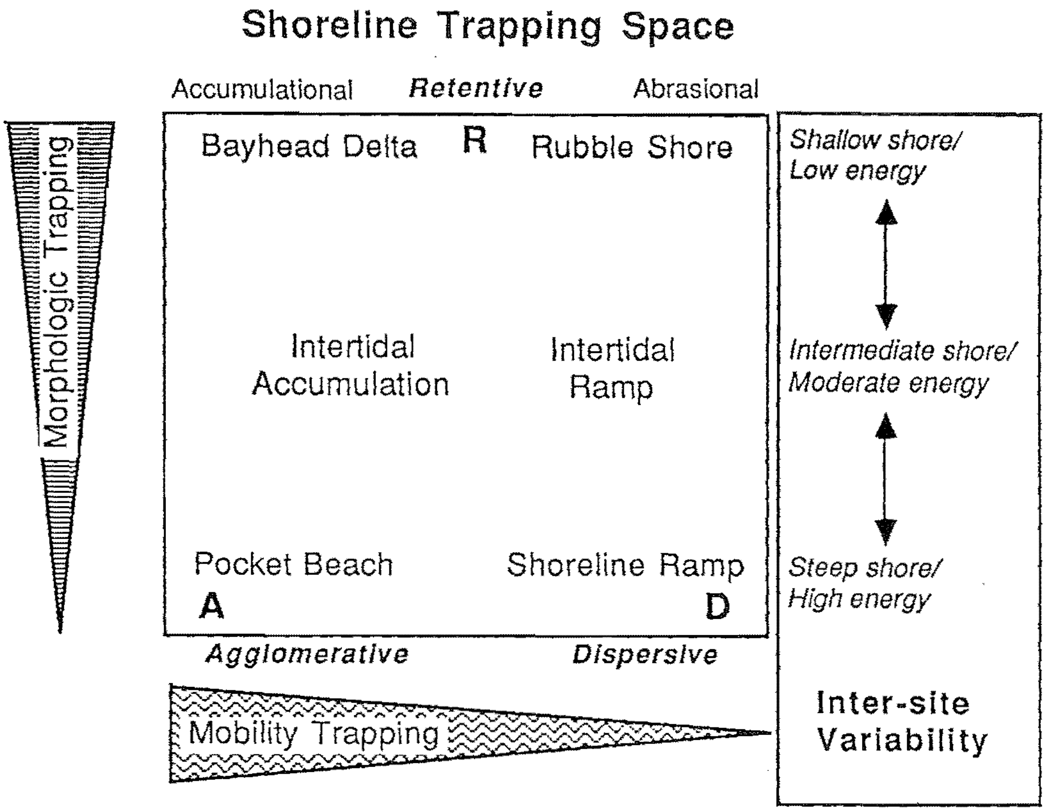
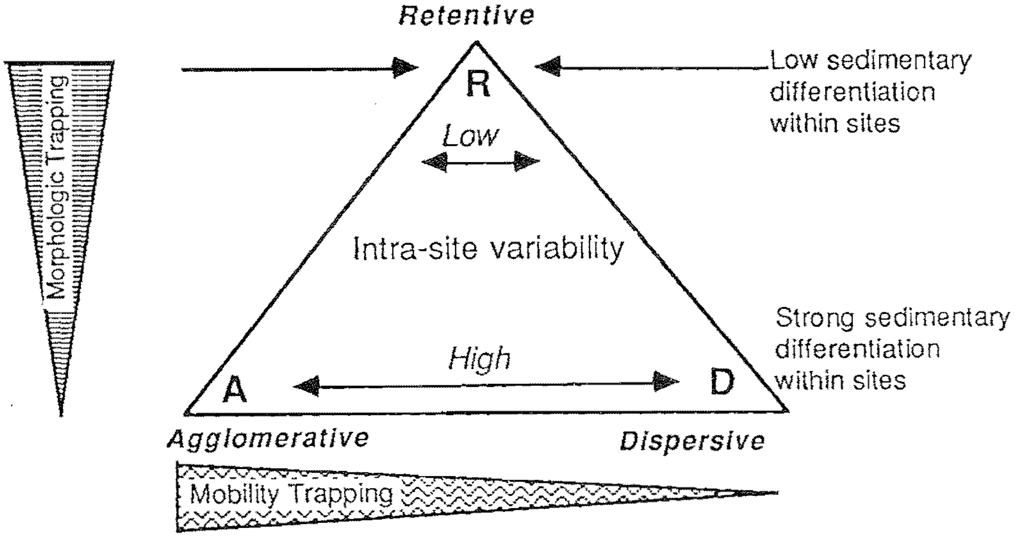


Figure 6.9b



In the retentive domain, intra-site differentiation between dispensive and agglomerative behaviour is muted, because sedimentary fractionation is constrained by the morphologic form of the shoreline environment.

apex (A) a beach is plotted. A complementarity can be recognised between the D and A apexes in that the rudimentary high water beach accumulations observed at the top of shoreline ramps represent the finer fractions eroded from the ramp surfaces.

At the intermediate levels a distinction is drawn between intertidal paved ramp surfaces and intertidal accumulations. These were shown to be the distinguishing features of shorelines of intermediate character - for example, on small bayhead deltas (Plate 6.1b and c).

Within a retentive environment the distinctions between dispersive and agglomerative behaviours become muted. The tendency for dispersion is counteracted by the tendency for retention - hence agglomerative behaviour is "forced" on the shoreline site. This leads to the conclusion that the domain of morphologic-mobility interaction is triangular, and tapering towards the retentive end of the morphologic scale, as shown in Figure 6.9b.

As noted above, the X-dimension of the shoreline trapping space leads to shoreline differentiation at the local (within-site) scale. The implication of the tapering form of the shoreline trapping space is that the scale at which shoreline variation should take place on a low-energy / low-gradient shore is smaller than would be expected on a higher mobility shore.

The utility of this schema lies in the links it establishes between the interaction between shoreline controls and their expression in terms of shoreline type. The specific nature of the linkages is now considered.

Functional Analysis of Interactions

In order to extend the analysis of coastal control beyond the descriptive association of control with observed form it is necessary to consider the specific nature of linkages between the controls acting on the system. Such an analysis was conducted in Chapter 4 and formed the basis of the Ordered Response Model.

The key distinction between the Ordered Response Model and Krumbein's Process-Response model was the introduction of two internal orders of response at which there was seen to be an increasing interdependence of control. At the first internal order the independent controls of morphology and materials were seen to interact to define a morphologic trap. At the second level the materials defined by the morphologic trap were subject to hydraulic control, giving rise to the mobility trap. The interaction between these paired interactions was seen to define the coastal response.

It is precisely these pairs of interactions which were defined above as accounting for the morphologic and the mobility continua. A brief consideration will be made of the linkages specified in the Ordered Response Model (O.R.M.) which are seen to determine these two trapping behaviours.

There are two concepts involved in these linkages.

Transitional Control

The two pairs of controls grouped at each order of the O.R.M. were morphology and materials, and materials and energy. The recognition above, that shoreline response can be seen in terms of continua between these independent controls, is an illustration of the concept which was defined in Chapter 4 as transitional control. The concept is of particular value on the low energy shore with mixed materials.

The generic behaviours on such a shore are different to those on high energy shores, or on pure sand shores. Short (1979) reviewed a range of modelling concepts for sandy, high energy beaches. The important distinction between sandy shores and the low energy mixed material shore lies in the responsiveness of shore deposits to energy conditions. Two dimensions of "unresponsiveness" are apparent: that attributable to morphologic retention; and that attributable to particle immobility.

Feedback Loops

In Chapter 5 it was shown that sedimentary trapping behaviour could be modelled by reference to feedback loops in the ordered response framework. The downward action of the arrows in the O.R.M. were regarded as the action of processes: the upward arrows (feedbacks) as the responses. For the hydraulically mobile fraction the feedback loop to the mobility trap was identified as the mechanism by which the trapping occurred. For the hydraulically immobile population, the feedback loop was from the domain of shoreline response to the morphologic trap at a higher order.

Coastal trapping behaviour was therefore defined as a feedback behaviour.

King (1970) reviewed the concepts of feedback relationships in geomorphology. Two types of feedback relationships are commonly recognised, positive and negative feedback. King defined these as follows:

> "Positive feedback results in the operating process further extending the change it has induced in the dependent variable.
> Negative feedback ... causes a self-regulating effect that reverses the change induced by the action of the process."
> (King, 1970, p147)

King noted (1970, p151-2) that amongst beach processes, feedback relationships are notably complex due to a large number of, and complex relationships amongst, the variables. King also cites a fundamental difficulty in applying feedback concepts to the longer term evolution of the coast:

> "The main reason why coastal changes can take place progressively over a long period of time is in fact a lack of feedback relationship, in that no state of dynamic equilibrium is possible." (King, 1970, p154)

To the contrary, in the framework of ordered response, it is possible to recognise that shoreline evolution takes place due to little else *but* feedback relationships - if feedbacks are recognised as operating within a broader framework.

Within the ordered response framework the linkage between shoreline behaviour and shoreline evolution can be recognised. An erosional trend in the shore is accommodated by a transfer of material from the morphologic level to the mobility trap. An accumulational trend is accommodated by the feedback loop from coastal response to the morphologic trap. This is shown in Figure 6.10a. The nature of the morphologic feedback loop must be inherently positive in its feedback behaviour. However, the overall equilibrium of the system (whether equilibrating or disequilibrating) will depend on the nested interaction between the feedbacks at the morphologic and the mobility levels.

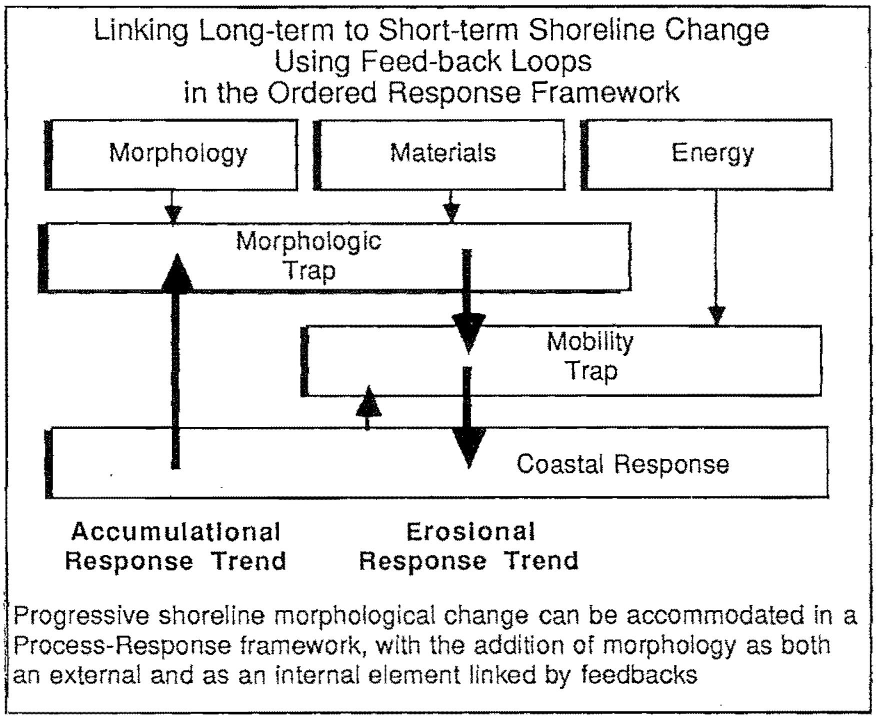
This recognition that there are two orders of control in operation, with nested feedbacks, is the central component of the ordered response framework. The nature of the nesting also involves an important extension of the concept proposed by Krumbein (1963) that the process and the deposit are "separate, though closely related aspects of shoreline phenomena", as noted in Chapter 4.

While process and deposit are closely related within the mobility trap, with the widening of the circle of feedbacks to the scale of the morphologic trap,

Figure 6.10

Interactive Shoreline Controls: The Nature of Interactions

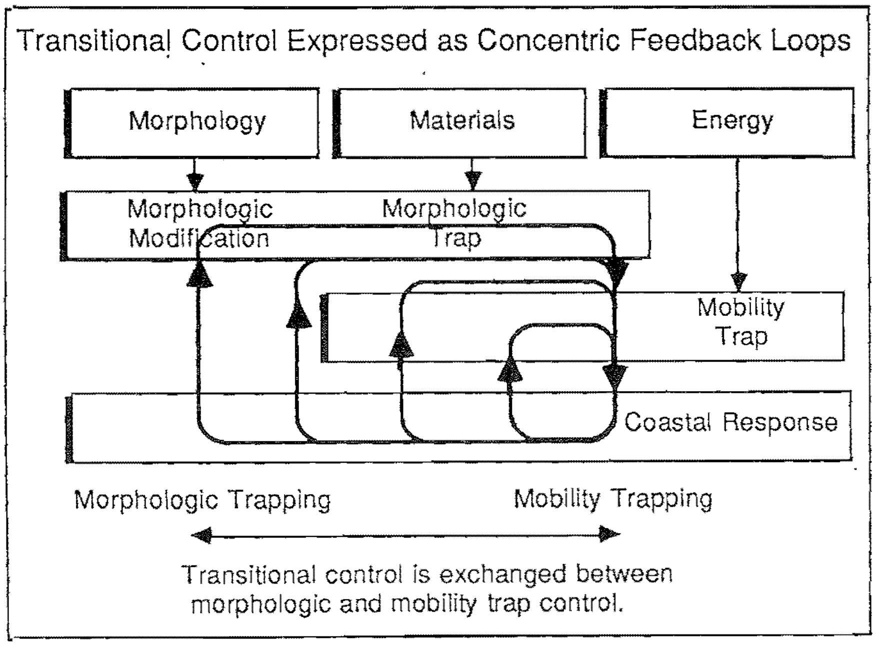
Figure 6.10a



Linking Long-term to Short-term Shoreline Change Using Feed-back Loops in the Ordered Response Framework

Progressive shoreline morphological change can be accommodated in a Process-Response framework, with the addition of morphology as both an external and as an internal element linked by feedbacks

Figure 6.10b



Transitional Control Expressed as Concentric Feedback Loops

Transitional control is exchanged between morphologic and mobility trap control.

Progressive shoreline morphological change can be accommodated in a Process-Response framework with the addition of morphology as both an external and internal element. The "internal" expressions of morphology are linked by feedbacks.

the relation between process and deposit becomes increasingly detached. This is shown schematically in Figure 6.10b.

Therefore, within a shoreline of low energy and mixed materials, not only are the processes and the deposits "separate, but closely related aspects of shoreline phenomena". The morphologic framework of the shore and the deposits are also separate but closely related aspects of shore sedimentary behaviour, but the nature of feedback between them must be regarded in a nested manner ie. at more than one order.

If this decreasing responsiveness to hydraulics is considered in terms of a transitional control departing from sediment-hydraulic interaction towards morphologic-sediment interaction, then it is apparent that the jump between the morphologic trap and the mobility trap is a progressive one.

Relative Mobility

It is possible to regard every coastal site as possessing a level of relative mobility which is the expression of the coadjustment between morphologic and mobility factors.

A condition of low relative mobility is defined by the coincidence of low energy, coarse materials and morphologic enclosure. Conversely, a condition of high relative mobility is defined by high energy, finer materials, and a rejective morphology.

The relative mobility concept extends beyond the concept of particulate mobility but refers to the broader scale expression of sediment behaviour between sites. Within a site a variety of elements may be subject to a transitional control ranging from morphologic to hydraulic control.

Relative Mobility Within Ordered Response

The outcome of the interaction of the three independent coastal controls leads to a differentiation between sedimentary materials within the shoreline domain according to their relative mobility within a given shoreline site.

Those elements which are least mobile are seen to be under the control of the morphologic trap, while the more mobile elements are controlled by the mobility trap. It is possible, therefore, to recognise that within the triangular frame of shoreline types developed earlier there are two principal planes of mobility behaviour, a static or morphologic plane, and a shoreline mobility plane. These are shown in Figure 6.11.

The Relative Mobility framework is thus a local restatement of some operational relationships of the Ordered Response Model.

There was a value shown in the first section of this chapter, and specifically in Figures 6.2 to 6.4, of distinguishing shoreline sediment accumulations from the morphologic frame upon which they develop. This is the physical expression of the morphologic plane and the shoreline mobility plane.

Identifying shoreline form within this conceptual framework has a number of useful dimensions. First, as seen in Figure 6.11, a distinction can be made between the abrasional shoreline forms (rubble shores, shoreline ramps) and the accumulational forms (intertidal accumulations, beaches).

Secondly, it illustrates the relationship between the transitional control and shoreline types. Transitional control acts between the planes. The morphologic trap controls the morphologic plane and the mobility trap the mobility frame.

Thirdly, the conceptual framework of relative mobility provides a means of visualising a number of specific shoreline behaviours which arise from the feedback loops specified in the Ordered Reponse Model.

Each linkage arrow in the O.R.M. implies a flow of control either as a process (downwards) or a response (upwards). In its empirical expression these are translated into flows of material and energy. The relative mobility framework is a semi-empirical statement of flow which lies between the entirely conceptual and the empirical expression of flow. It is through this semi-empirical statement that the model derives a practical utility.

Sediment Delivery and Shoreline Relative Mobility Behaviours

The key observation in Chapter 3 with regard to sediment delivery was the recognition that catchments delivered a wide size range of materials to the shore. In Chapter 5 an address was made to the fractionation of the finer (mobile) components of this delivered sediment, but it was shown that there were practical and conceptual difficulties in dealing with coarse materials. It was apparent, however, that immobile material was controlled under a fundamentally different regime to the mobile materials.

Figure 6.11
Caption: Relative Mobility Framework

The Relative Mobility Framework as an operational form of the Ordered Response Model.

The morphologic trap is shown to define the boundary framework within which sediment redistribution occurs. Morphologies plotted on the *Morphologic Plane* vary according to the conditions of relative mobility at the site: plotted as end members are a rubble shore and a shoreline ramp.

Materials mobile in the shore zone are seen to move on the shoreline mobility frame. In low mobility areas, materials are retained in the bayhead delta sites. With increasing mobility, sediment may be reworked into accumulations or be dispersed, depending on the conditions of mobility trapping.

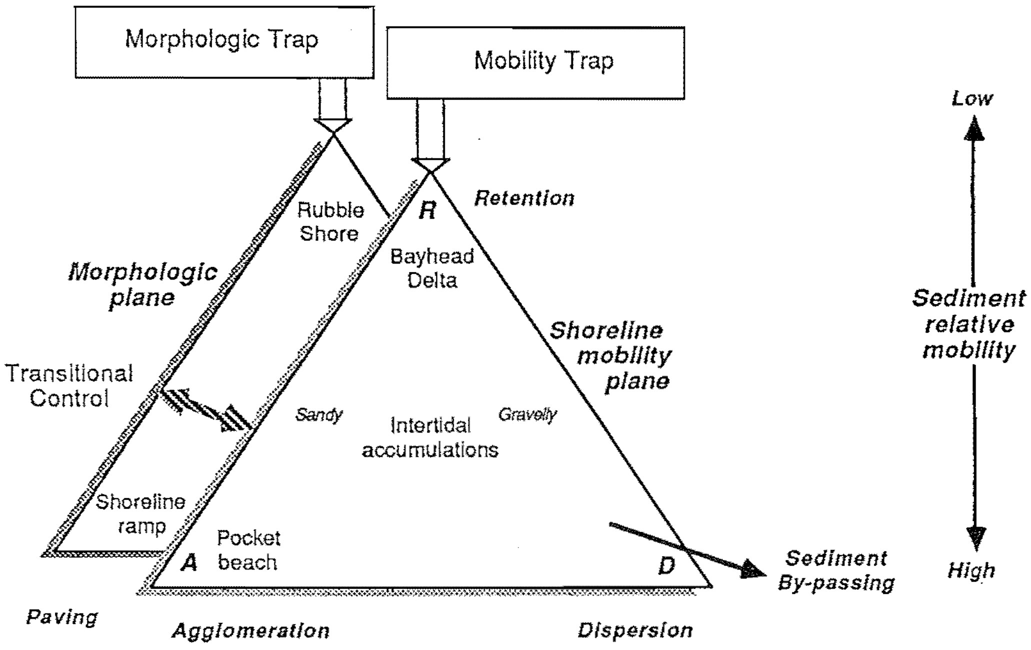
In agglomerative conditions, the material is reworked into beach accumulations. In dispersive conditions, the material is by-passed from the shore either alongshore or to the nearshore.

Figure 6.11 a and b

The Relative Mobility Framework and Shoreline Response to Sediment Delivery

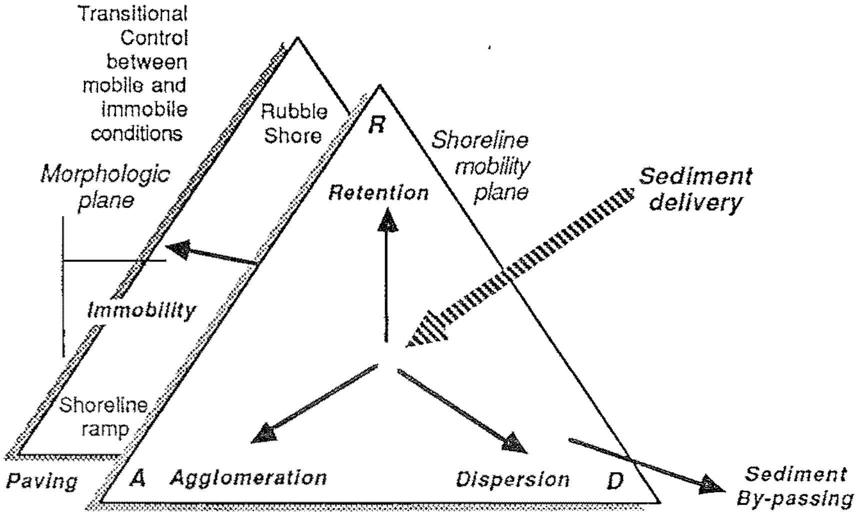
---

Relative Mobility Framework



Shoreline Response to Sediment Delivery

Five Mobility Behaviours in Response to Fractionaion



Sediment entering the shore zone is subject to one of five end-member behaviours.

1. If under low reltive mobility conditions, material is retained (R)
2. If higher relative mobility, material is either dispered (D) or it agglomerates (A), i.e. forms shoreline accumulations such as beaches.
3. If the material becomes immobile, and cannot be moved by shore processes, the material becomes subject to morphologic control and drops to the Morphologic Plane. This movement is an expression of Transitional Control.
4. If the material is so mobile that it is not subject to the shoreline Mobilty Trap, then it is forced up off the Shoreline Mobility Plane and dispersed from the shore. This is sediment by-passing.

This conceptual problem is resolved in the Relative Mobility framework. Shoreline elements under primarily morphologic control are regarded as lying at a behavioural plane below, but closely associated with, a plane which describes the shoreline elements that are mobile and, in part, under hydraulic control.

Tracing response to sediment delivery

Sediment delivered to a shoreline site can be visualised as entering at the centre of the shoreline mobility frame. From that point, there are three possible shoreline mobility behaviours to which it could be subject.

1. Retention. Sediment will be retained at the site of entry. Control is exercised by the morphologic trap and the two predisposing conditions are morphologic enclosure (low shoreline gradient) and coarse sediment.

   Such behaviour is to be expected in shallow bayhead locations and also on steep shores if the material is coarse. This is the behaviour observed in the Mahakipawa Arm which gave rise to the shoreline change associated with goldmining as described in Chapter 3. This also is the shoreline response after slippage onto the shore of coarse colluvial materials.

2. Dispersion. Sediment is dispersed from the point of entry. Control is exercised by the hydraulic conditions and the key conditions are a rejective (steep) morphology and fine sediment. This is the mechanism by which shoreline ramps develop from materials cut from backshore colluvium or from slip detritus.

3. Agglomerative response involves a migration of sediment from the point of entry. However, unlike conditions prevailing under dispersion, interparticle interactions result in the development of a collective morphological form. This collective form leads to the modification of hydraulic conditions and to the subsequent accumulation of more particles. This illustrates the operation of the mobility trap as a postive feedback between particle mobility processes and shoreline form. It is because agglomeration involves a morphologic modification of the shore on the shoreline mobility plane that agglomerative behaviour warrants a placement in the Relative Mobility schema at the "morphologic" end-point of transitional control.

Two further behaviours for the "injected" sediment can be identified. Each would move certain fractions of the delivered population out of the shoreline mobility plane: these are the end-point behaviours of shoreline relative mobility. The two behaviours are immobility and suspension. Under the former, the particles drop from the control of the shoreline mobility frame to the morphologic frame. Under the latter, the particles rise beyond the control of shoreline processes into the primary control of hydraulic processes.

This behaviour can be identified in the relative mobility framework as material exiting the shoreline mobility frame "upwards" from the dispersive apex of the plane. The modelling of fine materials is considered in Chapter 8.

The proposition was advanced in Chapter 1 that the key to understanding coastal sedimentation in the Marlborough Sounds lies in the recognition of the fate of several sedimentary fractions. Wth reference to the Relative Mobility Framework, it can be seen that the primary basis on which this fractionation takes place in the shoreline is that of *relative mobility*.

In the following chapter this framework is evaluated in the context of the processes of sedimentary fractionation which take place in a low energy shore. Given the relationships established with this framework it is to be expected that patterns of sediment mobility should be reflected in the behaviour and character of sediments on the shore.

Chapter 7

Shoreline Sediment Mobility on the Low Energy Mixed Material Shore

Shorelines which are comprised of a wide size range of sedimentary materials but which are subject to low wave energy levels are found to exhibit distinctive patterns of sediment mobility. This chapter examines these patterns and their implications for sediment fractionation.

Previous chapters have explored the relationship between sediments, their morphologic context and the hydraulic processes acting on them. It was shown that, as energy levels diminish, a transition in control can be recognised as taking place between hydraulic factors and morphologic factors as a determinant of sediment behaviour.. In Chapter 5 it was deduced that as a consequence of this transitional relationship there should arise a range of coastal behaviours which reflect primarily morphologic, primarily sedimentary or primarily hydraulic control.

Sediment texture at any site represents material delivered but not removed; consequently a sediment trapping has taken place. Sediment texture in the light of the Ordered Response Model was seen to be determined by either an immobile response (a morphologic trap) or a mobile response (mobility trap) to the prevailing controls. It was shown in Chapter 6 that these responses were part of a continuum of shore behaviour and that, as levels of shoreline sediment mobility diminish, the scale of differentiation between sites would be expected to diminish also.

The first section reviews the range of shoreline textures and identifies three shoreline sedimentary types found on the low energy mixed material shore. The second section identifies and considers the classification of a specific shoreline form associated with low-intermediate levels of relative mobility. The accumulation form is referred to as a clastic wave. The third section examines the implications of these forms for shoreline sediment fractionation.

A significant finding of this investigation has been the discovery of clastic waves. The form, texture and behaviour of the bedform has not been reported as a distinct class in the literature, but on the basis of evidence presented here would appear to warrant being considered as such. As a shoreline sedimentary behaviour it has important implications for sediment redistribution, sediment fractionation, stratification and shoreline development on the low energy tidal shore.

Sedimentary Shoreline Types

Chapter 6 identified the range of shoreline morphologies found in the Marlborough Sounds. This section resolves the sediment character of shores into three categories - rubble, ramp and agglomeration.

Shoreline Sedimentary Typology

Table 7.1 identifies three shoreline sedimentary types; the rubble surface, ramp surface, and agglomeration surface. For each category, the size, sorting and fabric of materials are specified in the first row. Fabric refers to the arrangement of the various sediment particles including the packing and orientation of clasts (Harms et al. 1982). In the second row, the origin of materials is specified; in the third some of the sediment fractionation processes associated with each.

On the shoreline a range of sediment surfaces can be identified with varying degrees of immobility. Plates 7.1a to f show images of the shoreline surface.

Rubble Shore Type

Rubble shores were defined in Chapter 6 and an example seen in Plate 6.2b. Rubble shores have an unordered fabric of poorly sorted, coarse gravel to cobbles and boulders, and a matrix of fine materials. Materials derive initially from backshore deposits, supplemented in some locations by slumping from upslope. Reworking of the deposits by waves winnows and disperses fine materials offshore but leads to only limited reorientation of the coarse materials.

Ramp Shoreline Type

Ramp shores are defined by a paved lag surface of orientated gravels overlying an unordered substrate of material derived from backshore and intertidal abrasion and possibly upslope slumping. As distinct from rubble shore surfaces ramps develop a configuration adjusted to wave conditions. Examples are seen in Plate 6.2a and Plates 7.1a to c.

Table 7.1

Sedimentary Shoreline Types

Shore Type: **Criteria**	*RUBBLE*	*RAMP*	*AGGLOMERATION*
Size / Sorting / Fabric	Unordered Fabric	Lag or paved surface unordered substrate	1) Sandy gravel a) well sorted b) poorly sorted 2) Sandy sheets 3) Muddy surfaces
Examples	*Plate 6.2b*	*Plate 6.2c*	*Plate 6.1c*
Initial Source Materials	Backshore erosion	Backshore and intertidal surface erosion	Stream deposition
Additional Source Materials	Slumping from upslope	Slumping from upslope	Intertidal redistribution Longshore and upslope
Modification of Materials (Fractionation Processes)	Winnow fines No imbrication	Winnow fines Reorient gravels Selective erosion	Intertidal migration and progressive sorting in "clastic waves"

Plate 7.1
Shoreline Sediment Surfaces

Plate 7.1a	Plate 7.1b
Plate 7.1c	Plate 7.1d
Plate 7.1e	Plate 7.1f

Plate 7.1a

Coarse lag gravel ramp surface, northern Kenepuru

Object is 200mm long

NZMS 260 P 27 GR 952 038 *Feb 1986*

Plate 7.1b

Finer lag gravel ramp surface, Waitaria Bay, Kenepuru

Object is 200mm long

NZMS 260 P 27 GR 793 047 *Feb 1986*

Plate 7.1c

Stream mouth gravel lag after flood deposition, Bythells Bay, Queen Charlotte Sound.

NZMS 260 P 27 GR 899 927 *Oct 1983*

Plate 7.1d

Intertidal gravel ramp surface adjacent Plate 7.1c

Gravel is derived from abrasion of underlying alluvial surface and from stream deposition, Bythells Bay, Queen Charlotte Sound.

NZMS 260 P 27 GR 899 927 *Oct 1983*

Plate 7.1e

Intertidal gravel-sand surface, Double Bay , Mahau

Grid Frame is 0.5 m wide, divisions are 100mm.

Coarser lag pebbles downshore of 7.1 f

NZMS 260 P 27 GR 824 942 *Aug 1986*

Plate 7.1f

Intertidal gravel-sand surface, Double Bay , Mahau

Finer gravel and sand upshore of 7.1e

NZMS 260 P 27 GR 824 942 *Aug 1986*

Plates 7.1a and b show two types of paved surface. The first has developed at a low gradient, cut from a remnant colluvial fan by scarp retreat under wave action. The surface is devoid of mobile particles and is referred to here as a paved ramp. The second was derived from the erosion of an alluvial terrace. The particles are consistently finer and better sorted. This intertidal surface is in a zone of very low wave energy, hence the particles upon the surface are relatively immobile despite a fine gravel composition which would be mobile on more exposed shores. There is a marked contrast in texture on all paved surfaces between the surface layer, 1 to 2 particles deep, and the underlying material which includes a wide range of particle sizes including finer materials.

There is a paucity of description of paved surfaces in the coastal literature, but a growing literature developing from the investigation of gravel bed rivers (Parker et al. 1982, Rákóczi, 1987). The conditions under which paving develops in a fluvial setting are identified by Rákóczi (1987, p29) as:

> "when the sediment-transporting capacity of streamflow is not sufficient to move all the available bed material."

Selective erosion processes, in which specific fractions of the surface are removed while others remain, arise from differences in the critical shear stress required to erode particles of different orientation and textures. Ultimately, a bed becomes covered by the coarsest fraction and erosion ceases. Hein and Walker (1977) report a process on gravel river beds of coarser lag gravel particles "jostling" and thus permitting the removal of the finer, underlying material. An equivalent mechanism appears to enable the intertidal ramp to be regraded to develop the characteristically uniform slopes reported in Chapter 6.

Ramp shores are a significant shoreline response of mixed-material shores to low shoreline energy. They evidence a capacity of the shoreline to self-equilibrate in spite of the low energy and low mobility. Rákóczi (1987, p35) identifies selective erosion and paving processes as part of "the natural self-regulating system of streams". By preventing excessive scour, the process helps to develop equilibrium conditions i.e. balanced flow and sediment regimes.

Newton (1977) established by tracer experiments that gravel particles on ramps could move intermittently under the largest wave conditions. Ramp development is observed on the flanks of slump lobes where they enter the sea, and

and on foreshores where a stream delivers particles coarser than the waves can ordinarily rework (e.g. gravel >100mm). Selective erosion permits a partial reworking of the material delivered until a static equilibrium is achieved. Stream-mouth intertidal ramp deposits have been observed to either break up (often in response to stream incision rather than wave reworking) or be smothered by mobile beach materials. As a consequence, stream-delta stratigraphy can include layers of imbricated coarse gravels interbedded with sand and granules.

From the viewpoint of the ordered response framework, ramp formation can be visualised as an illustration of the transitional feedback process pictured in Figure 6.10b, in which an hydraulic readjustment progresses over time to a more static adjustment under morphologic control.

Shoreline ramps and the process of their formation on low energy shorelines, warrant further investigation. Their significance in the context of this investigation is as a fate of the coarser (immobile) sedimentary fractions available at or delivered to the shore.

Agglomerational Shoreline Types

Agglomerational shore surface types refer to wave-worked beach deposits and intertidal accumulations of both mixed and sorted sands and gravel, as identified in Chapters 5 and 6.

Plates 7.1e and f illustrate the surface at two locations on a single shore. The former is comprised of a mixture of pebbles of diameters 10 to 30mm on an underlying sandy surface. The latter site lay 3m upslope and comprises a granule and fine gravel population of 2 to 10mm. Under swash action particles on these shore surfaces move up the shore leaving the coarser particles behind as a lag. However, on shorelines of intermediate to low gradient (i.e. alluvial shores and the more gently graded ramps) particles do not continue to migrate particle by particle, but collectively. This is the process of agglomeration.

There are three sub-types of agglomerative surfaces.

1. Sandy-gravel surfaces
2. Sand surfaces
3. Mud surfaces

Sandy-gravel surfaces vary in their degree of sorting.

The mechanisms of sediment redistribution on agglomerative shore surfaces lie at the centre of the functioning of the shore as a "sediment transform". Patterns of behaviour on such shores are discussed next.

Mobile Sediment Behaviours.

This section is concerned with the description, identification and classification of specific shoreline sediment mobility patterns.

Mobile Sediment Accumulations in an Immobile Frame

Plates 7.2a and 7.2b show the intertidal surface at Moenui Bay, Pelorus Sound. Tidal range is 2.4m (springs), and the material on the shore profile ranges in size from gravel (>100mm) to sand, with a mud apron at low water. The coarser gravel in Plate 7.2a is aligned parallel to the dip of the shore surface into a paved ramp, while the finer material has been reworked upslope into a beach deposit. This textural differentiation between populations of different relative mobility is characteristic of Marlborough Sounds shores. Plate 7.2b shows the intertidal accumulation of a population of finer gravels, incorporating sand, over a surface of coarser gravels. In the low energy levels prevailing, the coarser gravel population is effectively a lag ramp. The significance of the finer population on its surface is the migratory behaviour which these materials develop within the intertidal zone.

The migration of marginally more mobile populations of gravels within the shore is a collective transport phenomenon. It provides the mechanism for longshore transport in a low energy shoreline where lag surfaces predominate (i.e. there are few continuous strand shores). Predominantly, the transport is directly upslope and is the means by which beach deposits accumulate. This pattern of transport is also central to a recognition of shoreline distribution of material delivered to the shore from catchment sources and to the processes of shoreline sediment fractionation.

Intertidal "Clastic Wave" Accumulations

The term "clastic wave" defines an intertidal gravel-sand accumulation which exhibits a pattern of up-shore or along-shore migration in response to wave action.

Clastic waves develop on shores of intermediate to shallow gradient (<1:10, usually <1:20), with surfaces of ramp or agglomerative type. In all cases, they

Plate 7.2
Intertidal Surface, Moenui, Pelorus Sound

Plate 7.2a

Intertidal zonation of gravel lag ramp overlaindownslope with a mud apron and upslope with a mixed sand and gravel beach accumulation.

NZMS 260 P 27 GR 768 918

Apr 1985

Plate 7.2b

Site adjacent to tripod in Plate 7.2a.

Intertidal gravel and sand accumulations differentiated from coarser underlying material. Finer populations evidence migratory behaviour upshore under swash action.

This collective transport mechanism isthe principal mode of intertidal sediment transport on these shores which comprise largely immobile sediment fractions.

Apr 1985

develop only where there is an initial feedstock of sand-gravel material. The size range of material varies according to incident wave energy levels, but clastic wave forms have not been observed with materials over 40mm (intermediate axis) nor on surfaces without gravel content.

As will be shown, the widespread distribution of clastic waves within the Marlborough Sounds, together with this distinctive sediment texture, morphologies and dynamics are such as to warrant recognition of the feature as a separate defined class of sedimentary bedform.

Figure 7.1 shows sequential beach profiles surveyed on a transect at Bythells Bay, Queen Charlotte Sound at 6 monthly intervals. The profile location is in the background of Plate 6.2c. A nomenclature based on that developed by Allen (1970) for ripple forms is given in Figure 7.2.

Three morphologic units in the profile are first, the beach extending from high water to 0.5m below MHWS; secondly, a more gently sloping shore component at the foot of the beach; and thirdly, a migrating intertidal accumulation.

The difference in elevation of the crest to the trough varied from 280mm to 330mm. As the form migrated up-beach, there was an accompanying trend of combing down of the fore-slope. Morphologic changes involved primarily the redistribution of material within the clastic wave. The distances of crest migration between surveys in each of the first three intervening periods were 2.5m, 4.4m and 2.3m respectively. These equate to rates of 0.38m/month, 0.73m/month and 0.46m/month, and a mean rate of 0.58m/month (2cm/day). A range in bar heights from 0.05m to over 0.5m have been surveyed. Rates of migration measured at other sites vary from months of no migration, to rates over 12m/month.

Migratory shore forms on the intertidal surface of this form are the most distinctive intertidal accumulational morphology on the shoreline of the Marlborough Sounds. Examples have been seen in Plate 6.1b and in the Frontispiece Plate 1.

Characteristics of clastic waves, in relation to the classification of shoreforms, and the justification for their deserving separate classification are considered next.

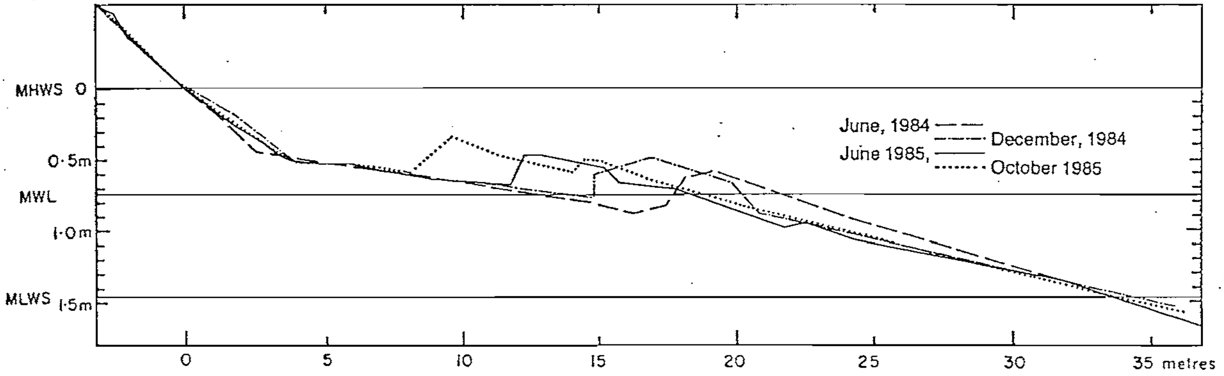
Figure 7.1 and 7.2

Shore Profiles: Example and Nomenclature

Figure 7.1 Bythells Bay, Sequential Beach Profiles

Shore profile resurveyed four times at 6 monthly intevals shows migration up beach of intertidal gravel-sand accumulations, named here "clastic waves".

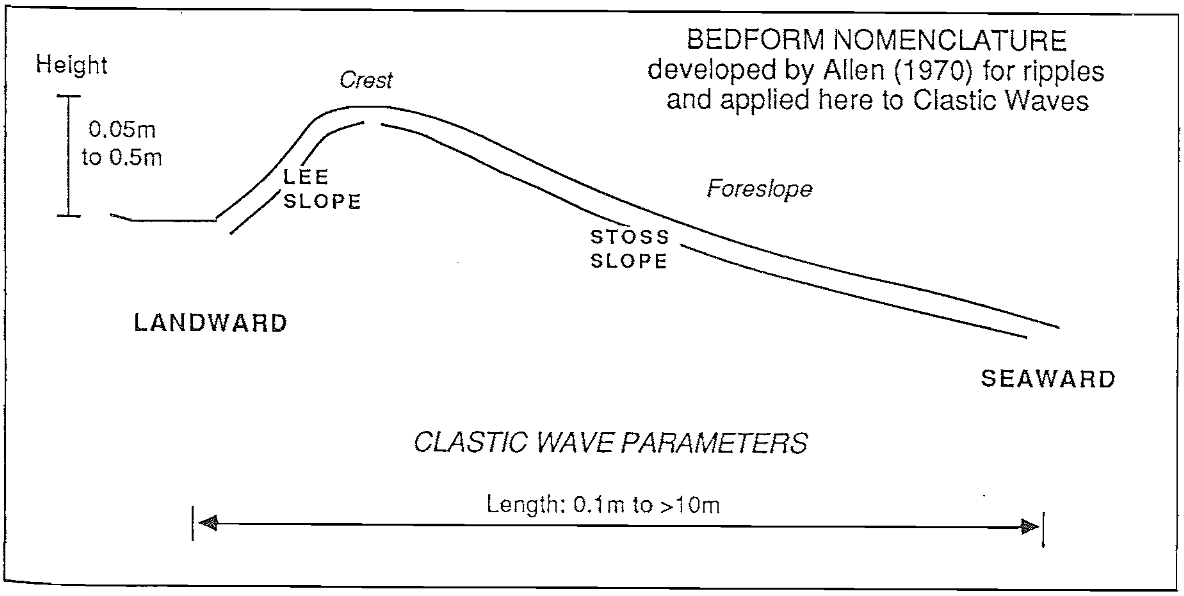
Figure 7 Sequential Beach Profiles, Bythells Bay



V.E. = 5x
NZMS 260 P 27 GR 938 927
Survey Profile 70m east of jetty, parallel to jetty seawards from berm. Location peg west end of concrete pipe in dinghy cradle.

Figure 7.2 Nomenclature of Intertidal Shore Forms "Clastic Waves"

Adapted from Allen (1970), applied here to mixed sand and gravel materials



Shore Form Classification and Clastic Waves

The definition of coastal bedforms is confused by a large number of classifications and lack of clear distinctions between them. The term "bar" is widely used as a general morphologic description, but as shore forms include many features which are not bar-like, its use is often inappropriate.

Greenwood and Davidson-Arnott (1979) reviewed a range of classifications for wave-formed "bars". They note the lack of standard nomenclature and a number of descriptive problems in the literature. Noted is the use of transverse profiles without reference to three dimensional form and the failure to record or present environmental data on wave climate, tidal range, sediment size and beach slope. Most significant is the failure to distinguish between different bar types and different processes controlling their formation.

In the following discussion of classification three factors are highlighted: processes controlling formation, size and location; and sediment composition. Wave climate tidal parameters were identified in Chapter 6.

Table 7.2 lists a number of coastal shoreform types, as identified by a range of authors. Also noted are the principal controls acting to form each, notes on distinguishing features and indices used within each class. The intention here is not to develop a further classification schema but to identify the appropriate descriptive indices for clastic wave forms.

Classification by Processes of Formation

The principal distinction is drawn between wave-formed bars (dependent on wave oscillatory currents and secondary wave-generated currents) and bars formed by tidal currents. This distinction was highlighted by Greenwood and Davidson-Arnott (1979, p313). They noted:

> "While reflecting bed deformation at the boundary between fluid and sediment, [wave-formed bars] cannot be analysed in the same way as true bedforms (i.e. in a flow regime framework) even though the larger forms of the latter may be very similar."

The first class of shore forms in Table 7.2, the "sand waves" in Allen's (1970) nomenclature, are true bedforms developed by tidal currents and are

Table 7.2

Shoreline Sediment Bedform: Notes on Classification Schema

Process of formation:

Tidal Currents	Control	Indices, notes
Allen, 1970 "sand waves"	Tidal currents Flow regime theory	L/H vertical form index Length measured perpendicular to crest

Waves and Swash	Location	Indices, notes
Greenwood and Davidson-Arnott 1970		
I Ridge and Runnel	intertidal	stationary
II Cusp or bar type sand wave	intertidal to low tide terrace	Form on low tide terrace and and migrate onto swash slope.
Sonu (1968)		Parallel to shoreline
Bar type sand wave		Sand, migrating
III Multiple parallel (Zenkovich, 1967)	nearshore and intertidal	Multiple (4-10)
IV Transverse bars	nearshore and intertidal	Oriented normal to shore

amenable to a description by flow regime theory. The key index of this theory is the vertical form Index (L/H) where wave length is measured perpendicular to the crestline and wave height (H) is measured from crest to trough.

The vertical form index (Allen, 1970) is not applicable to wave formed shore forms, because the processes of formation under tidal flow are fundamentally different from those under waves.

Classification by Size and Location

Allen (1970) distinguished "second order" from "third order" shoreline forms.

> "Counting the beach and nearby offshore as first-order morphological elements, the longshore and transverse bars ... constitute second-order sedimentary structures, which in their turn are associated with still smaller, third-order forms, for example tide shaped dunes in longshore troughs, current ripples, and wave ripples."

Allen (1970) further noted that distinction between orders can be blurred. Clastic waves are the only significant intertidal shoreform on Sounds shorelines, and thus are a small second-order form.

Greenwood and Davidson-Arnott (1979) distinguish wave-formed bars which develop in the nearshore and in the intertidal zone.

Clastic waves are intertidal forms. There are four categories identified by Greenwood and Davidson-Arnott as being on found on some occasions in the intertidal zone. These are specified in Table 7.2.

Category IV, transverse bars are orientated normal to the shoreline and thus unlike clastic waves. Category III, Multiple parallel bars are unlike clastic waves in that while more than one line of clastic waves may be found on some beaches, the regular spacing as identified by Zenkovich (1967) is not evident. Category I, ridge and runnel forms are defined as being static, non-migrating forms, and therefore unlike clastic waves.

Category II, cusp or bar type sand waves (Sonu, 1968) are defined by Greenwood and Davidson-Arnott (1979) as having heights of 0.2 to 1.5m, longshore extents of 10^2m, and they develop under breakers and surf-swash. Of the latter categories of wave-formed bars these are the closest to the clastic wave form.

The two sand wave types of Sonu (1968) differred significantly. Cusp-type sand waves were interpreted as being controlled by tidal currents and are aligned oblique to the shoreline. These are not wave-formed. Bar-type sand waves move only in the onshore direction and are most like barchan dunes as identified by Bagnold (1941), with an assymetrical profile of a steep front slope and a gentle nearslope. Bagnold (1947) also described the mechanism of migration in bars akin to that of the clastic wave:

> "Moving with the slowly advancing bar, the sand composing it must move over and backwards through it in just the same way as that of a wind-blown barchan dune".

Classification by Materials

None of the classifications referred to above mentions forms developing in materials other than sand. Clastic waves are of a mixed sand and gravel composition. Allen (1970) and Harms et al. (1982) noted that bed forms in mixed materials are not commonly reported and are dynamically different to sand bedforms. The physical origin of the difference stems from the relative dominance of sliding and rolling in gravel-sized particles over saltation and suspension in sands (Novak, 1973).

Clastic waves warrant further, focussed investigation of their particle migratory behaviour. However, exploratory observations show that rolling, sliding and limited suspension are dominant transport processes, both at the stage of initial development and subsequent migration (discussed below). These are swash-zone processes. By contrast, Sonu's (1968) classification of sand waves defined them as originating below low water due to the convergence of wave oscillatory currents, leading to the "sweeping together" of groups of particles. The initiation of clastic waves begins within interparticle interaction during up beach movement.

Until further evidence is gathered, there are good reasons to distinguish mixed sand and gravel shore forms from sand waves. The term clastic wave has been adopted as a suitable name.

Clastic Waves Undescribed

Reineck and Singh (1980, p368) make only one reference to shoreline bedforms comprised of gravel-sized material. The reference is to Hobday and Banks (1971) in a brief paper describing "landward migrating swash bars" on a pocket beach in Tanafjord, Norway. However, other than identifying the existence of the "bars", that they migrate, and that within them there is sorting by shape, the authors do not make reference to their mechanism of formation nor migration. Shape sorting does not appear to be a significant mechanism in the development of clastic waves although the differences in mobility between particles may be an expression in some cases of shape differences.

Boyce (1981) completed the first sedimentary shoreline investigation conducted in the Sounds. A survey of ten bay-head deltas in the inner Queen Charlotte and Mahau Sounds identified three shoreline morphologic elements: the landward (high water) beach, the intertidal surface, and intertidal accumulation. However, rather than identifying the clastic wave form as a migratory intertidal feature, Boyce referred to it (p92) as a "low tide bar".

> "At the approximate low tide level there is a steep rise in the sediment surface of 11 to 22 inches [0.28-0.56m]. The surface of the deposit, or bar, then slopes seawards at a greater angle than the inter-tidal slope profile. This slope is usually 3-4°. The size of the sediments, and improved sorting values [compared to the inter-tidal surface landward] indicate that the sediments of the bar deposits are very similar to those of the upper beach. The bar is generally lobate landwards. It has a certain degree of permanence in that residents claim that changes in the bar form are very infrequent, and usually associated with stream flooding." (Boyce, 1971, p92).

Clastic waves are as frequently found in the mid tidal zone as the lower-tidal zone. The form which Boyce describes, with a steep seaward face and a shallow landward face, is also not commonly found today. However, he presented photographic evidence of the veracity of his observations (Plate7.3c). The form is at Aussie Bay, Queen Charlotte Sound. Clastic wave forms on the beach there today are mid, rather than low tidal. This suggests that at the time of Boyces observations, the recent delivery of sediment to the shore (perhaps from a high rainfall event) led to a different pattern of sediment accumulation than is seen today.

Newton (1977) is the only other shoreline investigation completed in the Sounds, and was confined to the Tory Channel. Newton made reference to two aspects of intertidal accumulations. The first related to sweep-zone changes on repeatedly surveyed profiles of bayhead deltas.

> "Two areas of maximum sweep zone change were found, one on the foreshore proper, and a second at the outer extension of the fluvially deposited material. In effect, a second foreshore is formed at an elevation

> lower than, and at some distance from, the foreshore proper. Wave action tends to accentuate this outer area until it develops a ridge higher than the flattish area immediately onshore of it."

On two of the profiles, support for the hypothesis was cited as

> "A 10 to 15cm sweep zone was evident over the 10m extent of the foreshore and 8m lower foreshore. The 20m area between the two was not significantly altered. Volumes of change were not large on these deposits, and those which occurred appear to be a result of fluvial action, rather than of wave processes. Small fans of unconsolidated material were observed after periods of flood. These were gradually redistributed by wave action."
> (Newton, 1977, p180).

Newton's assessment of intertidal deposits as essentially low tide beaches accords with that of Boyce (1971); but Newton's reference to the redistribution of sediment fans more closely accords with the interpretation given here to all the intertidal deposits which are wave-worked, as being migrating "clastic waves".

Clastic Waves and Sediment Fractionation

While the morphologies of clastic waves are distinctive and the mechanisms of their migration warrant further investigation their relevance to this investigation is as a part of the "sediment transform" which was defined as one function of the shore. This section considers the role, mechanism and significance of sediment fractionation in clastic waves and related deposits.

Collective Sediment Transport Mechanisms

The analysis of sediment dispersal processes in the manner identified by Inman (1949) in terms of a progressive sorting mechanism referred to in Chapter 5, treats individual particle motions as if they were independent. Fine (mobile) grains should move ahead while coarser particles should lag behind. The recognition of collective sediment transport mechanisms acting in the shore zone casts the interpretation of sediment dynamics in a different light.

Sonu (1969) observed bar-type sand waves with a morphologic similarity to clastic waves (although larger) migrating at over 1m/hr onto the beach face. The significance of the migration was in terms of the addition of a pulse of material to the shore. Sonu (1969, p376) noted that bars have

> "a relatively obscure trough and a prominent crest, therefore they bore a resemblance to a solitary wave."

Because of this solitary wave form, the length/height ratio of the bar-type sand waves could not be determined; nor can that of clastic waves be with any meaning. The clastic wave form, as seen in Figure 7.1, has the translatory property of a solitary wave as noted by Sonu, which leads to its containing a substantial volume of material. The migratory volume of the clastic wave in Figure 7.1 had a mean of 2.1m^3/m. As can be seen, this volume exceeds the volume of sweep zone changes on the beach profile or at other locations on the profile by an order of magnitude.

Sediment Modification in Clastic Waves

Pre-conditions

Clastic waves develop initially on intertidal surfaces. As noted above, the precondition for development is a feedstock of mobile sediment.

Intertidal sediment surfaces vary in relative mobility in two ways. Ramp shores become immobile largely due to grain inertia, but also from particle orientation and grain sheltering (Plate7.1c). Alluvial shores which contain a high sand content (and some fine materials) develop a surface texture in which pebbles become sand-matrix-supported. An hydraulically smoother surface develops with a higher erosion threshold. Such surfaces are typical on alluvial foreshores. Neither of these surfaces, ramp or sand-smoothed, yield an abundant feedstock for clastic waves.

The feedstock for most clastic waves is therefore deposition from streams in the intertidal surface. Three patterns of intertidal streamflow and deposition are observed. The first is stream-mouth deposition. Coarser clasts (>100mm) are deposited immediately with the reduction in flow. This is reflected in the formation of gravelly surfaces which develop into paving in the upper shore area adjacent to larger streams. This pattern can be seen in Plate 7.1c. This is seen in the plan view of Momorangi Bay in Figure 7.3. Second, sediments are deposited across the intertidal surface in the form of a "diffuse gravel sheet" (Hein and Walker, 1979). During highest flow and at intermediate tide stages, the majority of streamload tends to be "dumped" in an unsorted deposit at the water line.

The third pattern of intertidal streamflow involves incision into the surface either of fresh alluvial deposits or the antecedent alluvial/delta deposit resulting in the incised stream channel referred to in Figure 7.1c and visible in

Figure 7.3 and 7.4

Shore Plan View:
Distribution and Nomenclature of "Clastic Waves"

Figure 7.3 Momorangi Bay, Intertidal Surface

Shoreline map prepared by theodolite.
Scale 1:500

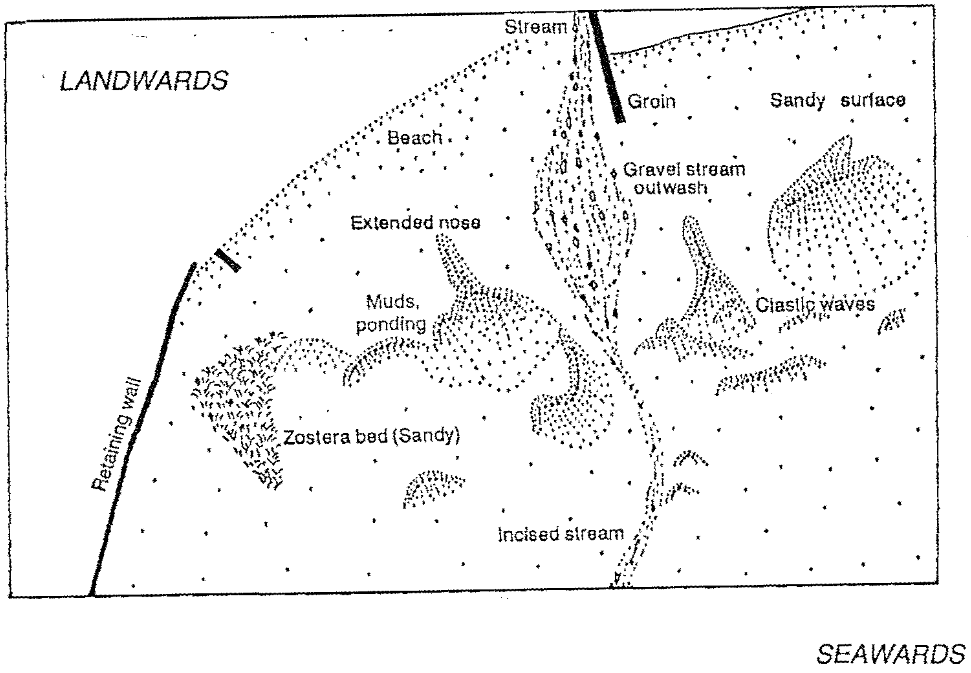


Figure 7.4 Form and Texture of "Clastic Waves"

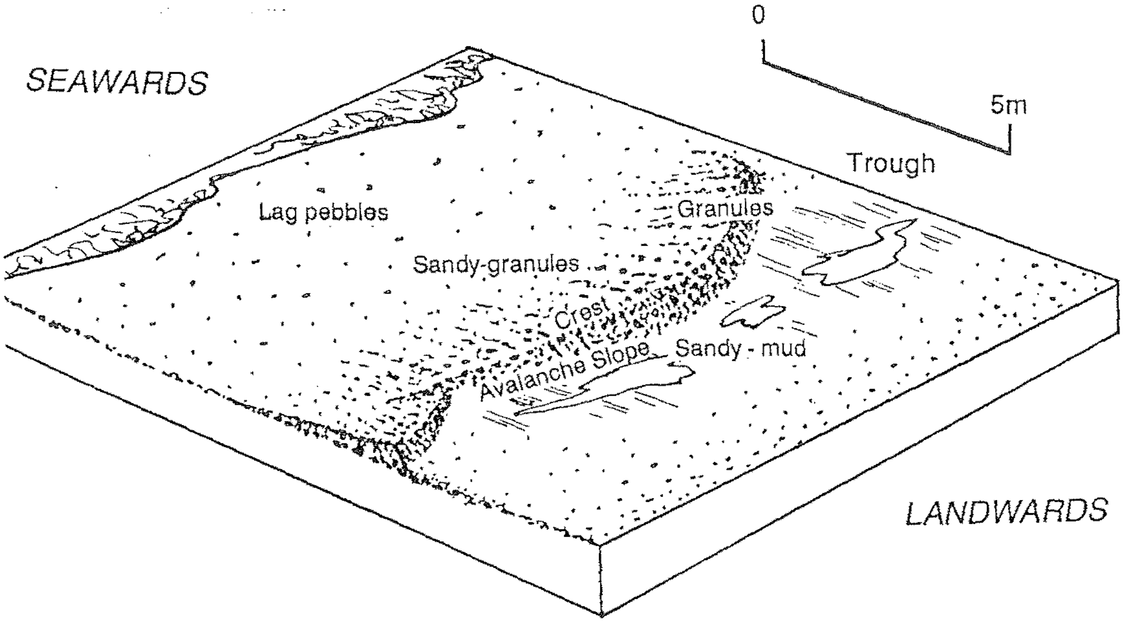


Plate 7.2d. When streams incise they redistribute intertidal material down the shore, and usually to low water. During reincision fine fractions are winnowed and swept into the nearshore.

Initiation of Transport and Agglomeration

The particle migration processes which lead to clastic wave development are observed to begin with the formation of "particle clusters" (Allen, 1970), comprising one or more larger particles and a number of smaller ones in the lee and backed up on the stoss. These become the nuclei for agglomeration. A small clastic wave building at low water can be seen in Plate 7.3a. The staff scale is 1.4m.

The processes of agglomeration can be viewed as a kinematic process, (Richards, 1982), in which differences in particle migration rates lead to mutual interference. Three key factors in this process are the mixed range of particle sizes, the low energy levels, and tidal translocation of the zone of wave working accross the shore.

Mixed particle sizes and low energy mean that different particle transport rates occur, leading to interparticle interference and the origin of kinematic behaviour (Richards, 1982). Low and variable energy also means that the clastic waves are a lag morphology, as has been recognised in many bar forms (Greenwood and Davidson-Arnott, 1979) i.e. they persist for a period after the processes responsible for their formation have ceased to operate.

Migration and Sediment Modification

As was shown in Chapter 6 the tidal translocation of the zone of wave work across the shore is an important control on morphology in the low energy shore. It would appear to be this factor which is a key determinant of clastic wave development. Rates of migration across the intertidal surface by the wave-swash system will tend to "drown" clastic waves on most shores before significant reworking takes place.

Migration takes place by the transport of sediment from the foreshore over the crest to the lee. In the lee, sandy mud deposits are common and are developed by diverted stream drainage and by the trapping of material migrating up the foreslope.

Plate 7.3
Clastic Waves on Intertidal Surfaces

Plate 7.3a

Emergent clastic wave on the lower intertidal shore at Aussie Bay, Queen Charlotte Sound. Staff scale is 1.4m.

Initial development of clastic wave form requires an supply of fine gravel, usually including a sand fraction. The distribution of clastic wave form around stream mouths indicates the importance of sediment supply in their formation.

Waves rework the crest material, which becomes increasingly well sorted. Improved sorting leads to increased permeability of the crest area, which promotes steepening of the crest slope as swash pushes material up beach, but infiltration of water into the beach diminishes back rush. The steepening of the foreslope accentuates wave reworking, and the clastic wave develops.

Refraction of small water waves around the forms can be seen in the plate. This refraction redistributes sediment from the flanks towards the nose. Hence, as they migrate, clastic waves tend to become more "Nasal".

NZMS 260 P 27 GR 878 923

April 1985

Plate 7.3b

Clastic waves on the intertidal surface, Ngakuta Bay. Staff scale is 1.4m.

A series of clastic waves demonstrate the "piggy-back" development in which a rejuvenation of transport on the foreslope (seaward side) of a clastic wave may occur with wave working as the water-line migrates across the shore.

The clastic wave furthest up the shore has begun to develop the "nasal" form referred to in the caption above, which is due to swash transport acting on the flanks of the clastic waves.

NZMS 260 P 27 GR 906 923

Jan 1985

Plate 7.3c

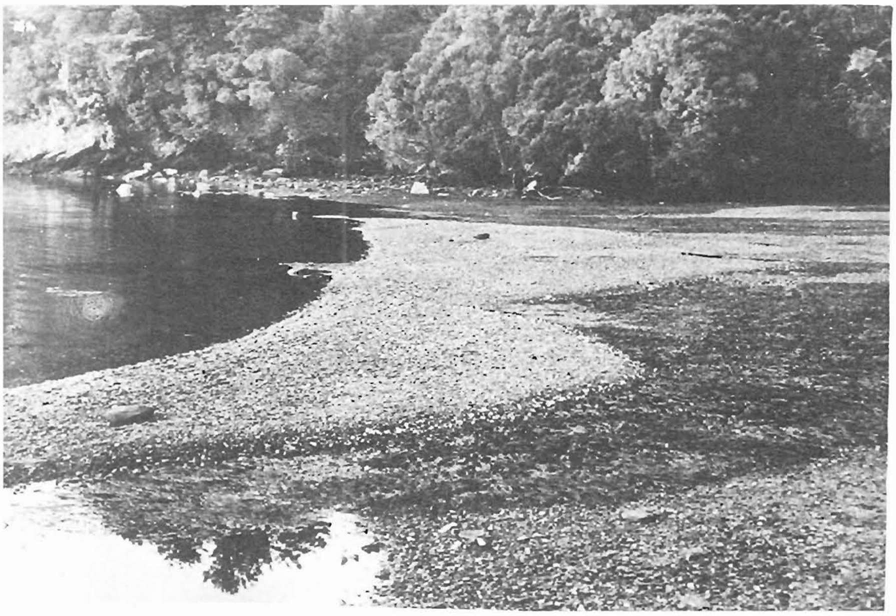
Clastic wave at Aussie Bay, 1971 (from *Boyce, 1971*).

The distinctive fetaure of the clastic wave in this plate is the steep seaward face and the more gentle landward gradient. Such a form of the clastic wave can be observed only under exceptional conditions- after storm reworking of a previously developed clastic wave. In this situation, of wave *suppression* , the crest material is swept landwards into the trough.

The characteristic form of a clastic wave can be seen in Fronticepiece Plate 1, with a gentle seaward slope and a steep landward avalanche face (see Figure 7.1-7.4).

NZMS 260 P 27 GR 878 923

From Boyce, 1971



Wave working on the foreslope of clastic waves leads to the suspension of finer materials and their transport seawards coincident with the migration upslope of the finer gravels and coarse sands. Three textural zones on the clastic wave are labelled in the block diagram Figure 7.4. These are a zone of granules at the crest, sand-granules on the upper foreslope, and lag pebbles at the foot of the foreslope.

This pattern of local sediment sorting is apparent even on shallow clastic waves i.e.clastic wave heights less than 100mm. Plate 7.3b shows a series of clastic waves on the lowest intertidal surfaces at Ngakuta Bay. The staff is 1.4m long. The height of the highest wave is 0.35m above the trough in the foreground.

Sediment grain-size patterns are shown on Ngakuta Bay clastic waves in Figures 7.5a and b. Each plot shows the pattern of grain-size sorting which takes place between the foreslope and the crestal position. In Figure 7.5a the crest sediments from two clastic waves are compared to the sediments on their foreslope (seaward) side. The much higher proportion of sand in the foreslope samples is apparent. In Figure 7.5b three samples from the same clastic wave were taken, the foreslope, the crest and the avalanche slope. The grain-size patterns show a complementarity between the lee-slope (avalanche face) and the foreslope sediments.

This pattern of grain-size sorting within clastic waves can be widely observed. Figure 7.6a shows size curves of a suite of samples from Double Bay, Mahau Sound. Notable in these samples is the bimodality (fine sand, coarse sand) of the foreslope population. In this site the stream meanders widely across the shore surface. This adds a sand population. The migration of the clastic waves leads to a small scale type of progressive sorting, the patterns of which can be seen in Figure 7.6a.

Once clastic waves build, they modify the water wave refraction patterns about them. This can be seen in Plate 7.3a. An outcome of this refraction, if ongoing, is the extension of the nose of the wave. Such a pattern is drawn in Figure 7.3. On the mid left of the drawing a long narrow lobe extends landward. In Figure 7.6b is shown a series of grain-size curves of samples from this feature.

The crest population identified was sampled from the crestline of the broader feature. The lobe samples were drawn from the surface, mid way down

Figure 7.5

Sediment Modification in Clastic Waves
Ngakuta Bay

Figure 7.5a

Two pairs of samples of intertidal accumulations. "Crest" samples from clastic waves are well sorted, with markedly less sand in the fine limb than is found in samples seaward down the foreslope. Distance between crest and foreslope samples not more than 5m.

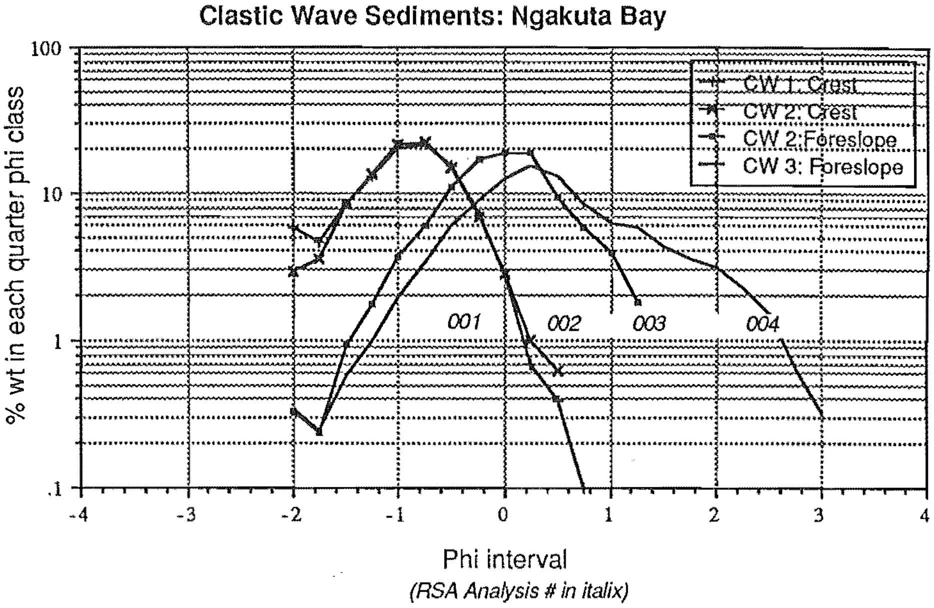


Figure 7.5b

A different suite of samples from clastic waves forms shows a similar pattern of increasing sorting "up-shore". Avalanche slope sediment lack fine-limb material. As waves wash over the clastic waves, finer sands are lifted in suspension forward into the trough. Only the coarser fraction moving by traction are rolled down the avalanche slope.

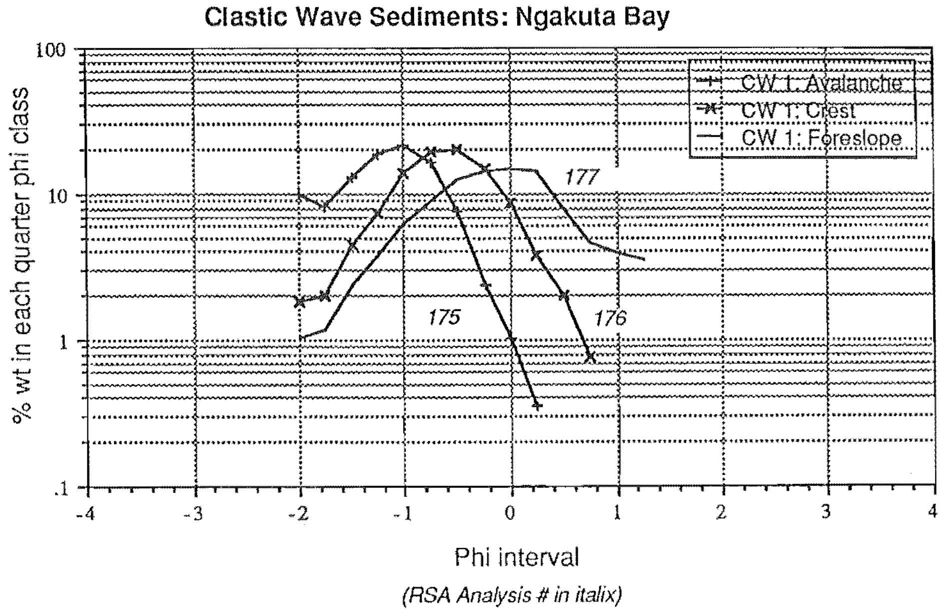
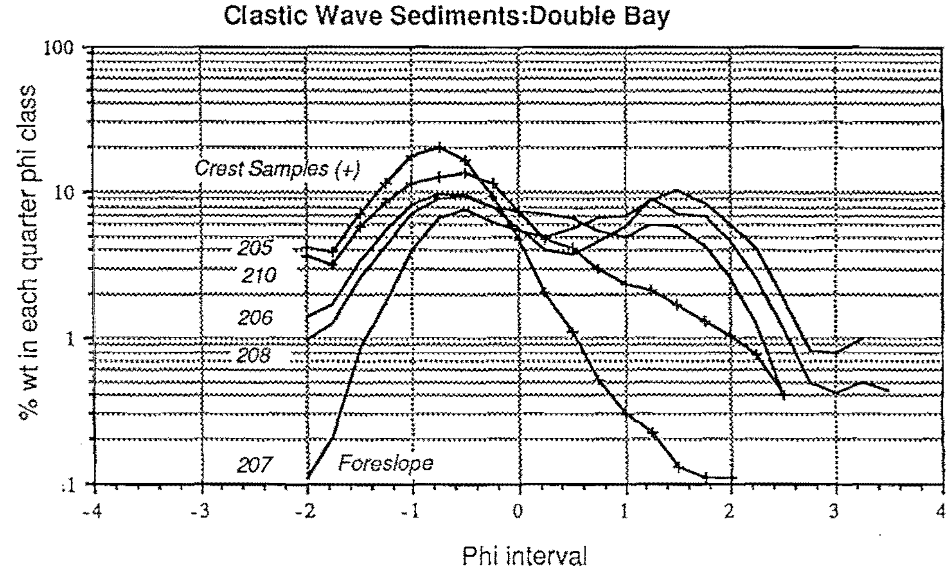


Figure 7.6

Clastic Waves Sediments
Double Bay and Momorangi Bay

Figure 7.6a

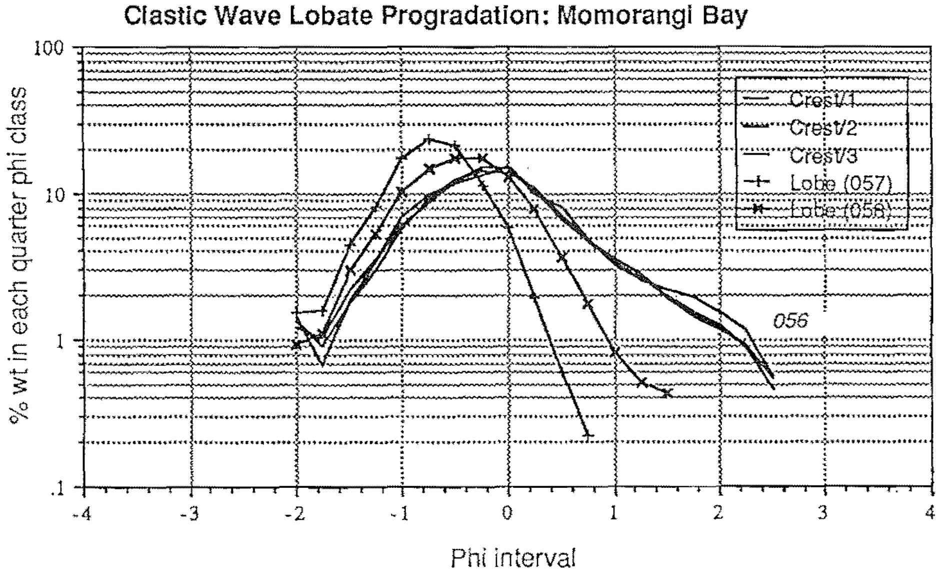
Bimodal sediment distributions on the intertidal surface, Double Bay, Mahau. Sand in samples relates to additions of finer sediments by stream meandering across the intertidal surface. Modification of sediment grain-size curves to a unimodal form can be seen in clastic wave crest samples, illustrating small-scale "progressive sorting".


Clastic Wave Sediments:Double Bay

(RSA Analysis # in Italix)

Figure 7.6b

Progressive sorting illustrated along prograding (migrating) "nose" lobe of clastic wave labeled "extended nose" in Figure 7.3.
Sand fractions become progressively reworked from intertidal deposits by an interaction of mobility and permeability factors.


Clastic Wave Lobate Progradation: Momorangi Bay

(RSA Analysis # in Italix)

the lobe and at the distal end. The progressive winnowing of the sand fraction is apparent.

The significance of these changes is both morphologic and textural. With increasing sorting at the wave crest the surface becomes more permeable. There is an associated increase in foreslope gradient towards that of a beach (see Chapter 5). The textural significance is that across the clastic wave a grain-size fractionation takes place.

An interesting pattern of cycles and feedbacks between migration, crestal steepening and wave processes can be observed. In moderate to low wave conditions, sorting of the upper foreslope takes place, with an associated steepening of foreslope gradient. As the tide level rises, translatory water flow over the crest leads to particle migration, which then avalanche down the lee slope. However, under higher wave conditions, deeper disturbance of the surface by waves leads to a mobilsiation of underlying sands. The crestal area becomes flattened and the toe of the lee face migrates into the trough. With a return to lower energy conditions, a second "piggy-back" clastic wave develops on the upper foreslope, which begins to become sorted. Material is added from down the foreslope, and the wave building begins again.

The Outcome of Fractionation

Figure 7.7a shows the contrast in grain-size between the beach deposit in Figure 7.1 and the clastic wave 1 metre seaward of the crest. Samples were taken in December, 1984, when the shore was surveyed. The contrast between the clastic wave and the beach with respect to sorting is apparent.

This pattern is general. 105 samples from beaches and clastic waves in the Grove Arm, in Double Bay, Mahau and in Lochmara Bay were subject to size analysis. The overall sediment character of samples was reviewed in Chapter 5. In a plot of percent sand against sorting in Figure 7.7b, a clear distinction emerges between the sorting on clastic waves and the sorting on beaches. Of the 58 beach samples, 68% are well or very well sorted, while only 12% of 47 clastic wave samples show the same.

Figure 7.7

Clastic Waves and Beach Sediments Contrasted Bythells Bay and Summary Plot

---

Figure 7.7a

- Sediment patterns in beach and near crest of clastic wave plotted in Figure 7.1. and sampled December 1984. The contrast between the beach sample and the clastic wave is alike that between the crest of the clastic wave and the foreslope - improving sorting.

Clastic waves migrate onto beaches, progressively sorting as they migrate.

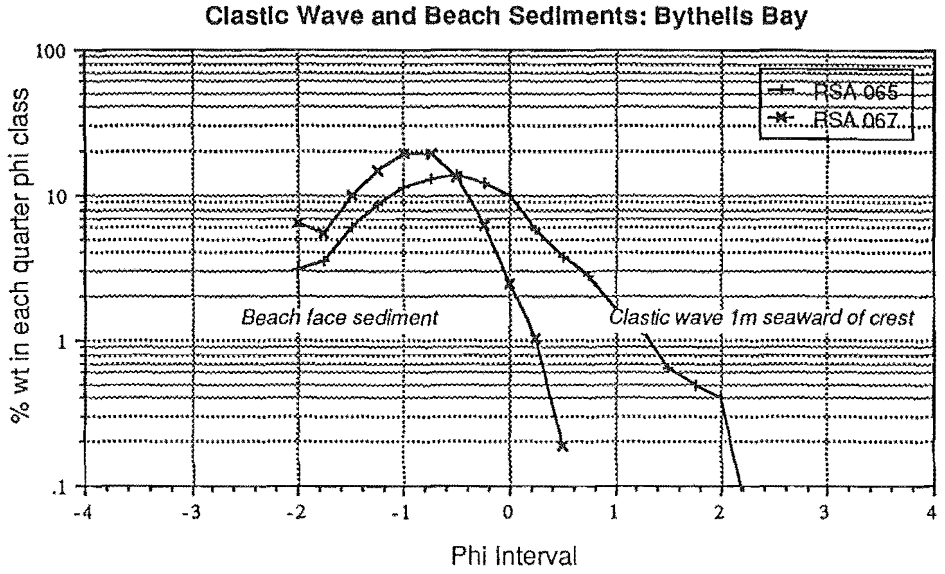
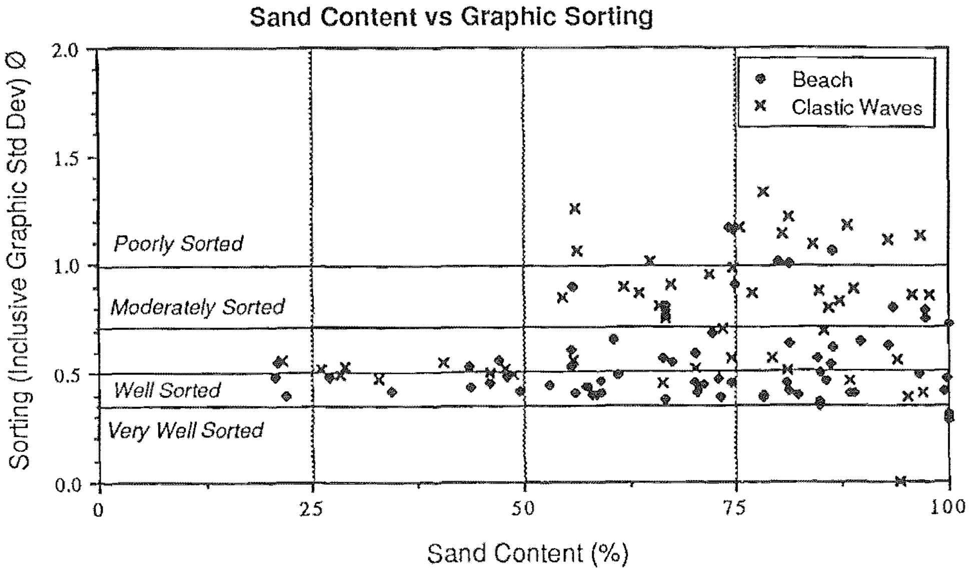


Figure 7.7b

Summary plot of 105 beach and clastic wave samples. A distinction netween well sorted beach samples and more poorly sorted clastic wave samples is apparent.



As clastic waves migrate, they tend to become better sorted. At the same time, however, the sand fraction is released from the intertidal deposits. This sand fraction is dispersed to one of three locations:-

a) the upper tidal zone - where it is eventually "run over" by the clastic wave; or

b) the lower tidal zone - where reference to sandy deposits was made (Chapter 5); or

c) the nearshore slope.

Clastic waves are thus part of a cycle of progressive sediment fractionation which takes place on the low energy and mixed material shore.

Stratigraphy and Sediment Trapping

The outcome of clastic wave migration into the trough area in its lee is that in the stratigraphic record of the beach a record of the passing of series of clastic waves is preserved. Plate 7.4a shows such a cross section at Double Bay, Mahau Sound. The clastic wave shown here can be seen in Frontispiece Plate 1. The sequence shows two grey sandy beds, each constituting the trough region in the lee of clastic waves. The middle portion identifies the migration of a previous clastic wave, which in grain-size analysis is indistinguishable from the crest deposits except for an addition of fine material.

Repeated patterns of well-washed granules and sandy beds, with a sequence thickness of 0.1 to 0.25m are characteristic of the sub-surface of stream-delta shorelines. At Ngakuta Bay, local residents report periods in the 1950's when the intertidal surface was much less granule-rich than it is today. Reports of low-water clastic waves with a height greater than those found on the shore today, and which link the reduction in height to the migration and spreading of the material, also correlates to the shore sub-surface stratigraphy. Given that sediment delivered to the shore generally does so in pulses correlated to high rainfall events, and that clastic waves are an intertidal mechanism for the gradual redistribution of this material, the investigation of the forms and their stratigraphic record would be a promising possible source of information about catchment sediment behaviour at the 1 year to 50 year time span. No other sources of information in the shore or offshore domain appear so promising.

Plate 7.4
Stratigraphy of Clastic Waves

Plate 7.4a

A cross-section through the clastic wave shown in Frontispiece Plate 1.

Double Bay, Mahau, NZMS 260 p27 GR 825 942. View west.

Frame is 0.5m wide, with 0.1m divisions.

Located 2m landward of crest, in lee trough. A muddy sand surficial deposit overlies better sorted granules with a sandy matrix. This sandy-gravel deposit develops as the consequence of clastic wave migration. A lag deposit of granules is the wave-worked deposit of the intertidal surface.

A sandy deposit like that at the surface is repeated below the granules. This sequence represents the depositional sequence of a clastic wave.

Plate 7.4b

Up-shore of Plate 7.4a (above)

Upper intertidal surface at the foot of the high water beach. Sediments are similar to those which develop at the foot of the seaward slope of clastic waves. The coarser materials tend to migrate onto and stop against the steeper shore accumulations. Coarser materials then contribute to the construction of a steeper shore face.

Plate 7.4b shows an excavation at the foot of the high water beach showing that the lag pebbles in the centre of the photograph are a surficial accumulation. The concentration of pebbles in this zone is attributed to their rounded shape which makes them more rollable and therefore more likely to roll to the foot of the beach.

Interpretations

Clastic waves, on grounds of behaviour and texture, would appear to warrant classification as a distinct shore accumulation form. In particular their dynamics and the detailed mechanism of sediment dispersal would justify their further investigation.

In the light of the Ordered Response Model, however, the clastic wave form is more than a sedimentary discovery. Clastic wave behaviour, in the context of a framework which includes paved ramps, is a direct illustration of a number of the propositions raised with regard to shoreline behaviour on a low energy shore. Clastic waves exhibit relative mobility and a local-scale expression of transitional control.

A particular outcome of the deposit-repository concept discussed in Chapter 5 (Keunen , in Winkelmolen, 1971) was that between deposits in a repository, there should be a complementarity between deposits which move ahead (lead) and those which lag behind, due to differences in what has been called here *relative mobility*. In dispersive or high energy environments, this deposit-differentiation may take place over some considerable distances.

It will be recalled that in the relative mobility framework, with diminishing mobility the differentiation between agglomerative (lead) and dispersive (lag) deposits was expected to diminish. The clastic wave is an illustration of these reduced differences - for the difference between a lead and a lag deposit here is a matter of metres. However, it is not simply the texture of the form which reflects ordered response but the behaviour of the shore as a whole.

Most importantly it is seen that ,while a progressive sorting takes place within the shore zone, this is by no means unconstrained by morphologic factors. Rather, morphologic factors, both due to the clastic waves producing small traps of their own ahead of them, and stemming from the form of the shore in relation to the the form of the wave, mean that clastic waves will be in a long-term state of readjustment.

The factors which determine the rate and nature of sedimentary fractionation within the shore can be seen as a balance which exists between the hydraulic dispersing factors on one side, and the morphologic retaining factors on the other. The central element in the balance stems from the relative mobility of both individual sediment particles, and of the collective forms.

In determining those factors which control shoreline form and the patterns of sediment within it, the ordered response model has provided a means of recognising three key aspects of control - the existence of control operating at different levels; the existence of transitional control between the higher order controls; and the importance of relative sediment mobility. Within this schema, it has been seen that the manner in which shores respond to sediment delivery depends largely on the relative mobility of several sedimentary fractions.

Chapter 8

Submarine Morphology and Sedimentation

The offshore domain represents the downstream end of the sediment cascade from catchment to coast. Sediments not retained by the shoreline traps are by-passed to the embayments. The factors which control the accumulation of sediments in the offshore domain are the focus of this and the subsequent chapter.

The Pelorus Sound has been identified by Carter (1976) as a "double ended sediment trap". On the basis of the semi-enclosed form of the inlets, of the ongoing inflows of sediment, and of oscillatory tidal flows, a trapping behaviour would appear to be a fundamental characteristic of the Sounds.

The classification of the inlet as a "double ended sediment trap" derived from three principal sources of evidence. Carter (1976) and Burns (1977) showed that in the outer parts of Pelorus Sound, the distribution of marine dinoflagellates in bottom sediments suggests that a component of contemporary sedimentation in the outer parts of the inlet stems from material swept into the inlet by tidal flows. Carter presented evidence of suspended sediment inflows from the Pelorus River (at the head of Pelorus Sound) in high and mean flow conditions, and thus demonstrated that sediment was being injected into the inlet from the inner end also. Also presented was a sub-bottom seismic profile along the axis of the Pelorus Sound, as referred to in Chapter 2. This seismic data indicated an undulating bottom and sub-bottom form along the axis of the Sound from the confluence with the Kenepuru to Tawero Point.

Formulating the Investigation of Offshore Sedimentation

Three factors which are liable to determine the form of the offshore, and the redistribution of sediments within it are therefore:-

1) Tidal hydraulics,
2) Sediment inflows, and,
3) Inlet morphology.

It has been widely recognised (Bruun, 1978) that elements of inlet geometry tend to reflect the hydraulic conditions prevailing - especially the dynamics of tidal flows. The cross-sectional areas of channels, for example, have been correlated to the flows which pass through the inlet, driven by tidal and river processes.

A second aspect of hydraulic control of sediment distribution that has been widely reported is attributable to estuarine salt-wedge processes - notably the interaction between fresh and saline waters (Dyer, 1979). In certain conditions of the relative dominance of tidal to river flow this interaction has been noted to develop a "turbidity maximum" in the middle reaches of estuarine inlets.

The location of sediment inflows might be expected to be a primary control on sediment distribution. It has been shown in Chapter 5 that the nearshore slope sediments in the Sounds have a higher sand content than offshore sediments. This was interpreted as reflecting the primary fractionation which took place at the shore between sandy and gravelly sediments and the finer components. Offshore sediments therefore comprise fine fractions which are highly mobile while in suspension, and responsive to hydraulic conditions. It is a matter for investigation to identify the extent to which offshore sediment patterns reflect the distribution of sediment inflows.

The third control acting on sediment form and patterning is inlet morphology. The form of the Sounds and of their marginal embayments are the most apparent control on offshore sedimentation. Antecedent river valley form might be expected to exercise some control over bathymetry, but the extent to which this is so has not been reported in the literature.

Previous chapters have shown the utility of the distinction made in the Ordered Response Model between the concepts of a morphologic and a mobility trap. The concept of a morphologic trap is defined by a boundary framework within which sedimentation takes place, linked to an inflow of sediment. The concept of a mobility trap specifies that sediment is retained within a frame defined by hydraulic rather than morphologic factors. In this and the following chapter, this framework is employed in the context of a study of offshore sediment behaviour.

The matter for investigation is the extent to which these traps can be recognised in the offshore domain. Of primary importance at this stage of investigation is the need to identify the scale at which trapping occurs - i.e. whether the offshore traps operate at the scale of embayments or at the scale of the inlets as a whole. The need is to identify whether the offshore domain should be regarded as a single system, or as a series of partially closed systems, with marginal embayments operating to a degree independently from the axial channels. This matter of scale is relevant for the investigation of sediment dynamics in this and subsequent studies and also of practical importance to those with a responsibility for the management of activities in both catchment and marine domains.

From an analytical point of view, there is also an interest to identify the nature of *transitional control* in the context of an offshore system. It was shown in the investigation of shoreline behaviour that the relative mobility of sediment particles provided a continuum of responsiveness between shoreline sites which could be seen to be under primarily hydraulic, primarily sedimentary, or primarily morphologic control. The relationship between these various levels of responsiveness to shoreline processes provided a framework within which it was possible to distinguish the manner in which shoreline sites might respond to sedimentation. Given the radically different levels of particulate mobility in the offshore domain between fine sediments and the morphologic framework within which they accumulate, it is a parallel purpose of these chapters to consider the operationalised form of the Ordered Response Model in the offshore domain.

Two sources of evidence are used to assess the controls acting on offshore sediments. In this chapter, reference is made to the morphology of the receiving environments, to the factors which determine this form, and to the thickness of accumulated sediment within the Pelorus Sound. On these bases, it is possible to identify the morphologic controls acting on sediment distribution, and the importance of the location of sediment inflows to the distribution of sediment i.e. a morphologic trap.

In the following chapter, the sediment textural analysis presented in Chapter 5 is evaluated in detail with reference to the patterns of sediment distribution within marginal embayments. From this evaluation it is possible to make an assessment of the extent to which sediment distribution is controlled by hydraulic factors or a mobility trap.

The dimensions of channels and embayments were identified in Chapter 6. The first section of this chapter presents an analysis of bottom form (bathymetry) and a number of distinct patterns are identified. In the second section, reference is made to the thickness of accumulated sediments, based on data obtained by the analysis of seismic profiles of the sea-bed. In the third section, a consideration of the detailed sub-bottom form provides evidence which extends the present knowledge of morphologic control exercised by sub-bottom form in determining bottom form.

Bathymetric Form

Analysis is based on three sources of evidence. The first is bathymetric charts, the second echo-soundings, and the third sub-bottom seismic profiles. Those used are identified specifically in Table 8.1. The focus of this analysis is on five sub-regions: the inner Queen Charlotte (from Okiwa to Dieffenbach Point), see Map 1, outer Queen Charlotte (from Dieffenbach Point to White Rocks), Tory Channel, the inner and middle reaches Pelorus (from Havelock to Tawero Point), and Kenepuru Sound.

The Long Profile

The "long profile" of axial channels might be expected to reflect the long profile of antecedent rivers with a secondary modification of form by either marine erosion or deposition. Figure 8.1 shows the long (seabed) profile of the axes of three components of Queen Charlotte Sound including Tory Channel. Figure 8.2 shows the equivalent for the Pelorus Sound including the Inner Pelorus, Kenepuru Sound and Nydia Bay. In general, the deepest point in a transverse section lies at or close to the axis of the channel but in the inner Pelorus the deepest point in the channel (thalweg) meanders from the channel sides. The plotted profile traces the thalweg, not the geometric centre of the channel. In the Kenepuru and Nydia profiles, the profile is of the axis.

Queen Charlotte Sound and Tory Channel

The overall bottom gradient of the inner 17km of Queen Charlotte Sound (from Okiwa to Blackwood Bays) is 1:450, as shown in Figure 8.1a. This gradient is concave, and includes an inner subtidal segment (1km to 5km, to Ngakuta Bay) with a long-profile gradient of 1:180, and a lower segment (from 10 to 17km, Lochmara to Blackwood Bays) of 1:1800. In the inner portion (0 to 10km) there is a marginally deeper "thalweg" (the deepest part of a channel) located on the southern shore that can be identified on hydrographic charts (see Table 8.1). In the remaining 7km the bottom is largely planar.

In the vicinity of Dieffenbach Point, there are two particular morphologic features. The first is the deep channelling associated with the junction with Tory Channel and the confinement by the West Head/ Lukes Rock ridge (Map 1 GR 606 998). The second is a shallow area in the south extending into Kahikatea East Bay

Table 8.1

Sources of Evidence
Bathymetric and Sub-bottom Investigations

Echo Soundings

Echosoundings completed in this investigation Total Distance: 125.2km

Sounding taken at 5kt from 4m craft with Ferrograph 500G.
(Dept of Geography, University of Canterbury)

Opua Bay, Tory Channel:	16km
Grove Arm, Queen Charlotte:	4km
Clova Bay, Pelorus Sound	5km
Tennyson Inlet, Pelorus Sound	6km
Total	31km

Soundings taken from 6m craft with Raytheon Survey Echo sounder.
(Marlborough Harbour Board)

	Cross-profiles	Nearshore profiles
Grove Arm	18km	14 x 300m
Kenepuru Sound	8km	10 x 300m
Total	26km	7.2km
Inner Pelorus	19km	6 x 500m
Pelorus Channel	34km	10 x 500m
Total	53km	8km

New Zealand Oceanographic Institute (J. Irwin, pers comm, 1985)
Unpublished echosoundings of Pelorus Sound, cross profiles 0.5km spacing

---

Seismic Profiles

Raytheon RTT-1000A (3.5/7.0 kHz) shallow-water seismic profiler.
New Zealand Oceanographic Institute (J. Irwin, pers comm, 1985)

Profiles:

Inner Pelorus (4 profiles)	6.3km
Pelorus Channel (4 profiles)	14.7km
Nydia Bay (3 profiles)	3.1km
Kenepuru Sound (9 profiles)	11.9km
Tennyson Inlet (3 profiles)	5.7km
Total (23 profiles)	41.7km

Bathymetric Charts

New Zealand Hydrographic Survey Published Charts

Chart 615	Marlborough Sounds
Chart 6153	Queen Charlotte Sound

New Zealand Hydrographic Survey Unpublished Charts
1:25,000 chart, Queen Charlotte Sound, Lowry (1943)

Figure 8.1

Seabed Profiles, Queen Charlotte Sound

Figure 8.1 a

Inner Queen Charlotte Long Profile

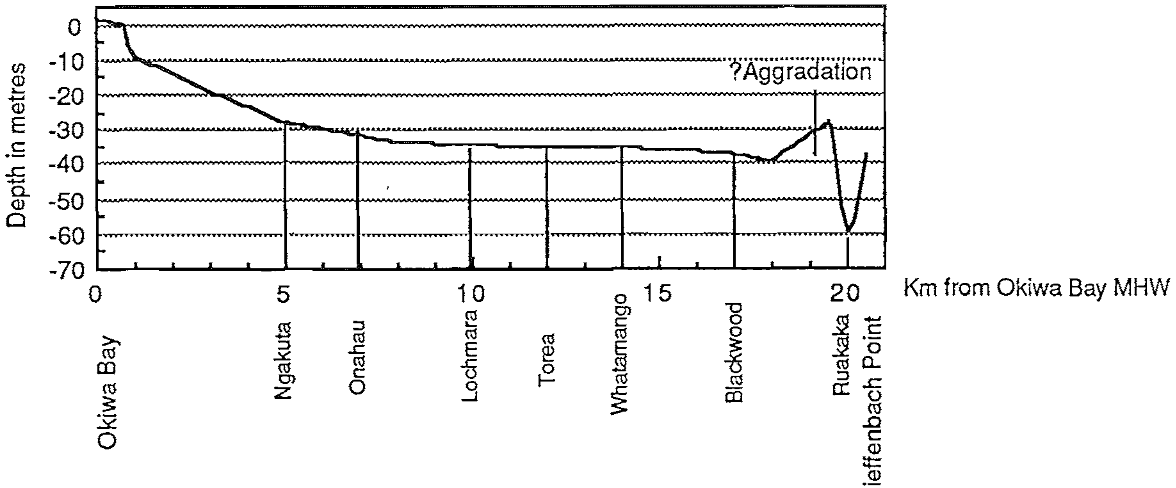


Figure 8.1 b

Outer Queen Charlotte Sound Long Profile

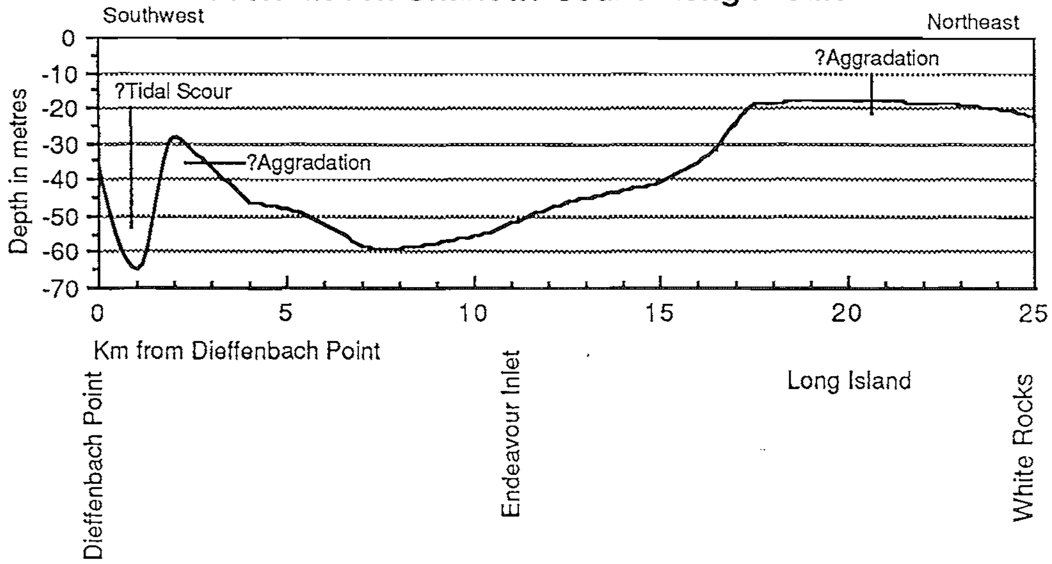
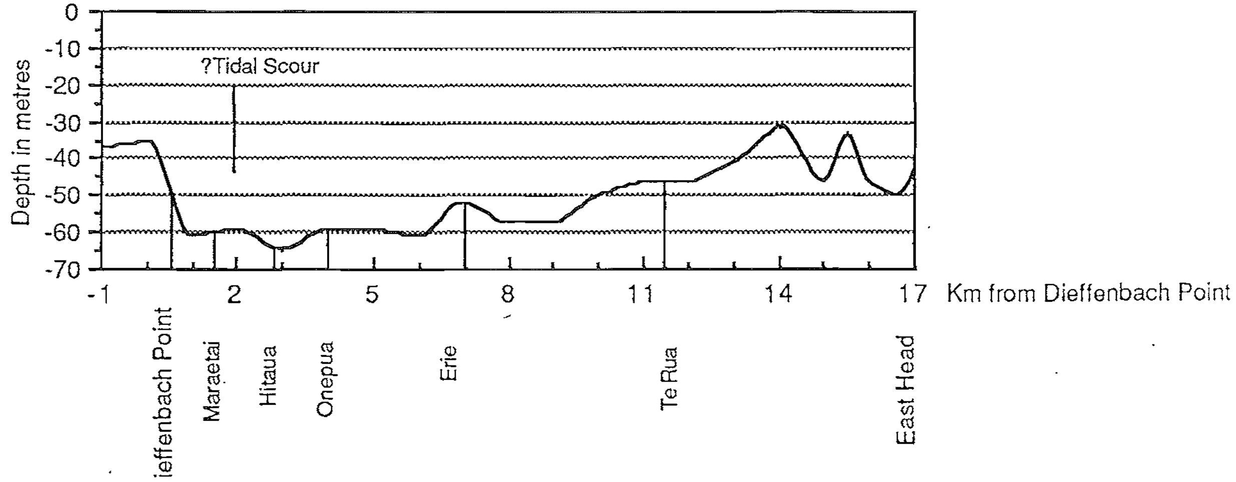


Figure 8.1 c

Tory Channel Long Profile



(GR 604 996) shown in Figure 8.3. The steep slope component seen in Figure 8.1a has a long-profile gradient of 1:15. The shallow area seen in the Figure shoals from approximately 20 fathoms (37m) the depth of the sub-regional seabed, to shallower than 10 fathoms (18m) at its shallowest point. This bottom feature is of the order of 1.5km square. Contour lines at 20 fathoms trace the mean bottom surface of the Sound, while the contour at 2 fathom intervals above this indicates the extent of the mound.

The outer Queen Charlotte profile (Figure 8.1b) shows a channel and shoal pattern near Dieffenbach Point similar to that seen in Figure 8.1a. Northeast of the shallow there is a deep-point of nearly 60m at 7.5km northeast from Dieffenbach Point (in the vicinity of Oruawairua Island). On its northeastern side there is a shallowing to less than 20m in depth between Motuara and Long Islands (see Map 1).

The inner Queen Charlotte thus shows a consistently deepening trend from Okiwa Bay to Dieffenbach Point which may be interpreted as stemming from the antecedent river valley form. The first of two exceptions to this is a prism of sediment at the inner end at Okiwa Bay. This is evidence of Holocene progradation of the stream delta, as discussed in Chapter 6. A second exception is the presence of shoal areas and channels in the vicinity of Dieffenbach Point and in the outer Queen Charlotte Sound.

The Tory Channel profile (Figure 8.1c) has axial shallows at 30m depth, but undulates, with a deep-point of 64 m. The ends of the channel are shallower than much of its middle portions. A summary contoured chart of Tory Channel bathymetry is produced in Figure 8.5.

Pelorus and Kenepuru Sounds

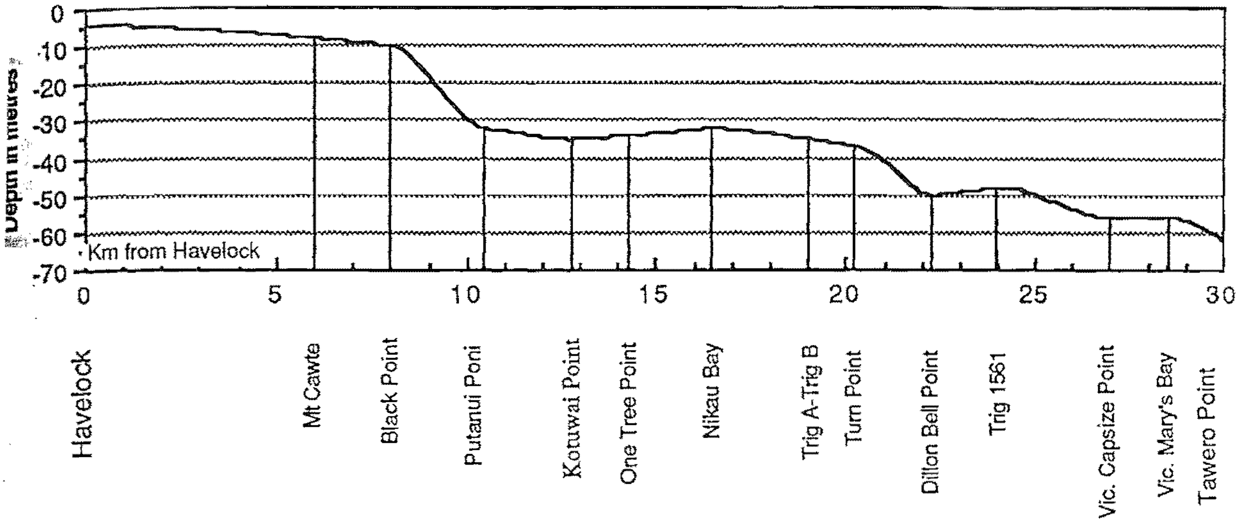
The inner Pelorus profile and those of the flanking inlets of Kenepuru and Nydia (Figure 8.2) show consistent deepening trends in the long profile. The inner Pelorus from Havelock to Tawero Point has an overall gradient of 1:520 over 30km, or 1 in 525. The inner 10km to Putanui Point comprises an 8km component to Black Point with a channel gradient of 1:1430, and 2km at 1:115 to drop the channel bottom to between 30 and 35m. The bottom stays in this range for the 10km from Putanui Point to Turn Point (see Maps 2 and 3). The final 10km undulates and drops to a depth of over 60m at Tawero Point. The appearance of the long profile is thus of a series of "steps".

Figure 8.2

Seabed Profiles, Pelorus Sound

Figure 8.2 a

Inner Pelorus Sound Long Profile



Kenepuru Sound Long Profile

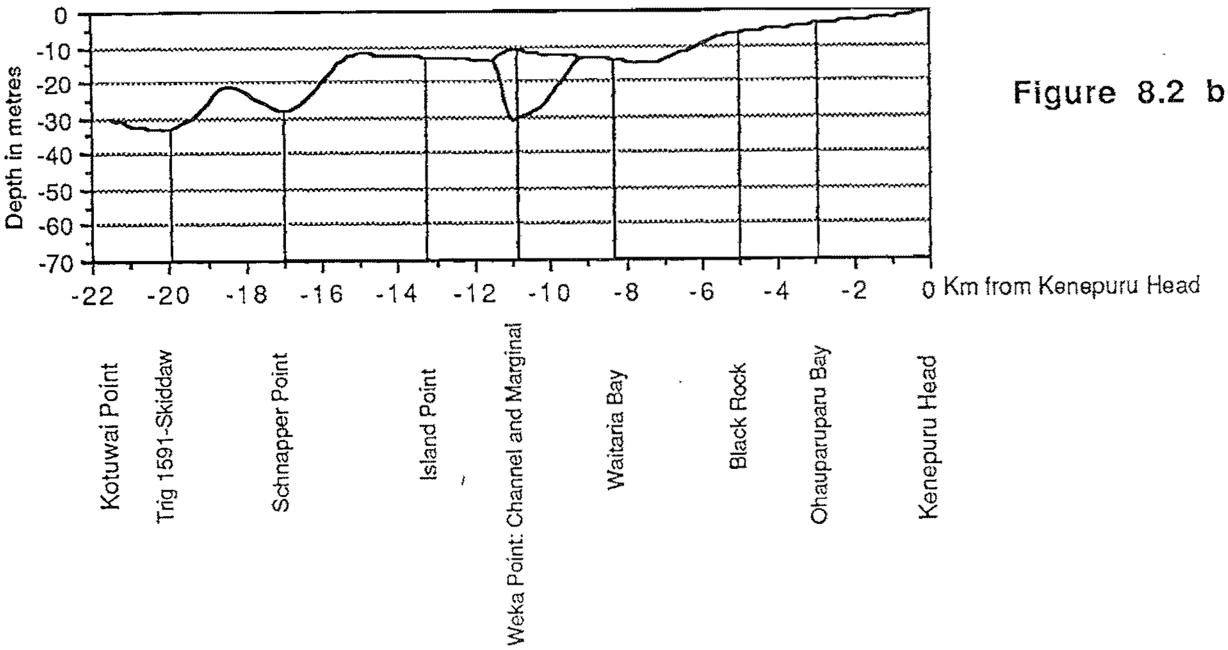


Figure 8.2 b

Nydia Bay Long Profile

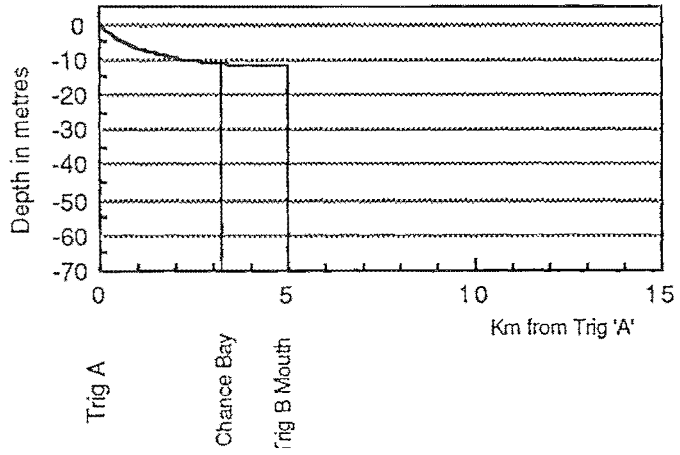
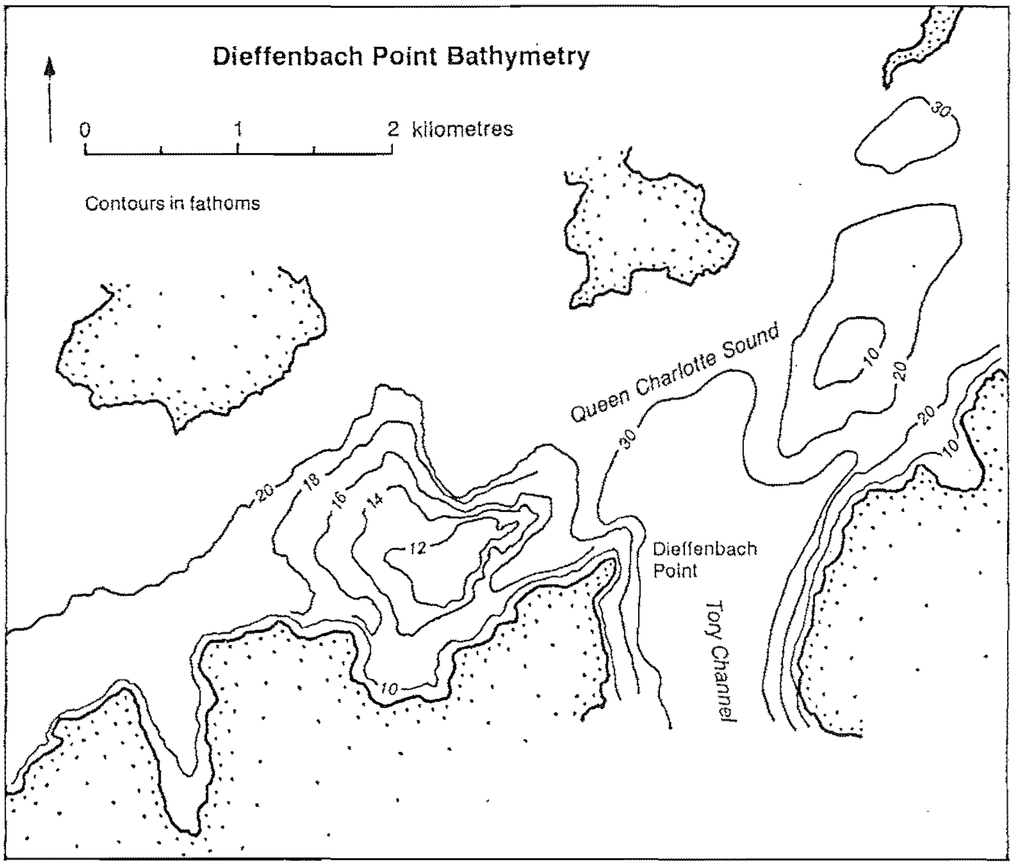


Figure 8.2 c

Figure 8.3

Bathymetric Forms Attributable to Tidal Hydraulics, Queen Charlotte Sound



Two shoal features flanking Tory Channel entrance to Queen Charlotte Sound. Mean seabed contour of Queen Charlotte Sound in middle reaches is 20 fathoms (38m). Tory Channel axis is deeper than 30 fathoms (55m).

Shoals are attributed to the tidal redistribution of material scoured from Tory Channel.

Source: Contoured from Lowry (1943)
Queen Charlotte Sound Bathymetry 1:25,000

A similar "stepped" long profile is found in the Kenepuru Sound. The steepest components are associated with the proximity of the channel to rock headlands and the gentle components with the broader unconfined reaches. The overall gradient of 1:570 in 20km The upper reach of Kenepuru Sound slopes for 5km (to Black Rock, see Map 4) at 1:820. A gradient of 1:285 is found in the thalweg on the reach south of Waitaraia Bay. At Weka Point the bottom drops to below 30m in the channel before rising again to less than 15m at Island Point. Figure 8.2b shows both the axial channel bottom and the depths in marginal bays. These show that the deep point is found only in the main channel suggesting that the deep channel is the result of confinement between headlands. The lower Kenepuru is again confined from Schnapper Point to the junction with the Pelorus, by which point the bottom undulates to a depth of below 30m at Kotuwai Point.

The Nydia Bay profile (Figure 8.2c) has an axial gradient of 1:410 over its 5km extent. The profile is of the axis, rather than the thalweg which is shown for the Pelorus profile (Figure 8.2a). This accounts for the discordance between the baymouth depth of 12m in the Nydia profile, and the correlative 32m value for Nydia Bay shown on the Pelorus long profile (Figure 8.2a). This discordance between baymouth depths and the depth of channels which they join is a distinctive bathymetric form.

The Transverse Profile

Two characteristic forms identified from bathymetric analysis are the "W-profile" and the "discordant junction".

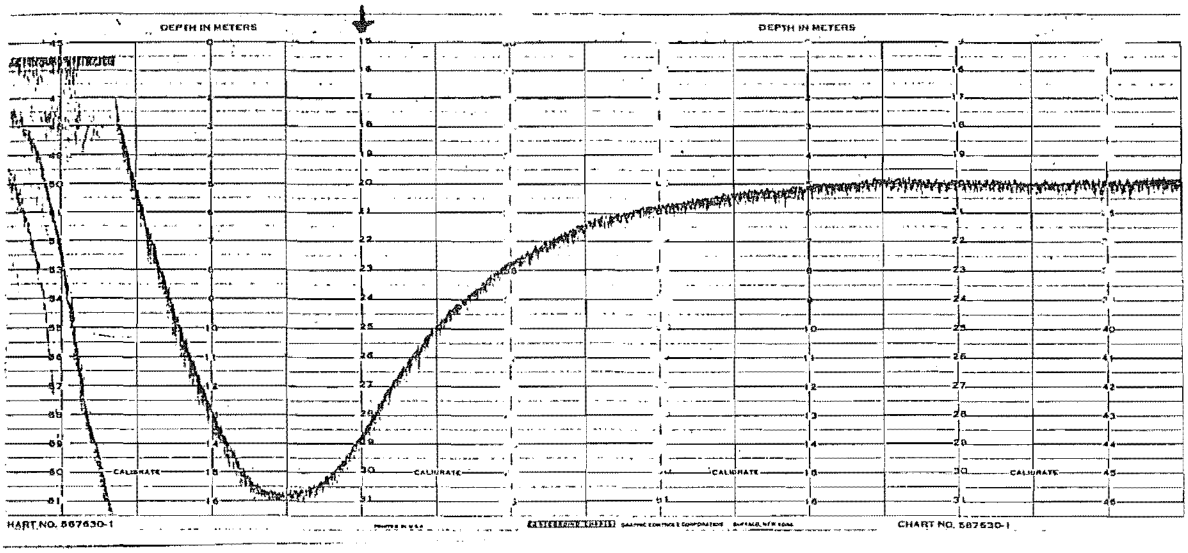
Cross-profiles of many channels and baymouths show a characteristic form with deeper segments close to the shore and a shallow portion in the centre. This is referred to as the "W-profile". Examples are shown in echo grams in Figure 8.4.

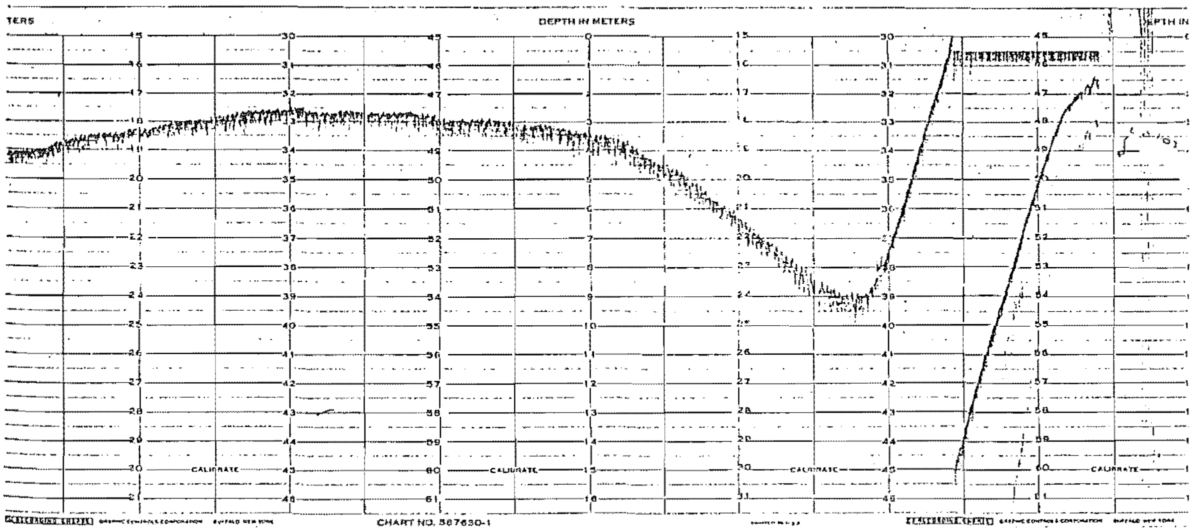
Transverse profiles also show a discordance between baymouth axial depths, and the depths in the adjacent channels. The terms "junction accordance" and "junction discordance" are adopted from "Playfair's Law" of Junction Accordance (Tinkler, 1979). The relation between the axial profile of the marginal bays and the profile of the main channel is akin to that of a hanging valley of glacial form. Most bays with junction discordance also have a W-form

Figure 8.4

Echo-grams of W-form Bathymetric Profile

Typical form of sounding profiles in marginal bays shows channels incised near shore. Often found on both sides of the bay, referred to as "W-form" profile.
Sub-bottom profiles show that bottom form is attributable in part to hydraulic and in part to sub-bottom form.





Location: Four Fathom Bay, mid-way down bay.
Scale: one bar vertically equals 1m.
Each segment 200m long.

bay-mouth transverse profile. The discordance only applies to a profile taken down the bay axis, as a profile taken down the axis of the marginal channels is usually accordant with the bottom depths of the main channel.

An outcome of the W-form profile in baymouths is the appearance of baymouth mounds, as can be seen in the Tory Channel bathymetry plotted in Figure 8.5. Contours at 10, 20 and 30 fathoms trace the channel and show the distribution of scour in the mid reaches. Selected contours show the extent of baymouth mounds.These forms were referred to by Newton (1977) and Sherriff (1983). The former attributed the surface texture of the mounds to hydraulic reworking by tidal currents. The latter speculated on the migration of the forms into bays as migrating bars. The forms have significance for the interpretation of sedimentation rates and sub-bottom bathymetry, as is discussed below.

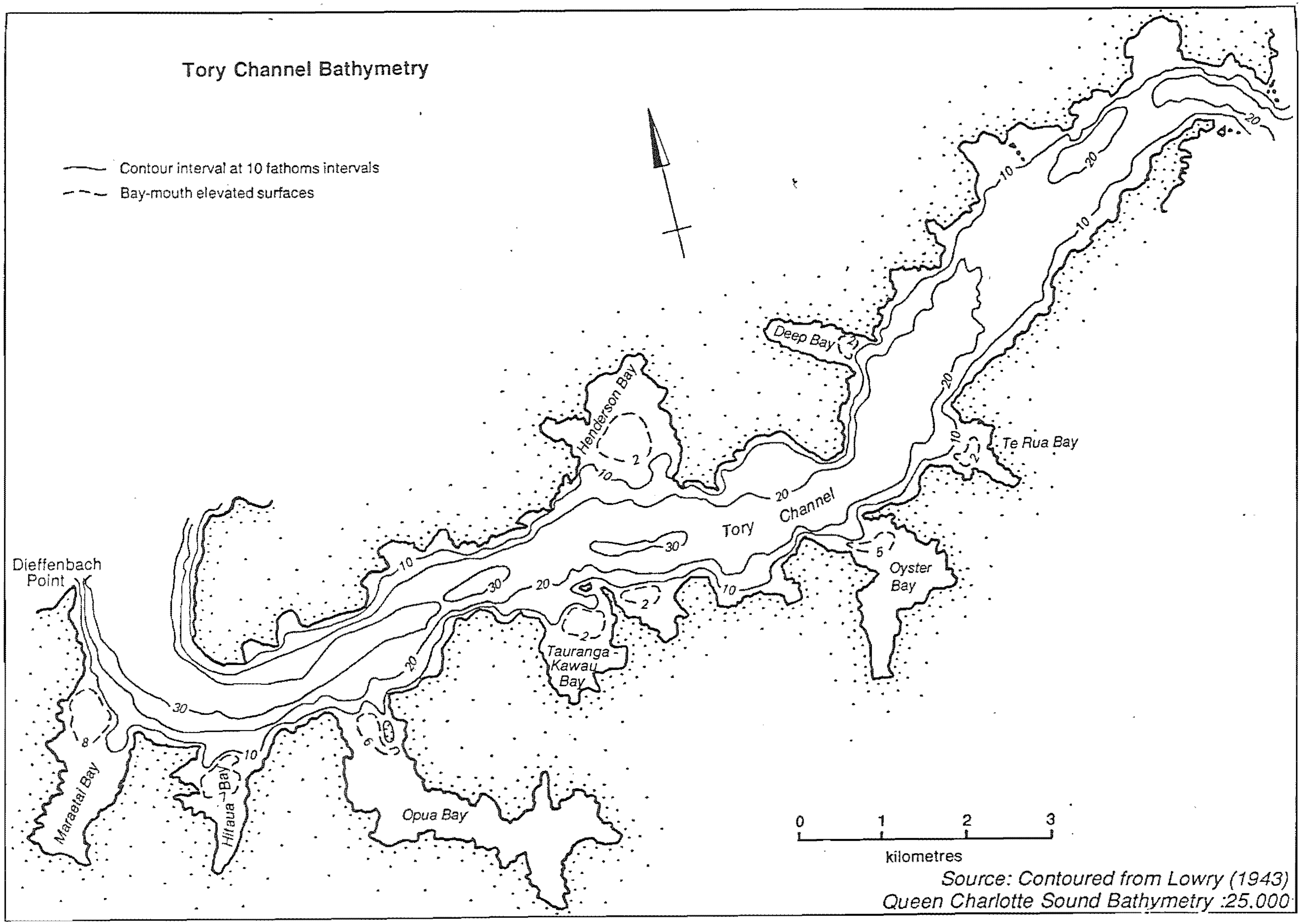
A bathymetric map of the middle reaches of the Pelorus Channel is shown in Figure 8.6 (from J. Irwin, N.Z.O.I. Pers comm. 1985). Contours are in metres. Key features of the bathymetry are the evidence of the W-form channels in the mouths of each bay (Nikau, Four Fathom, Maori, and Nydia Bays), and the patterns referred to here as depth discordance, in which marginal bay depths are markedly shallower than axial channels.

A comparison of the relationship between marginal bays and the axial channels in the inner Queen Charlotte and in Tory Channel, highlights the marginal bay relationships.

Inner Queen Charlotte Sound

Figure 8.7a shows an axial plot of inner Queen Charlotte Sound with the superimposition of the bay depths in the mouths of marginal bays. The bottom line traces the depth of the axis of Queen Charlotte Sound from the Grove Arm to Dieffenbach Point, as given in Figure 8.1a. Also fitted through these points is a second-order polynomial curve, which is seen to intersect the bayhead delta at Okiwa Bay at close to sea level.

A second set of points plotted represents the depths in the mouths of the marginal bays as labelled on the plot. While there are some higher and lower points, most fall close to a curve plotted through the points with the same correlation coefficient as the fit to the axial channel points. Depths in marginal bay mouths are therefore slightly shallower than those in the main channel to



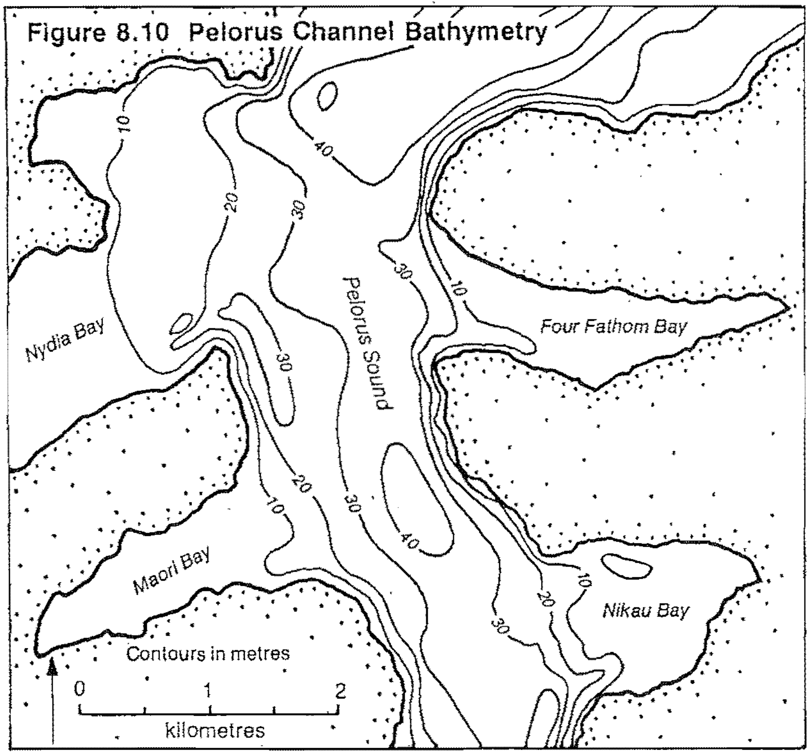
Source: Contoured from Lowry (1943) Queen Charlotte Sound Bathymetry :25,000

Figure 8.5

Bathymetric Form
Relationship of Marginal Bays to Axial Channels
(Tory Channel Bathymetry)

Figure 8.6

Bathymetric Form
Relationship of Marginal Bays to Axial Channels
(Pelorus Channel Bathymetry)



Bathymetric form of Pelorus Channel shows shallow bays flanking the deeper channel, the form referred to here as marginal bay depth discordance.

Source: J. Irwin, DSIR, <u>pers. comm.</u> 1985.

which they join. Overall, however, the depths bear a geometric relationship to the axial depths and both curves intersect the Sound head at a similar position.

Thus, either the underlying sub-bottom or sediment accumulation over the bottom are responsible for developing an evenly graded seabed with the pattern identified as marginal bay accordance.

Tory Channel

A plot of the long profile of Tory Channel and some of its marginal bays is shown in Figure 8.7b. The bottom line traces the bottom profile of the Channel, as shown in Figure 8.1c. Also plotted are points which identify depths in the marginal baymouths. Point depths were identified on bathymetric charts at a scale of 1:25,000 (see Table 8.1). Points selected were on the surface of baymouth mounds. Baymouth mounds are located on Figure 8.5.

The notable feature is the contrast between depths in baymouths and in the thalweg channel. The mean channel depth adjacent to the eight examples is 52m, and the mean baymouth depth is 5.8m. The mean difference is 46.3m. This pattern is referred to as marginal bay junction discordance.

A linear curve fitted through the points in the baymouths is shown on Figure 8.7b. The line indicates a baymouth pattern deepening east to west, i.e. towards Queen Charlotte Sound, with a gradient of 1:715. The equation of this is shown below the Figure. The correlation coefficient for the line is 0.93.

Discussion

General bathymetric features of Pelorus, Queen Chalotte and Kenepuru Sound show a simple deepening trend. Distinctive features are:-

1) Mounds and channels in Queen Charlotte Sound at Dieffenbach Point and in the outer reaches;
2) Deep incision of Tory Channel;
3) Stepped profiles of Kenepuru and Pelorus Sounds;
4) Marginal bay discordance in Tory Channel and Pelorus Channel and,
5) Baymouth mounds in both Tory Channel and Pelorus Channel, asscociated with W-form baymouth channellisation on the flanks.

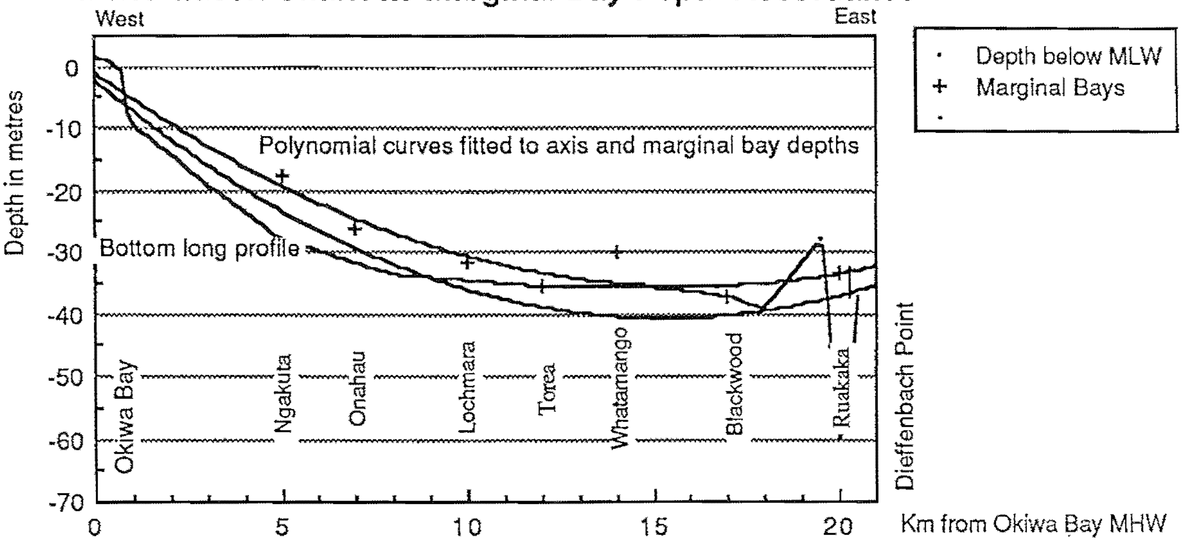
Figure 8.7

Relationship of Marginal Bays to Axial Channels Marginal Bay Depth Accordance and Discordance

---

Figure 8.7 a

Inner Queen Charlotte Marginal Bay Depth Accordance



2nd order polynomial curve fit through axial channel gives regression:

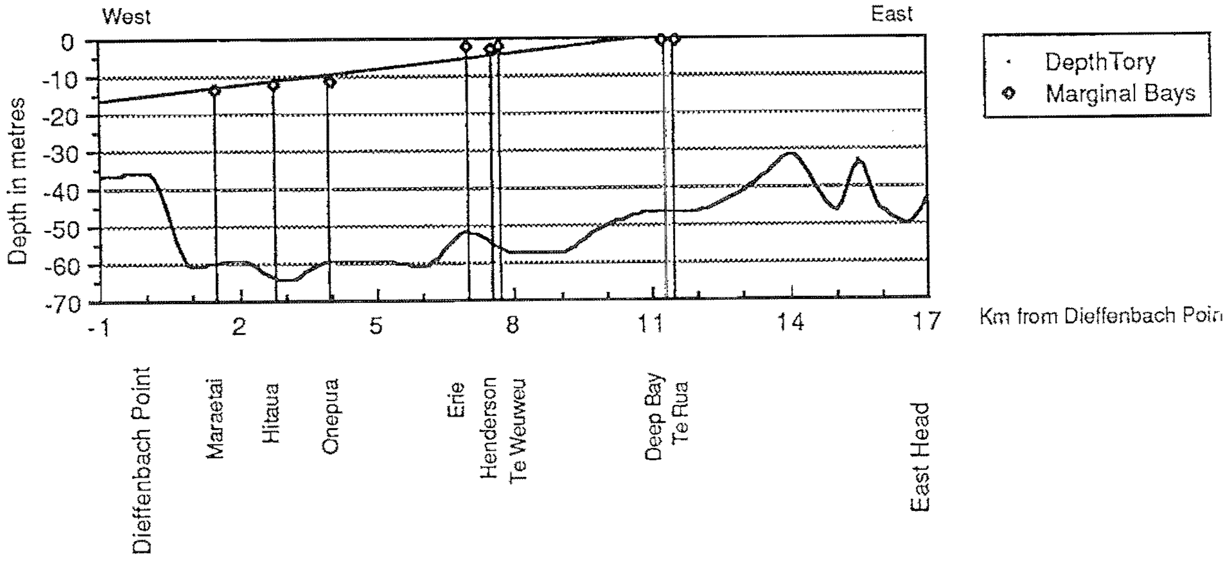
$y = -2.2205 - 5.0209x + 0.164x^2 \quad R = 0.92$

2nd order polynomial curve fit through bay-mouth depths in marginal bays gives regression:

$y = -1.0262 - 4.2929x + 0.1336x^2 \quad R = 0.92$

Figure 8.7 b

Tory Channel Marginal Bay Depth Discordance



Linear curve fit through bay-mouth depths in marginal bays give regression:

$y = -15.1722 + 1.4155x \quad R = 0.93$

Dieffenbach Point and Outer Queen Charlotte Mounds

The morphology of bottom "mounds" in the vicinity of Dieffenbach Point shows them to be independent of adjacent ridges and to be confined to tidally worked areas. The proximity of the mounds to the deep channel at the mouth of Tory Channel suggests that the forms have an origin associated with tidal scour in the channel and that they comprise a redeposition of tidally scoured material.

With regard to bottom form in the outer Queen Charlotte, an hypothesis advanced by W.R Lauder (1970) attributed the shallowing to the remnant crestline of a subsided ("tilted") catchment divide, as noted in Chapter 2. Alternative interpretations would be to attribute the aggradation to tidal redistribution of bottom materials, or to wave erosion and littoral redistribution of material derived from exposed cliffs on the northern shores of Arapawa Island and Port Gore. Such a littoral redistribution could have occurred during the period of rising sea level.

The major accumulations in the vicinity of Dieffenbach Point can be accounted for by tidal redistribution and vigorous erosion of the outer shores is characteristic. Either of these explanations could be proposed to account for the outer Queen Charlotte shallow areas without reference to a sub-bottom remnant ridge. Confirmation of hypotheses will depend on sub-bottom profiling of the features, but their sandy surface texture as mapped by Lewis and Mitchell (1980) and the northern swell wave climate would suggest a littoral origin.

Deep Incision of Tory Channel

Tidal streams in Tory Channel (N.Z.H.S. Chart 6153) exceed 1m/s, and funnelling of the flow at constrictions increases tidal velocities. The profile form of Tory Channel would therefore appear to reflect tidal hydraulics. The observation of hollows in the long profile, below the depths at the ends and which at the seaward end is rock-controlled, is evidence of tidal scour below any river base-level.

The extent to which the scour of the channel was of river infill or bed-rock is not established, although a proportion of the scour must have been into rock.

Stepped Profiles of Kenepuru and Pelorus Sound

Sediment delivery to the Pelorus Channel and to Kenepuru is assumed to be derived principally from catchment or shoreline sources. Consequently, the stepped profiles in these inlets reflect either retention of material behind barriers imposed by constrictions in the inlet cross-sections or they reflect sub-bottom gradients.

Marginal bay discordance in Tory and Pelorus Channels

The observation of tidal scour in Tory Channel suggests that one explanation of the relatively more shallow bathymetry in marginal bays could be tidal scour of the axial channels. A second explanation would be to attribute the shallow bathymetry to sedimentation in the marginal bays- due to either infilling from the landward ends, or to tidal deposition from the seaward end. The interpretation is related to the explanation of the baymouth features.

Baymouth mounds and W-form channels

The sandy surface texture of bay-mouth accumulations in Tory Channel, in the context of strong tidal currents, suggests an hydraulic component in origin as noted by Newton (1977). The logical interpretation of the W-form channels in this light would be as tidal scour channels. Such an explanation would also be coherent with the distribution of channels in the Pelorus Sound. This interpretation is discussed in the context of further evidence, below.

Controls on Bathymetric Form

The patterns of bathymetry discussed in this section have been identified with three principal controls. The effect of tidal hydraulics is apparent in the Tory Channel area and may be a contributing factor to bathymetry and sediment redistribution in other sub-regions. Sedimentary infilling may be a factor in bay-infilling and in accounting for the shallow bathymetry in the inner Sounds. Thirdly, the form of the antecedent river landscape can be seen to show through the pattern of Holocene sedimentation, but to an extent which has not yet been established.

The purpose of the following section is to examine the thickness of the layer of sediment which overlays what has been identified by Carter (1976) as the sub-bottom river surface of the pre-drowned landscape in the Pelorus Sound. The examination of spatial differences in sediment thickness gives evidence relevant to two aspects of this investigation. The first is a gauge of the mean rate of sedimentation in the offshore domain over the period since occupation of the river valleys by the sea. This period is taken arbitrarily as 6,000 years. The second aspect relates to the variability between sediment thicknesses at different locations. This pattern serves to establish whether the location of sediment inflows (notably, the Pelorus River at the head of the Sound) is a primary control of the thickness of sediment accumulation or whether the distribution is uniform over the bed.

In the third section of the chapter, the analysis of the sub-bottom seismic profiles is extended as a means to assess the extent to which antecedent topography is a determinant of bottom form and a factor in sediment redistribution.

Sediment Accumulation in the Offshore

The thickness of accumulated sediment on the offshore bed can be estimated by the use of sub-bottom profiles. Redrawn at a small scale, 23 profiles used in this study are shown in Figures 8.9-8.12. Only data from Pelorus Sound and Kenepuru Sound are presently available. The Queen Charlotte Sound is expected to have a thickness of sediment cover which is less than that in the Pelorus Sound due to the absence of a large river inflow such as the Pelorus River. Reference is made in the following section to a number of correlations which can be made between the Pelorus and the Queen Charlotte bathymetric and sub-bottom morphology.

The locations of the profiles are mapped in Figure 8.13. The bottom and sub-bottom traces of a number of transverse profiles in the inner Pelorus Sound are shown in Figure 8.9. The profiles are arranged in this Figure from north (top) to south (bottom). One profile from the Pelorus Channel area (PC 1) is shown and one from the lower reaches of Kenepuru Sound (KC 1) near the confluence with Pelorus Sound. Figure 8.10 shows profiles in Kenepuru Sound arranged from the eastern head of the Sound (top) to the lower reaches near Pelorus Sound (bottom). In Figure 8.11, three profiles in Nydia Bay are shown in order from inner to outer reaches along with three profiles from the northern portion of the Pelorus Channel (north of Nydia bay). Figure 8.12 shows three profiles in Tennyson Inlet.

The vertical exaggeration is 25 times. Orientations of the profiles to the maps is accomplished by corresponding x symbols on both.

It should be noted that the coverage of sub-bottom profiles presented here is confined to regions inland from Tawero Point, and in the Tennyson Inlet area. The focus is restricted to an interpretation of offshore sedimentation in the more enclosed parts of Pelorus Sound, with a focus in this section and the next on the relation between marginal bays and the axial channels, as specified in the introduction to this chapter.

Seismic sub-bottom profiles obtained by a Raytheon 3.5-7.0 kHz echo-sounding profiler in the Pelorus Sound identify sub-bottom form by differential reflection off surfaces of unconformity. Interpretation of the output was made with reference to techniques described in detail in Payton (1977). The details of the equipment used are specified in Table 8.1.

The profile data, an example of which is shown in Figure 8.8, show two distinctive reflectors. The upper is the sea bed, the principal water-mud interface while the lower identifies an unconformity. While some profiles indicate a gas-rich layer of probable organic origin (identified by a "fuzzy" sub-bottom reflection), most give a clear line. The latter are interpreted as fluvial gravel surfaces, possibly with estuarine material overlying them (L. Carter, N.Z.O.I., Pers comm. 1984).

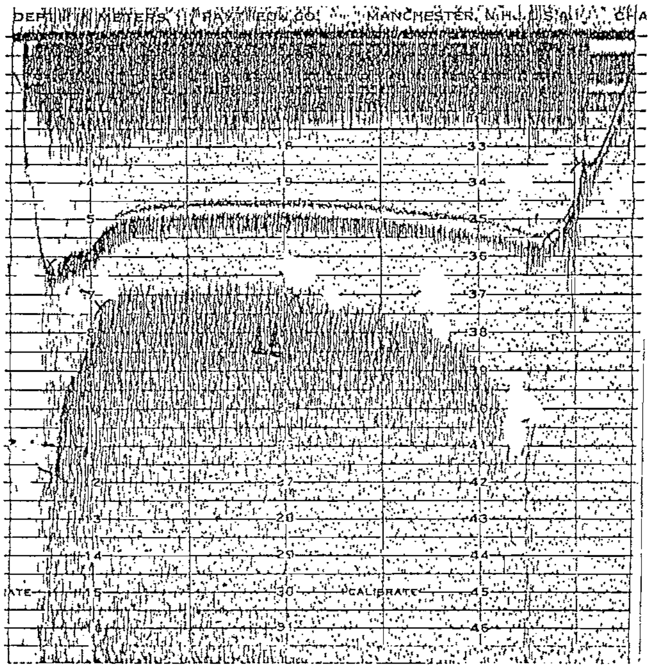
Figure 8.8

Sub-bottom Seismic Profiles, Pelorus Sound Examples of Profile Data

---

Sub-bottom seismic profiles taken by Raytheon RTT-1000A (3.5/7 kHz shallow water seismic profiler (D.S.I.R. Division of Marine and Freshwater Research).
Profiles show two reflectors - upper is seabed water-mud interface, lower is sub-bottom attributed to fluvial gravels (L. Carter, DSIR, per. comm.).

Sub-bottom profiles used here to identify thickness of Holocene mud accumulation and to investigate antecedent river-valley morphology. Examples below show channels attributed to river incision of alluvial aggradation surface ("Nydia Surface") found in Nydia Bay.



Sub-bottom profiles, Nydia Bay . *Above*, Profile NB 2 , *Below*, Profile NB 1.
For scale and locations, see Figure 8.11 and 8.13.

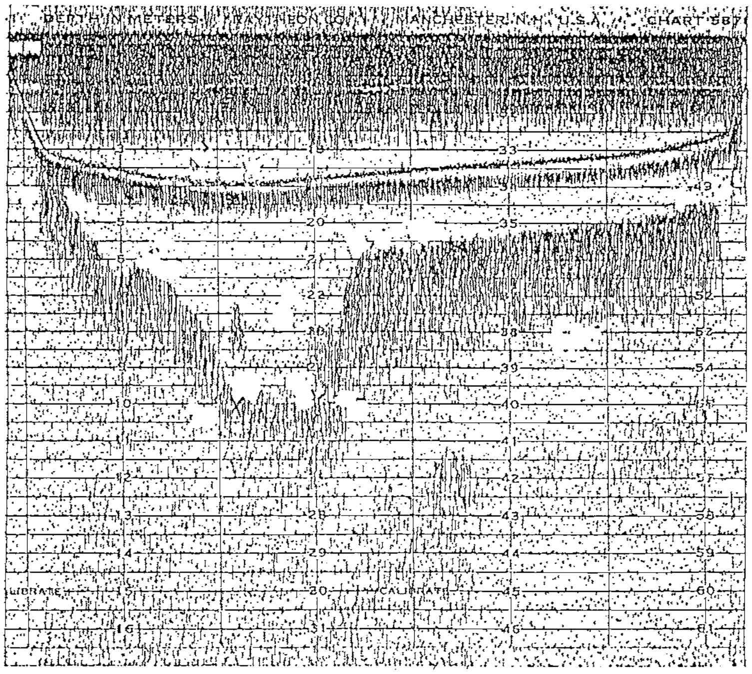


Figure 8.9 Sub-bottom Seismic Profiles, Inner Pelorus Sound

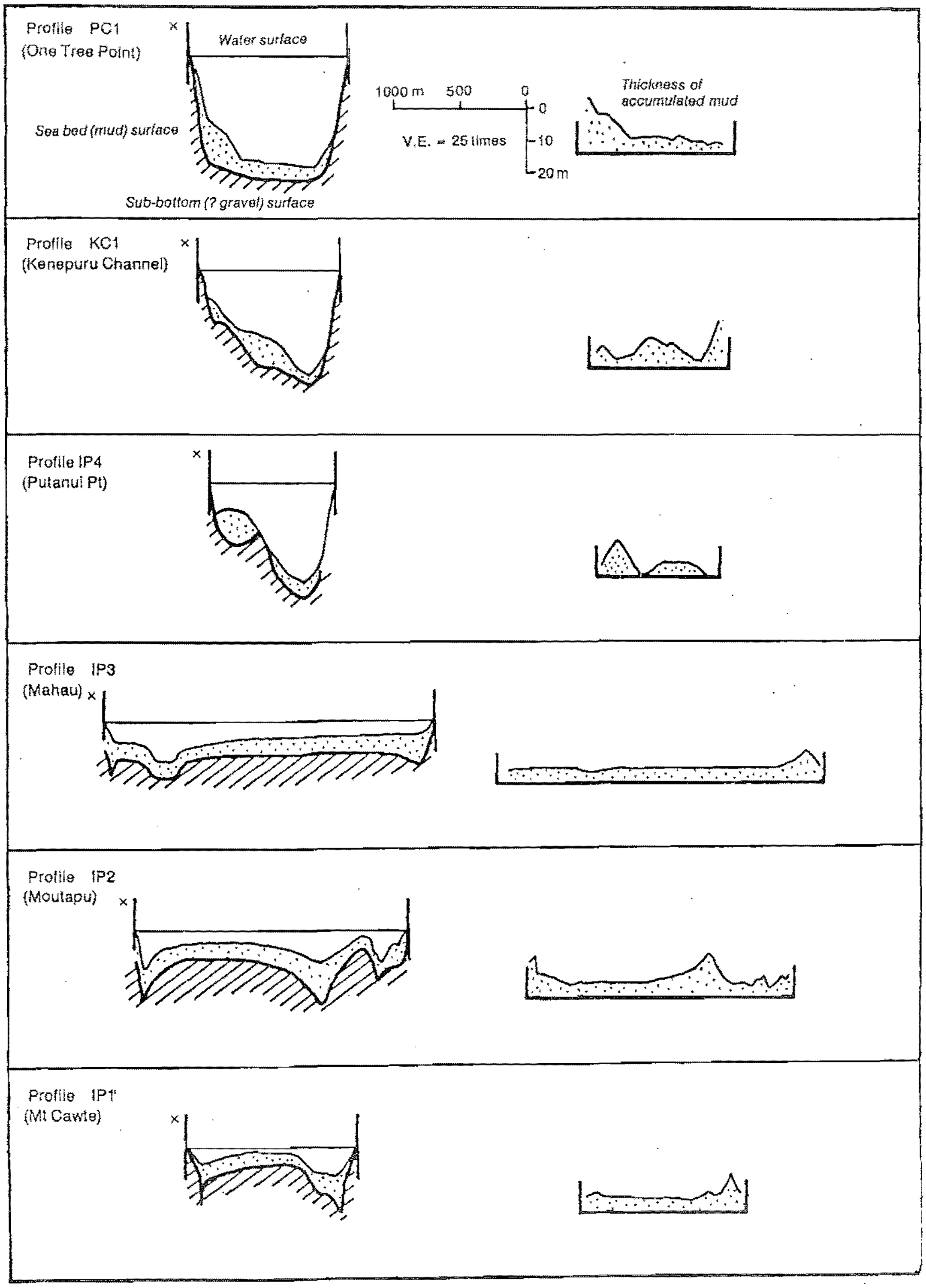


Figure 8.10 Sub-bottom Seismic Profiles, Kenepuru Sound

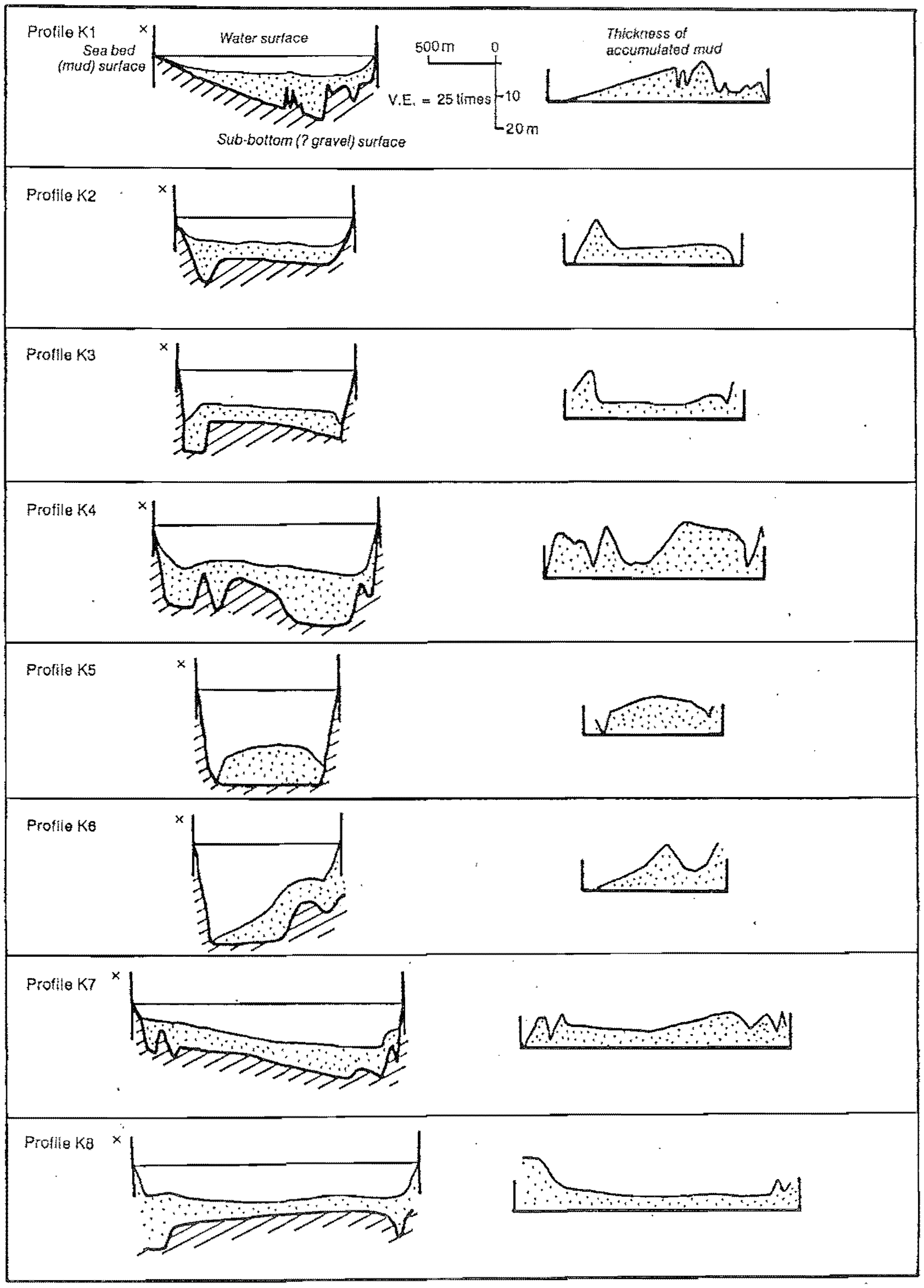


Figure 8.11 Sub-bottom Seismic Profiles, Pelorus Channel and Nydia Bay

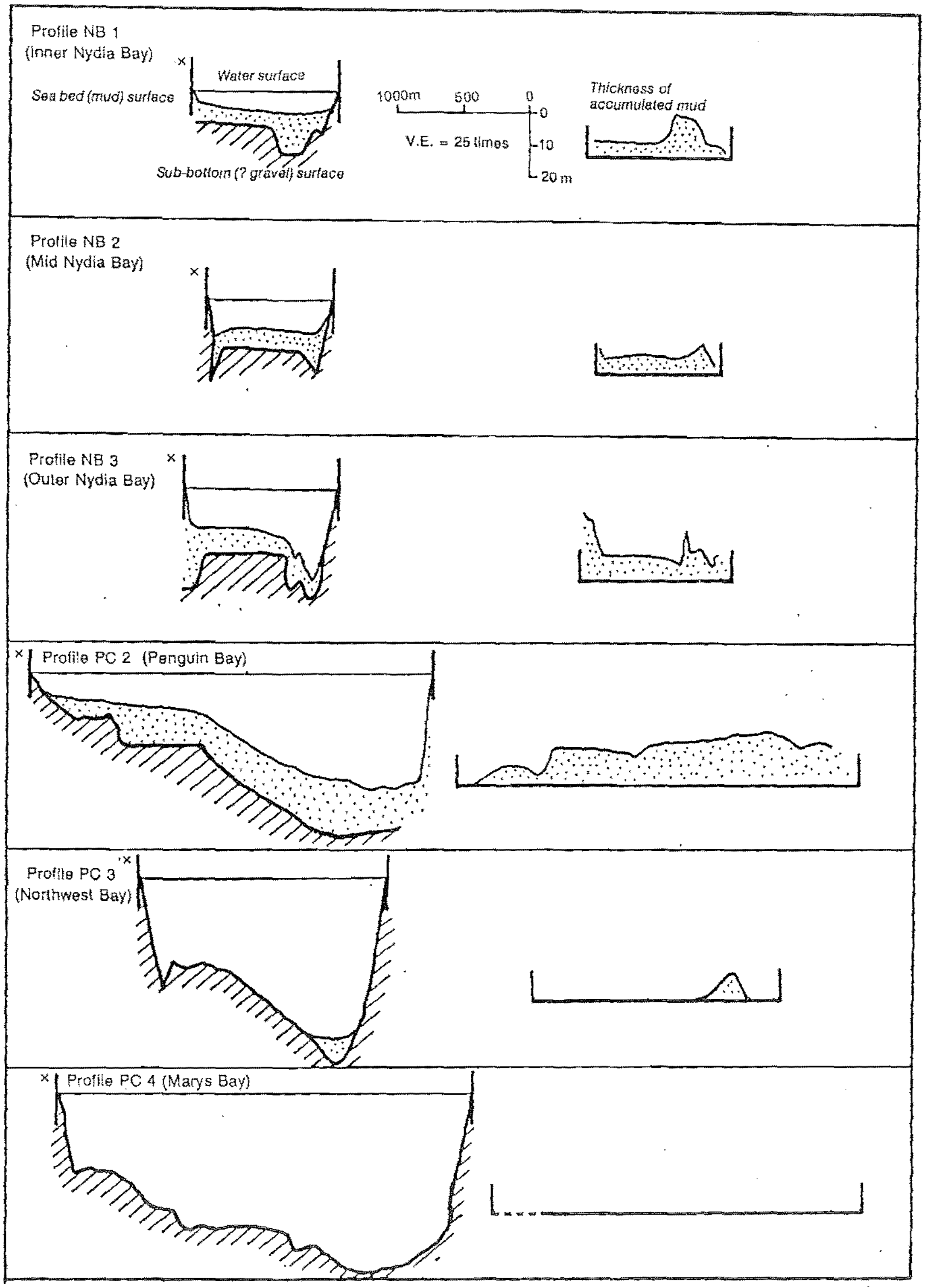


Figure 8.12 Sub-bottom Seismic Profiles, Tennyson Inlet

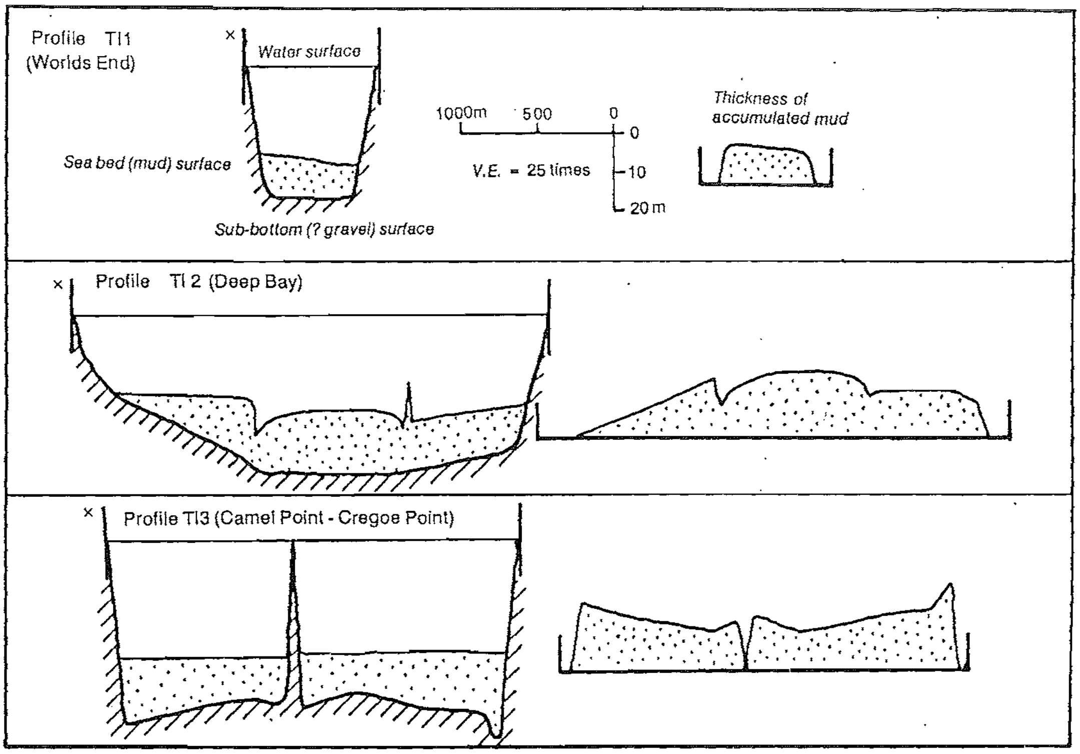


Figure 8.13

Location Map of Sub-bottom Profiles, Figures 8.8 to 8.12 Pelorus Sound, Kenepuru Sound, Tennyson Inlet.

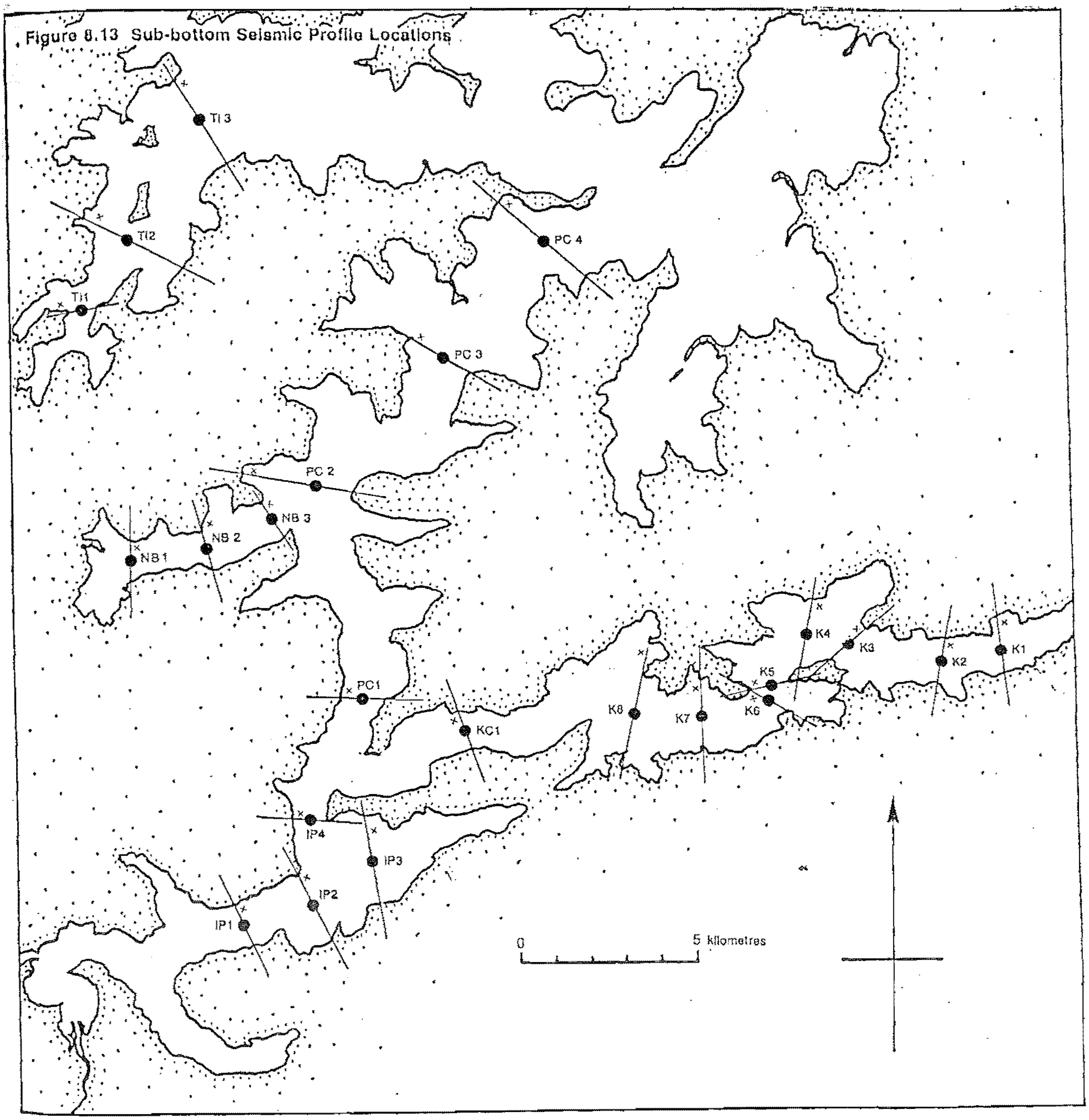


Table 8.2

Sedimentation Rates, Pelorus Sound

(Compare to Profiles, Figures 8.9 to 8.12)

ProfileLabel		Width of Sed in XSect (m)	Mean Depth of sediment in x sect (m)	Mean Depth *Sub-regions* (m)	Mean in x-sect/ Mean Over all (Ratio d / 7.33m)	Rate per year over 6,000yr (mm/yr)
Inner Pelorus						
IP 1	Mt Cawte	1240	4.10		0.56	0.68
IP 2	Moutapu	2000	5.97		0.81	0.99
IP 3	Mahau	2450	7.42		1.01	1.24
IP 4	Putanui Point	830	5.52		0.75	0.92
Inner Pelorus Mean				*5.75*		*0.96*
Pelorus Channel						
PC 1	One Tree Point	1170	5.96		0.81	0.99
PC 2	Penguin Bay		1070	6.92		0.94
	1.15					
PC 3	Northwest Bay	310	4.60		0.63	0.77
PC 4	Marys Bay		0			
Pelorus Channel Mean				*5.83*		*1.18*
Nydia Bay						
NB 1	Inner	1070	5.92		0.81	0.99
NB 2	Mid	930	6.13		0.84	1.02
NB 3	Outer	1100	9.01		1.23	1.50
Nydia Bay Mean				*7.02*		*1.17*
Kenepuru						
K1	Upper	1655	5.63		0.77	0.94
K2		1170	6.04		0.82	1.01
K3		1310	6.93		0.95	1.16
K4		1655	11.32		1.54	1.89
K5		1000	8.42		1.15	1.40
K6		970	7.64		1.04	1.27
K7		2000	7.04		0.96	1.17
K8	Lower	2140	6.38		0.87	1.06
Kenepuru Mean				*7.43*		*1.24*
KC1		1310	3.63		0.49	0.60
Tennyson Inlet						
TI 1	Worlds End	620	8.20		1.12	1.37
TI 2	Deep Bay	2590	11.97		1.63	2.00
TI 3	Gregoe Pt	2520	12.77		1.74	2.13
Tennysin Inlet Mran				*10.98*		*1.83*
Mean of all Profiles				**7.33**		**1.22**

Calculated from digitised areas on Figures 8.9 to 8.12, Initially measured by seismic profiles.

Mean Thicknesses of Bottom Sediments

Mean values of thickness at each location were calculated by digitising the area of accumulation and dividing by the width over which sediment had acumulated. Values for each profile are listed by sub-region in Table 8.2. The thickest body of mud was found in Tennyson Inlet, with a mean depth in one cross-section of 12.97m. In some locations in the Pelorus Channel (Marys Bay, PC 4), no mud cover could be identified. These locations are subject to tidal scour.

The mean thickness of sediment of over all profiles was 7.33m.

Sub-regional Variations

The mean depth in the inner Pelorus was 5.75m, in the Pelorus Channel 5.83m, and in Kenepuru Sound 7.43m. In a marginal embayment of Pelorus Sound (Nydia Bay) mean thickness was 7.02m, and in Tennyson Inlet thickness was 10.93m.

In the fourth column of Table 8.2 are shown ratio values for the mean mud thickness at each location as a proportion of the overall mean thickness(7.33m).

Inner Pelorus sites have values of 0.56 to 1.01 times mean thickness, Pelorus Channel from 0.63 to 0.94, and Kenepuru Sound from 0.77 to 1.54. Nydia Bay values range from 0.81 to 1.23, and Tennyson Inlet from 1.12 to 1.74.

It is significant to note that the thicknesses of sediment in the inner Pelorus are not higher than in other sub-regions, despite proximity to a major river source. Higher values are found in Kenepuru Sound and in Nydia Bay i.e. in marginal embayments of the main tidal channel. The thickest mean accumulations were found in the deepest waters - in Tennyson Inlet - but other than this sub-regional difference the thickness of sediment does not correlate with peak depth in the profile.

Variation within Profiles

Profile Types

On the basis of profile bathymetric form and the distribution of sediment within the profile, two profile types can be recognised. The first is a channel profile (PC1, KC1, IP4, K5, K6, PC3, PC4). These have a deep and narrow channel form and an uneven distribution of sediment within the profile. Some profiles show evidence of some tidal scour on the flanks of channels (KC1, IP4, K5, K6) and elements of the W-form profile referred to above. Others show a principal central channel (PC1) or a profile largely devoid of sediment (PC3, PC4).

The second profile form is an embayment profile (IP1 to 3, K1 to 9 not K5, NB1 to 3, TI 1 to 3). These profiles range from having a broad shallow form (IP1 to 3) to a deep form (TI1, TI3), but are distinguished from channel profiles on the basis of the distribution of sediments within the sub-bottom frame. All have a continuous sediment cover over the width of the profile except on the most steeply sloping nearshore sectors. Some also show the superimposition of a channel form on the surface (K3, NB2, NB3).

Distribution of Sediment across an Uneven Sub-bottom

Two patterns of distribution can be observed. In inner (shallow) sites the sediment overlay drapes the sub-bottom form but does not conceal it (IP1 to IP3). In each of these cases, sub-bottom highpoints are reflected in bottom highpoints. In Kenepuru Sound the opposite pattern prevails. Sediment drapes conceal a detailed sub-bottom topography. Nydia Bay profiles (NB1 to 3) show a mixture of both distribution types, in which in NB3 the sub-bottom form is concealed on one side of the bay, and revealed on the other.

Sedimentation rates

The thickness of sediment gives an estimate only of gross sedimentation rate. Its value here is as an index of variation from location to location. The right-hand column of Table 8.2 shows values calculated in mm/year from sediment thickness over an arbitrary baseline of 6,000 years. Sea level is recognised to have stabilised at about its present level between 5,000 and 7,000 years ago. The detailed investigation of sedimentation rates and of dates of landscape change is a matter for subsequent investigation.

Sediment thickness in channel profiles is not considered as a useful index of sub-regional sedimentation rates due to the role of hydraulic scour. Rates in marginal embayments and in Kenepuru Sound can be treated with greater confidence. The mean rate in the Kenepuru Sound is calculated at 1.24 mm/yr, in Nydia Bay at 1.17 mm/yr, and in Tennyson Inlet at 1.83 mm/yr. The mean of these values is 1.41 mm/year.

The mean sedimentation rate calculated for the inner Pelorus profiles is 0.96mm/year. This rate (based on thickness of accumulated sediments) is significant, in view of both of the proximity of the Pelorus River, and of previous interpretations made of sediment behaviour.

> Carter (1976, p263) wrote:
> "Muds are thick at the head [inner Pelorus] where an extensive delta extend from the river mouths, mud gradually thin seawards and then thicken markedly in the vicinity of the Sound entrance."

The assumption that rates of sediment accumulation are highest in the inner Sounds compared to the middle reaches must be revised in the light of the evidence presented above. Two factors, interacting, can be seen as determining this. These are sub-bottom form, and hydraulics. The sub-bottom lies close to present sea-level in the inner Sound, and as a result offers limited scope for thick sediment accumulation in the presence of tidal scour. The bottm mud drape follows the sub-bottom profile, suggesting a balance in control between sub-bottom morphology and tidal processes of sediment redistribution.

Lewis and Mildenhall (1985) report on sub-bottom stratigraphy in Evans Bay, Wellington Harbour. Accumulation of laminated sandy muds above a surface dated at 10,350 years B.P., overtopped by finer muds showed thicknesses comparable to those reported here for the Sounds. The former sandier sequence was 3.5m thick, the latter muddy sequence 6 to 9m thick. A sedimentation rate of 1.6mm/year was calculated for the period until c.9,000 years ago. variations since were correlated to varying inflows of sediments with migrating stream courses. These rates are comparable only to the sites in Pelorus Sound with the thickest accumulations of sediment.

While the Pelorus Sound system may act as a sediment trap, some refinement of the view of the Sounds as a double ended sediment trap seems warranted. First, account must be taken of sub-bottom morphology as an overall controlling factor. Secondly, the significance of *embayment* trapping may exceed the importance of Sound-head trapping of fine sediments delivered to the coast.

In the following section, a more detailed examination is made of the relationship between bottom form and sub-bottom form.

Offshore Sub-bottom Form

It has not been established in published or unpublished sources to what extent bottom topography can be attributed to sub-bottom form. The pre- or early Holocene in the Sounds was an era of fluvial activity in the valley bottoms. Incised terrace remnants have been mapped in the lower Pelorus River valley and at Linkwater, but no systematic investigation has been completed on the distribution of terraces and antecedent fluvial channels in the "flooded" Sounds. Special reference is made to two case studies - the axial channel of Pelorus Sound including Nydia Bay and Tory Channel and its marginal bays.

It was apparent from the long-profile data presented in Figures 8.1 and 8.2, that components of the long (axial or thalweg) profiles of the present bed of the Sounds could be accounted for with reference to an antecedent river long-profile form. However in the long profile there are to be found "mounds" and "holes" which might be attributed to hydraulic processes of sediment redistribution. In the relation of marginal bays to the principal channels there are found baymouth bar forms and also marginal channels that demand more detailed investigation.

River Gradients and Terrace Remnants

In Chapter 2, the hypothesis of block tilting and drainage reversal were discussed. The view proposed in that chapter was that the cited evidence for submarine terrace remnants in the Queen Charlotte Sound (Beck, 1964) had not been substantiated and that the hypothesis of drainage reversal was only one of several possible explanations.

It would appear, from the evidence presented above, that the best source of evidence for geomorphic interpretation of the Sounds landscape and its sub-bottom form lies in a better recognition of the patterns of remnant antecedent fluvial forms and in correlation between subaerial and submarine evidence. This observation is a departure from the manner in which the Sounds landscape has been previously interpreted (i.e. with a focus on the region as a tectonically controlled tilting block). It is also in part a contradiction of the proposition of this thesis - that the key to understanding coastal sedimentation lies in recognising the fate of sedimentary fractions. This point will be raised again in the conclusions of this chapter.

River long profile gradients and the distribution of subaerial terrace surfaces are the two elements of subaerial landscape form which are of the most direct value to the interpretation of sub-bottom form in the offshore domain.

The river long profile gradients for local streams depend on the factors of coastal gradient discussed in Chapter 6. The characteristic long profile of streams is concave. Consequently the gradient of a shoreline site will tend to reflect the position which that site would have held in the fluvial landscape, either in the headwaters or in the lower reaches. For the major river inflows (notably the Pelorus) the gradient is largely set by landscape factors ouside the Sounds. The mean gradient of the lower 40km of the Pelorus (including the Rai and Opouri Rivers) is 1:400. The lower reaches have a lower gradient. This is identical with the gradient in the lower Wairau River (Brown, 1981b).

Valley bottom fluvial forms are generally drowned within the Sounds region. It is only in the inner areas in the Pelorus, Queen Charlotte and Kenepuru Sounds where substantial surfaces are subaerial. Plate 8.1a shows an alluvial fan surface in the northern Kenepuru.

Terrace remnants in the inner Pelorus were discussed in Chapter 2 as having been identified in the Linkwater areas and in the lower reaches of the Pelorus River (Beck, 1964; Esler, 1984). Plate 8.1b shows terrace remnants in the Kaituna Valley, south of Havelock.

Remnant terraces have been identified by the author and others (see Chapter 2) in bayheads of the Pelorus Channel, notably Paradise Bay, Mud Bay, and especially Nydia Bay. Shoreline deposits in Nydia Bay seen in Plate 8.1c relate to antecedent landscape conditions, which developed the substantial fan deposits upslope. In the head of the bay in the background, terrace remnents can be traced to the topp of the alluvial valley flats.

Terraces and colluvial fans of this extent are also found in Tennyson Inlet, in Harvey Bay and Duncan Bay. A deeply weathered alluvial/colluvial surface on the east shore of Ngawhakawhiti Bay at up to 10m above sea level is being actively eroded by the sea. Active erosion is also found in Harvey Bay, and in Nydia Bay. The significance of the terrace remnants is the manner in which they serve as an index of the pre-Holocene or early Holocene dynamics of the sub-aerial landscape; and also as a marker surface which has value in tracing forms from one location in the Sounds to another, and especially here, between the catchment and the offshore.

Plate 8.1
Alluvial Forms in the Subaerial Landscape

Plate 8.1a

Alluvial fans, Northern Kenepuru Sound

Nopera fan, looking north.

NZMS 260 P 27 GS 9003

1984

Photograph, W. R. Esler

Plate 8.1b

Post glacial degradation terraces near State Highway Bridge over Dangerous Creek, Kaitua Valley.

NZMS 260 P 27 GR 740 803

1984

Photograph, W. R. Esler.

Plate 6.3c

Remnants of the "Nydia Surface" in Nydia Bay,

NZMS 260 P 27 GS 7603

Looking south. Terrace remnants can be traced along the axis of the valley in the rear of the view.

1984

There is some importance in distinguishing the terrace surface from the remnant terrace form. While the aggradation of a surface can be attributed to the abundance of sediment production in a catchment the development of an incised remnant (referred to as a terrace) reflects post-depositional erosion. It is generally accepted that there are two factors involved in terrace cutting. These are upstream changes in sediment load and thus changes in the excess stream capacity to transport sediment; and downstream changes in base level. There will be a diminishment of the role of the latter the further "inland" is the site under consideration.

Incised surfaces can be found at the Kenepuru Head and in the Clova Bay catchments, but there is insufficient evidence to relate these to any other terrace remnants in the Sounds. In the Queen Charlotte Sound there is no published evidence of terrace remnants to correlate with the Pelorus Sound, despite the apparent reference to "drowned terraces" by Beck (1964) discussed in Chapter 2. Because of the proximity of the Queen Charlotte Sound to the sea (the "Cook Strait canyon") during the Pleistocene sea level low, it might be expected to find some base level related incisions which might have risen to terraces, with the radical fluctuations in base level that resulted. In the absence of seismic profiles interpretation of terrace remnants or their absence is speculative. However, it seems likely that the fundamental reason for the absence of terraces in the Queen Charlotte axial Sound is the lack of substantial catchment sources of sediment.

Terrace remnants can be traced more than 50km inland up the Pelorus River and its tributaries into the Opouri River. The vertical extent of the terraces diminishes inland. At Havelock, remnants of an extensive surface can be traced from the site of Havelock itself (see Map 2),across the Pelorus to Whakaretu Bay, to numerous sites in the re-entrants immediately north and west of Canvastown. Esler(1984) makes the correlation between this surface, which he refers to as the "Havelock Surface", and prominent terrace remnants in Kaiuma Bay. Beck(1964) mapped the Havelock remnants and those in the Linkwater area as "Speargrass Formation" from the Wairau terrace sequence (Figure 2.3), but such a mapping should be regarded as tentative until a fuller understanding of the Pelorus River system is recognised. No correlations have been made of the terrace remnants elsewhere in the Pelorus Sound reported here but as will be demonstrated shortly, these can be related to submarine forms.

Sub-bottom Form

Analysis is based on the sub-bottom seismic profiles discussed in the previous section and summarised in miniature in Figures 8.8 to 8.12. The original profiles contained substantially greater detail than is possible to reproduce in the Figures.

The sub-bottom thalweg is traced in long profile in Figure 8.14 for the inner Pelorus and the Kenepuru. Superimposed on each is the bottom thalweg, for the Pelorus Sound and the bottom axis for the Kenepuru. The depths of "mud infill" shown in these profiles are the channel infill and not the average depths of mud across the section. This is apparent if Figure 8.14a is compared with the relevant profiles in Figures 8.9 to 8.12. This depth is either thicker or thinner than that shown in Figure 8.14, depending on whether the mud drape has tended to infill the channel or be scoured out from it.

The most important observation with regard to the sub-bottom profiles is their general coherence with a fluvial channel long profile form. The inner Pelorus long profile from Havelock to Tawero Point gives a sub-bottom gradient of 1:480 against a bottom gradient of 1:520. These gradients are based on measurements of the axis of the valley rather than on the meandering channel (thalweg) gradient. The sub-bottom gradient is more consistent along its length than the bottom gradient. The same "stepped profile" form is evident, but at a much smaller amplitude. The maximum thickness of infill is 14m.

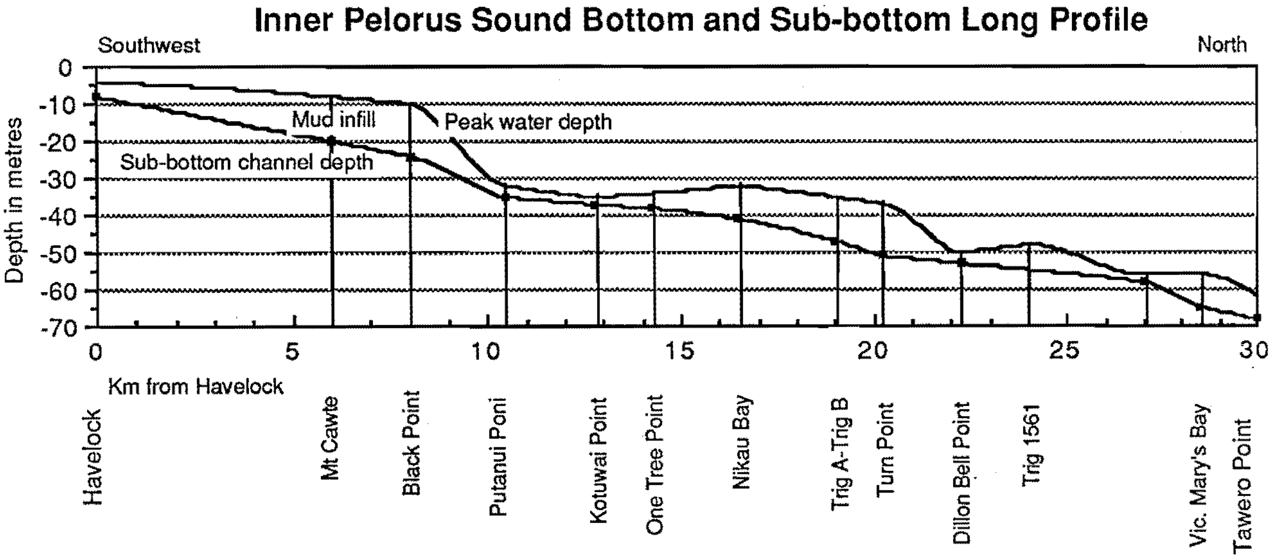
The Kenepuru profile shows some irregularities in sub-bottom profile, notably a reversal of slope between Weka Point and Island Point. The sea bottom at Weka Point is shown to have been scoured of all the mud drape in the channel at Weka Point and the bottom at this point rests on the "sub-bottom" materials. It would appear that the reversal of the sub-bottom long profile gradient at this point can be attributed to the tidal hydraulic scour of the "sub-bottom", probably immediately after flooding and before the deposition of the mud drape.

Nydia Bay profiles in Figure 8.15 show evidence of a number of sub-bottom features which are significant in terms of the interpretation of sub-bottom form on a wider basis.

Figure 8.14

Long Profiles of Sub-bottom Pelorus and Kenepuru Sound

Figure 8.14 a

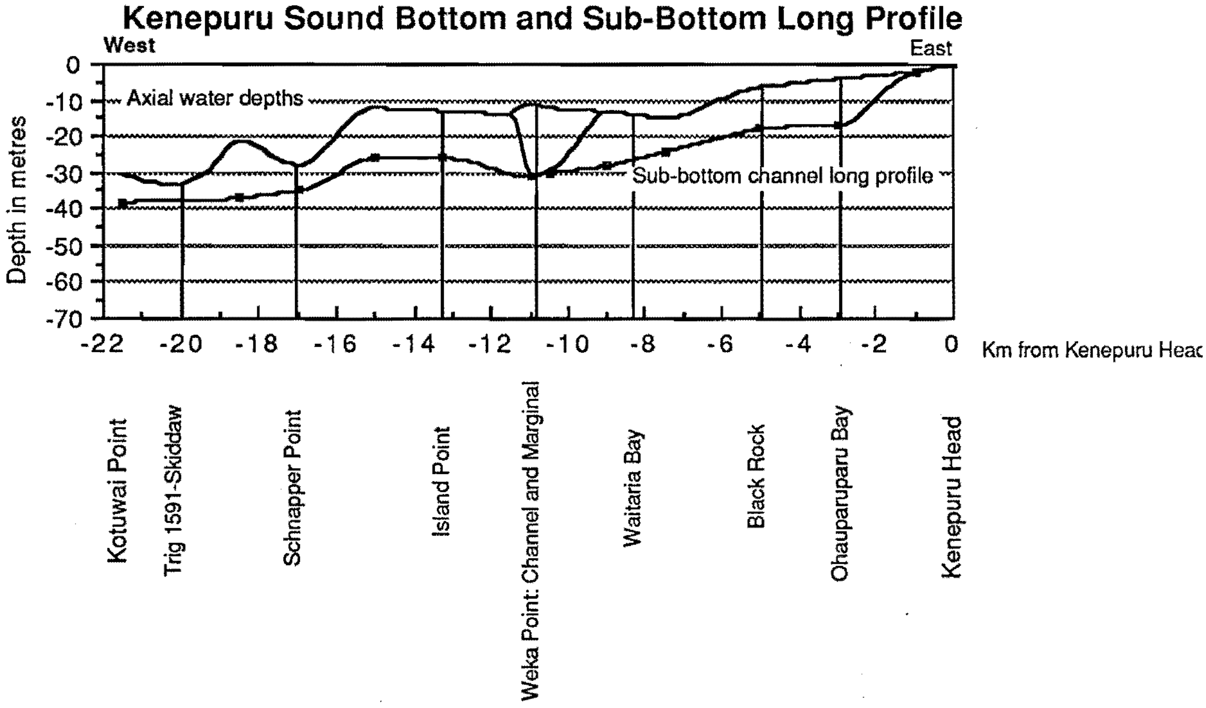


Inner Pelorus Sound Bottom and Sub-bottom Long Profile

Stepped pattern in long profile of bathymetry is also apparent in the sub-bottom form,

Sub-bottom line in Pelorus Sound traces the deepest point (thalweg) not the axis.

Figure 8.14 b



Kenepuru Sound Bottom and Sub-Bottom Long Profile

Nydia Bay: Case-study of Sub-bottom Form

The three profiles in Figure 8.12 evidence the pattern that was referred to above as a W-form with bottom channels proximal to headlands and the shore on either one or both sides of the bay. The bottom form was apparent on the bathymetric map of the Pelorus Channel (Figure 8.6).

Examination of the sub-bottom profiles shows a correlation between bottom and sub-bottom channel form. Two interpretations are possible for the sub-bottom channels. One is that they are tidally scoured, like the Kenepuru Sound bottom near Weka Point, or the Tory Channel axis. The other interpretation is that they are antecedent forms which can be traced to a fluvial origin. The evaluation as to which interpretation is the most coherent hangs largely on the long profile of the sub-bottom channels and on the interpretation of the surface into which they have been incised.

The long profile of all W-form channels in the sub-bottom would appear to be accordant with the axial channels into which they "flow", and to have a long profile which deepens in one direction only. This is not usually so for tidally scoured channels which, as has been shown, are often most deeply scoured in the central portions. This suggests a river origin for most if not all the sub-bottom marginal channels.

The surfaces which lie between the channels (i.e. the bay-mouth mounds) are therefore of particular interest. Figure 8.15 shows a long profile of Nydia Bay. The right-hand portion of the graph continues as a long profile of Pelorus Sound to Tawero Point. Three lines are plotted.

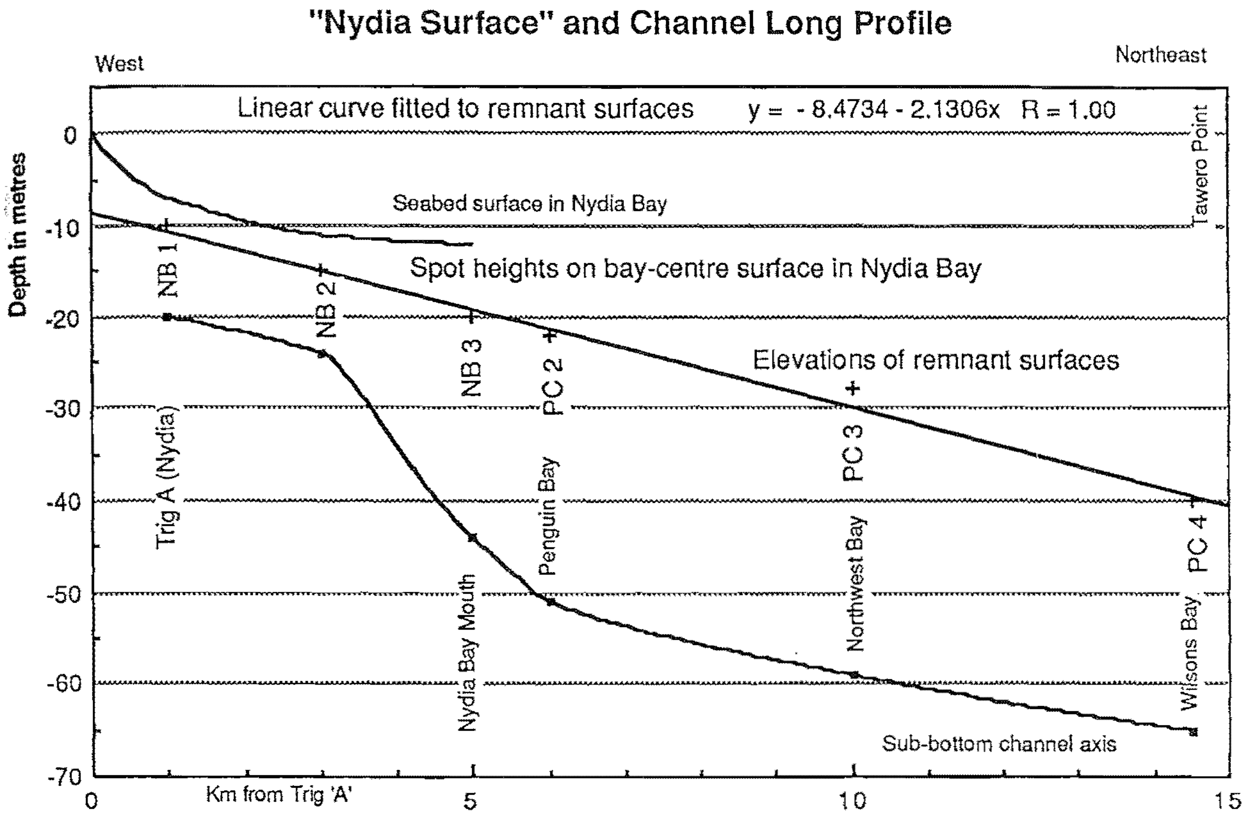
The top line is the profile of the bottom of Nydia Bay shown in Figure 8.2c. This is discordant with the Pelorus channel bottom gradient.

The bottom line traces the thalweg of the sub-bottom channel on the southern side of the bay which can be seen to be accordant with the sub-bottom thalweg of Pelorus Channel. This sub-bottom profile is continued down the Pelorus Sound to Tawero Point.

The middle line is plotted through a series of points taken on "mound" surfaces, within Nydia Bay or within marginal bays of Pelorus Sound. Points were taken from profiles in Penguin Bay, Northwest Bay, and Wilsons Bay. The points at

Figure 8.15

Sub-bottom Surface Remnants
Pelorus Sound



Long profiles taken from Nydia bay extending to Tawero Point in Pelorus Channel.

Lower line traces sub-bottom depths on the axis of Nydia Bay and the sub-bottom depth of the Pelorus Channel to Tawro Point. (See Figure 8.14)

The upper line traces the mud surface in Nydia Bay.

+ Symbols identify spot heights taken from what are interpreted as a remnant surface in Ntdia Bay and in bays flanking the Pelorus Sound. A linear curve fit through the points over a 14km section gives an excellent regression (r=1), suggesting that the points lay on a common surface of river ori gin.

which the depths were obtained from the marginal Pelorus bays are marked on Figure 8.13. The line is a linear curve fit through three points within Nydia Bay, and three points taken in the marginal bays mentioned above.

Interpretation

The sub-bottom profiles taken along the axis of the marginal channels show an accordance with the sub-bottom in the Pelorus Channel, as discussed above. The origin of these channels is attributed to flow of the antecedent river.

The surficial form of the sub-bottom underlying the baymouth mound has the appearance of a remnant river terrace surface. In particular, the sharp edge of the forms is consistent with an interpretation as a terrace-edge incised by stream flow.

To test the extent to which points within Nydia Bay and those lying outside the bay might lie on a related surface a linear curve was fitted through the points. This is shown in Figure 8.15 . The correlation (r) between points lying on this surface is statistically perfect (Pearsons R=1.00), which, though not of itself geomorphic proof, shows a strong geometric relation between the depths of remnant surfaces.

The gradient of the line is 1:475, conformable with a surface of fluvial origin (given that the lower Pelorus has a gradient of 1:400) and the excellent correlation over the 14km axial distance suggests that the Nydia spot heights and the Pelorus marginal spot heights have a geomorphic significance.

Projecting the line of the surface landwards, a prominent subaerial feature can be identified on Map 3 as Trig "A". The trig has an elevation of 2m on a peninsula projecting into Nydia Bay (see Map 3, GR 748 153).

The deposit which underlies the Trig surface is imbricated alluvium to a depth of between 1 and 5m. The surface is incised by a variety of channel remnants, which conform to a drainage surface higher than that of streams currently draining the catchments to the rear of the peninsula. Remnants of this higher surface can be seen lying atop various islands and intertidal shoals in the western part of the bay. On the southeast shore of the inner part of the bay the shore comprises well weathered alluvium and colluvium that is cliffed at the shore to a height of up to 5m, as seen in Plate 2.2c. In the bayhead stream catchments, terrace remnants can be traced 2 km up the valley to the south, to GR 762 013. The terrace form can be seen from the form of contour lines on Map 3 in the vicinity of that grid. Projected into the bay, this surface would conform to the surface found at the Trig A peninsula. The streams in the bayheads have incised into this higher surface and material will have been redistributed down channel into the area which is now the offshore.

Evaluation

It seems likely that a correlation can be made between the Quaternary or early Holocene catchment behaviour and the aggradation of a surface in the bay area which is identified as the bay-centre surface in the sub-bottom profiles. The intersect of the linear regression through the sub-bottom points gives an intersect at Trig A at 8.5m below present sea level. This difference between the sub-bottom terrace and the Trig surface may be too large to assign them to the same surface, although the gradient of the sub-bottom surface could be expected to steepen towards the bayhead (i.e. the curve fit should be exponential and not linear in the upper reaches). The coherence among elements of surface morphology appears to warrant regarding the sub-bottom surfaces identified as remnants of a fluvial aggradation surface and their adjacent marginal channels as being attributable to post-depositional incision during sea level lows.

Extending the interpretation down the Sound towards Tawero point, there is evidence for an aggradation surface which extended across the Pelorus Channel and into the marginal bays, and that this surface extended at the gradient of between 1 in 450 and 1 in 500 to Tawero Point. The surface has not been traced further. Near Wilsons Bay the sub-bottom pattern would suggest that the subsequent incision by the antecedent "Pelorus River" incised terraces over 25 m in elevation above the river channel. This incised terrace surface is named here the "Nydia" surface, after the bay in which its origin can be most clearly traced.

In the transverse profiles in the Pelorus Channel south of Nydia no equivalently clear terrace remnants can be traced. It is possible that incision has modified or removed the antecedent surface, or that the surface in the lower Pelorus channel (the Nydia remnants) are related to a different fluvial system. No terrace remnants are evident in the Kenepuru Sound.

The interpretation of terrace remnants in marginal bays, and their subsequent incision, seems to account well for the distribution of W-form baymouths in the Pelorus Channel. It is possible to apply the interpretation to the similar pattern found in Tory Channel.

Tory Channel: Interpretation Extended

It has been established that the deep axial channel can in part be attributable to tidal scour. It was suggested above that one interpretation of the marginal bay discordance was the tidal scour of a fluvial aggradation surface, as distinct from substantial infilling of the bays by sedimentation. If tidal scour is sufficient explanation for the origin of the channel itself, it may also account for the origin of the W-form channels as features of hydraulic origin.

However, there is morphological similarity in the Tory Channel features to those in the Pelorus Channel. In particular, the manner in which the channel thalwegs deepen towards the channel in a one-directional manner suggests that they are of fluvial and not tidal origin. This would suggest that the incision of the ?alluvial surface which infills the bays is attributable initially to fluvial processes and subsequently to tidal scour.

If the marginal bay surfaces are of fluvial origin were they part of the anetcedent Queen Charlotte River as it flowed eastwards through the Tory Valley, or part of a local Tory River surface? The limiting factor on gradient of this river is the rock-bottom at the mouth of the Tory Channel, which is at 20 fathoms (Figure 8.5). This is the present depth of the (mud-covered) bed of the Queen Charlotte in the areas inland from Dieffenbach Point. This would mean that the antecedent river system would have lacked any appreciable gradient to flow seawards unless there had been aggradation in the inner portions of Queen Charlotte Sound. There is, however, no evidence of surfaces to support such an hypothesis. It would seem necessary to accept that the surfaces in the marginal bays of Tory Channel should be attributed to a local Tory River surface. If part of a Tory "surface", in which direction did the river flow?

The orientation of the gradient of the best-fit line through the marginal bay depths shown in Figure 8.7b would suggest that the antecedent Tory surface was deposited by a river system flowing eastwards, from a catchment head in the middle or at the eastern end of Tory Channel. In the bayhead at Okukari Bay (Map 1, GR 620 000) the fan surfaces show a distinct "two level" incised form suggesting incision of a higher remnant. No dates of the surfaces are available.

For a river to have flowed eastwards, the present channel at the heads at the eastern end of the Channel, where it enters Cook Strait, would need to have been sealed. The ridge has clearly been continuous at some stage in its history, and energetic cliffing by southerly swells is a characteristic of the outer coast.

This would account for the breaching of the catchment divide. Before breaching, aggradation in the Tory River from local catchment sources would have led to the development of the Tory surface, remnants of which underlie the baymouth accumulations. These are probably also surficially reworked by tidal processes, with the deposition of sands and shell.

Under the hypothesis which is proposed here, after breaching while sea level was at its present level or lower, the Tory River would have been diverted into Cook Strait. For a period, two rivers may have flowed, one east, and one west, with a catchment divide in the middle of the Channel length. Headward stream capture would proceed in a westerly direction with the stream flow energy offered by the radical drop of baselevel into Cook Strait. Eventual capture along the length of the Channel may have taken place, possibly also with the diversion of the antecedent Queen Charlotte River through the Channel. Streamflow from the marginal Tory Channel Bays was insufficient to entirely remove the bay-bottom surface, and so the central portions remain as remnants of this antecedent surface.

While there is only limited evidence for this interpretation of Quaternary landscape change in the valley bottoms, the focus on relict fluvial forms, and on hydraulic modifications of these, is an approach which offers good potential for testing and either validating or modifying these hypotheses. This is distinct from several other approaches to the interpretation of geomorphic patterns in the Sounds- specifically, the hypotheses of tilting, or drainage reversal (W.R Lauder, 1970) or submarine ridge notching (Gibb, 1979).

Interpretations

This chapter has presented an analysis of the bottom and sub-bottom morphology of the principal channels and embayments of the Malborough Sounds. It set out to identify the extent to which the pattern of sediment accumulation could be used as a means to identify the operation of morphologic or of mobility traps within the offshore domains, and at what scale these traps might be seen to operate.

As well as reaching certain conclusions pertaining to sedimentation it has been possible also to extend the interpretation of offshore form to a revision of certain propositions about the origin of elements of bathymetric form. This has led to the identification of some significant new features of antecedent land form.

These points are picked up in Chapter 10. The following discussion is focussed on the sedimentary aspects of the analysis.

At the broadest scale, the Pelorus Sound has been seen to trap sediment to a mean depth of 7.33m. Spatial variation in thickness of accumulated sediment does not reflect a primary control by proximity to the inflow of sediments at the Pelorus River end, but to morphologic factors in the receiving environment. In marginal embayments - Nydia Bay - and in the Kenepuru Sound, sediment thicknesses are greater than in the inner Pelorus. In the Kenepuru Sound more than any other site, sediment is least responsive to sub-bottom form. Large marginal embayments would seem therefore to act as "morphologic traps".

Along the axis of the Pelorus Sound, a stepped profile was seen in both the bottom and the sub-bottom form, and was associated with alternating confinement and unconfinement of the tidal flows. At each of these steps, a degree of morphologic trapping would appear to occur. In general, channel sites are dominated by hydraulic mobility.

The detailed distribution of sediments was shown to indicate elements of control exercised by hydraulics and by antecedent form.

Hydraulic domination of sediment distribution prevails in channel areas where tidal currents are most effective in redistributing material. This pattern is seen in the scouring of the sub-bottom surface of any detectable mud drape and in some cases (Tory Channel, Weka Point in the Kenepuru Sound, and in the Pelorus Channel at Tawero Point) in erosion of the sub-bottom itself. This was highlighted as an illustration of the concept of the transitional control which exists in a region of strong topographic form and variable hydraulic effectiveness.

These relationships indicate that in the offshore domain the transition between a morphologic and a mobility trap depends primarily on the level of tidal energy in the environment. This depends on a locational factor i.e. the relation of the site in question to the axial channels along which tidal flows occur, and to the degree of *embayment* of a site. While data were available at only a limited number of marginal embayments, it would appear that sites which are "deeply embayed" (see Chapter 6) i.e. with a length more than twice the width at their mouth, have a significant element of sedimentary control in their bottom morphology.

It would also appear that the restatement of the Ordered Response Model made in Chapter 6 could be validly applied as a conceptual framework for offshore behaviour, on which a distinction can be made between offshore sites.

At levels of higher tidal energy (i.e. of higher relative mobility), there is a very clear differentiation between locations at which sediment accumulation takes place and those where scour takes place. In this high mobility situation, the transitional control between morphology and hydraulic control is radical- and could be regarded as a threshold over which control jumps from strong hydraulic domination of form, to minimal hydraulic control as the overlying sediment drape is removed. Hydraulic modification of the morphologic frame can then proceed, but at a much slower rate.

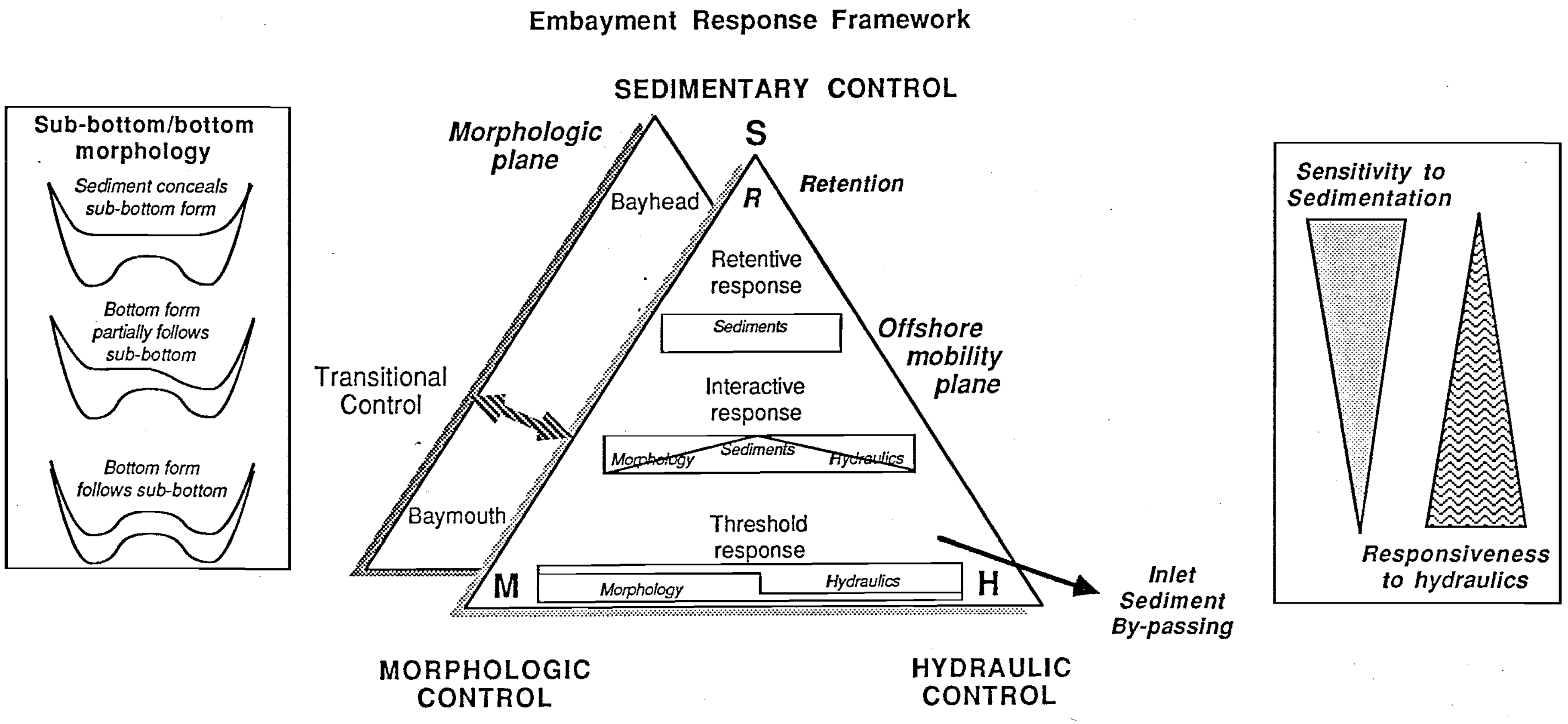
This transitional leap in control from hydraulics to morphology is pictured in Figure 8.16. It can also be visualised in terms of the Ordered Response framework as a sudden leap from a mobility trap to a morphologic trap. In these locations, the role of sediment is minimal: it is an entirely permissive element in a system whose behaviour is determined by the end-member controls of morphology and energy.

In zones of low mobility - such as might be expected in the bayheads of deeply embayed sites - it is to be anticipated the sedimentary control will dominate. In these sites the inflow of sediments will have the maximum role in determining site form and textural character.

In zones of intermediate mobility, the expression of transitional control identified above will be seen - and the morphological expression is in the partial hydraulic exploitation of the opportunity presented by sub-bottom morphology.

Reference was made during this chapter, to the statement that the investigation of sub-bottom morphology, and not of the fractionation of sediments, appeared to be the key to the understanding of submarine sedimentary behaviour. This observation was made on the grounds that sediment distribution appeared to be affected not so much by the inflow of sediments as by the influence of bottom morphology.

In the light of the interpretation of offshore behaviour in terms of transitional control, it is apparent that indeed in some situations - notably those with the highest hydraulic mobility- the defining role of sediments (and thus the value of the gauge of sediment fractionation) is relatively insignificant in terms of



Conceptual framework of Offshore Sediment Behaviour.
Three locations within embayment (Bayhead, mid-bay, baymouth) are distinguished according to their morphologic and hydraulic conditions.
Embayment response to sedimentation makes site dominated by morphology(in condition of where sediment has been scoured), hydraulics, or by sediment accumulation.

Figure 8.16
The Embayment Response Framework

a control on offshore behaviour. However, the contradiction can be resolved by the recognition that control is transitional between hydraulics, sediment character and morphology, and that in situations of moderate to low tidal energy, sediment texture and the nature of sediment inflows are liable to be determining factors on offshore behaviour.

The extent to which this can be observed in sediment textural patterns is evaluated in the following chapter.

Chapter 9

Embayment Sediment Trapping

The operational logic developed in the latter sections of Chapter 8 showed that in sites of high mobility, the transitional control that exists betweeen hydraulic and morphologic factors in offshore sediment dynamics operates in a manner likened to that of a threshold, in which there was an abrupt leap of control from hydraulic control and high responsiveness (in the presence of sediments) to morphologic control and low responsiveness (when the materials were mobilised in a rock walled inlet setting.) This fundamental relationship was recognised within the domain of ordered response, although a mechanistic analogy exists in the differences identified by Hjulström (1935) and Sundborg (1956) between the critical erosion velocities and the velocity required to maintain suspension transport for fine particles.

The focus in this chapter is on the next lower level of sedimentary mobility, as identified in Chapter 8. It was shown that with diminishing levels of tidal hydraulic control, offshore sediment systems should begin to evidence behaviours in which a transitional rather than a threshold response could be identified. On the basis of observations of the relative effectiveness of sediments in modifying sub-bottom morphology it was shown that in marginal embayments where the effects of tidal flows are relatively less dominant, in some cases (e.g. Nydia Bay) bottom form reflected sub-bottom form, and in some cases it masked it. In other cases of even lower mobility or higher sediment trapping (e.g. Kenepuru Sound) the role of sediment supply was primary.

It was proposed that in sites which were deeply embayed, a range of sedimentary behaviours should be expected at different sites along the length of the bays according to the relative tidal energy levels. In the outer reaches, the threshold control between hydraulic control and morphologic control would determine the sediment textures and the morphology. In the mid reaches, relatively high but diminishing mobility should develop the conditions of a mobility trap. In the bayhead areas it was shown that if hydraulic control was suppressed and morphologic trapping was strong then the primary control on sites form and sediment texture would be the sediment inflow itself. These relationships were summarised schematically in Figure 8.16.

The purpose of this chapter is to evaluate these propositions. It has two specific aims.

The first is to determine the magnitudes of sediment textural differences both within sites (i.e. within embayments) and between the sub-regions in which sampling took place (Pelorus Sound, Queen Charlotte Sound, Tory Channel). This first section establishes the appropriate scale of analysis for investigation of sediment fractionation in the offshore.

The second aim is to take the proposition that there should exist a transitional control along the axes of marginal bays, and examine whether or not such a pattern can be seen in the evidence of bay-profile sample texture.

From the total suite of offshore samples presented in Chapter 5 a number of case-study suites are presented here.

Variation in Grain-Size Distributions Within and Between Marginal Embayments

It is a convention in sedimentary studies to plot grain-size distribution such that the "measured frequencies are integrated to yield a curve relating grain size*D* to a quantity representing the percentage weight of all grains smaller than *D*." (Bagnold and Barndorff-Nielsen, 1980, p199). It has also been conventional to plot such curves on "probability paper", on which a (cumulative) normal distribution appears as a straight line. On such plots, the tails of the distribution are magnified against the centre portion. In this investigation, the summary measures of size and sorting for submarine samples have been the median grain size (50th percentile), and the Phi Quartile Range (half the difference between the 75th and the 25th percentiles, or (ø75 - ø25)/2). A prime intention of grain-size plots is to show clearly these values and how they plot in relation to the curve as a whole.

No particular import is attached here to an absolute "expected" distribution (e.g. log-normality) as distinct from relative differences between samples. The reason for this was spelled out in Chapter 5. In a trapping environment, or one of moderate to low mobility, the textural character of sediments will express both a source area and an hydraulic component. Therefore, to anticipate that the grain-size distribution will be normally distributed on either count (i.e. due to the normality of the supplied population, or normal because of hydraulic sorting) is inherently ambiguous.

For these reasons data are presented as a cumulative curve of logarithmic (phi) size and are plotted on an arithmetic y axis. Such a plot has the advantage of ease in interpreting the proportion of samples in each class.

In Figures 9.2 to 9.5 a total of 35 offshore samples are plotted in a standard format. The offshore samples were taken from Pelorus Sound (Four Fathom Bay, Nydia Bay, Maori Bay), Kenepuru Sound and the inner Pelorus (Mahakipawa Arm); from Queen Charlotte Sound (Grove Arm, Ngakuta Bay, Onahau and Ruakaka Bays); and from Tory Channel (Maraetai Bay, Hitaua Bay, Opua (Onepua) Bay, and Deep Bay). The samples are presented in such a sequence in the Figures with the replotting of some samples from preceding suites, that it is possible to identify similarities and differences between sites and between sub-regions. Figure 9.5b has a summary set of curves from a range of sub-regions. The grain-size curves are discussed in sequence.

Reference to Figure 5.4 shows that while Pelorus Sound offshore samples were predominantly mud (silt and clay) with low sand content (<20%), Tory Channel offshore samples included sand contents of up to 73%. Queen Charlotte offshore samples were predominantly sandy silt or sandy mud (i.e. with a sand content 10-50%). Silt:clay ratios in Pelorus Sound showed a relatively higher clay content than in Tory Channel samples. This gives an initial impression of regional differences in the abundance of certain sedimentary fractions. However, the samples also reflect local hydraulic conditions at the sites of sampling. In the following sub-regional review the extent to which systematic variation occurs in embayment sediments between sub-regions is examined,

Grain Size Curves Case Studies: Pelorus Sound

Four Fathom Bay

Site Description

Four Fathom Bay is a narrow embayment 2.6km long and 800m wide at its mouth, on the eastern side of the Pelorus Channel (Map 3, GR 840 058). A narrow alluvial fan fills the bayhead and extends 1km up valley at a mean gradient of 1:25, with a bayhead catchment area of 6.3km. The bay is flanked by steep hillslopes (>1:2.5 gradient) with a more gentle gradient (1:10) on the lower slopes below 40m above sea level. The long-profile of the bay has an axial profile gradient of 1:350, with a depth of 7.3m in the bay centre at its mouth. This bay-centre is a mound flanked by channels within the bay of up to 18m depth on the southern side of the bay. Immediately outside the bay, the depth of the Pelorus Channel is over 30m. Echo soundings reproduced in Figure 9.1a show the baymouth mound and the steep drop-off outside the baymouth. Figure 9.1b locates samples within the bay.

The water of the bay, as in most bays of the Pelorus Channel, has characteristically low visibility (<1 m when diving) especially when tidal flows around the baymouth suspend sediments. Flows are stronger near the headlands and along the bay flanks coincident with the channels referred to above. The micro-morphology of the bed is dominated by the "hummocky" form developed by tube-worms, and locally some extensive accumulations of broken and live shells.

Grain Size patterns

The grain size curves of eight bottom samples from Four Fathom Bay are plotted in Figures 9.2a and b. Samples were taken on a series of transverse lines across the bay, at points on the northern and southern sides of the bay, at an equidistant spacing from the bay sides and from each other. Sample 10 was in shallow water (2.2m) 100 m from the bayhead stream delta. Sample 20 was 300m down the bay centrally placed in 5.5m of water at low water. Samples 30 and 31, 40 and 42 were respectively from north and south positions, 1300m for the first pair and 1800m for the second, down the bay from the bayhead. Sample 50 was from the north and 51 from the middle (axial) positions in the bay mouth, 2600m from the head.

The northern suite (samples 10, 20, 30 and 40) is plotted on Figure 9.2a, and a sequence is apparent of fining from outer to inner (bay-head) samples. The median grain-sizes diminish from 5.7ø (medium silt) to 7.3ø (very fine silt). The southern suite (samples 31, 42), the outer samples (50, 51) and for comparison samples 10 and 20 also, are plotted on Figure 9.2b. Outer samples are coarser (medians of 6.0ø and 6.6ø) than the others, but not as coarse as sample 40 (Figure 9.2a). The southern samples show no systematic trends, but lie in an envelope largely between samples 10 and 20. Silt contents (4ø to 8ø) range from 55% associated with a clay content of 30% and 5% sand (sample 10), to 70% (with clays of 15-20%). Sand contents do not exceed 15%.

Figure 9.1
Pelorus Channel Sediment Sample Locations

Figure 9.1a

Axial echo-sounding of Four Fathom Bay mouth region. The sounding is viewed from north facing south across the bay entrance, with the bayhead to the left.

Apparent in the echo-sounding track is the bay-mouth mound and the steep drop-off into the Pelorus Channel. Sounding scale is the shallowest on the chart- ie a mean depth of about 10.5m in this section of bay.

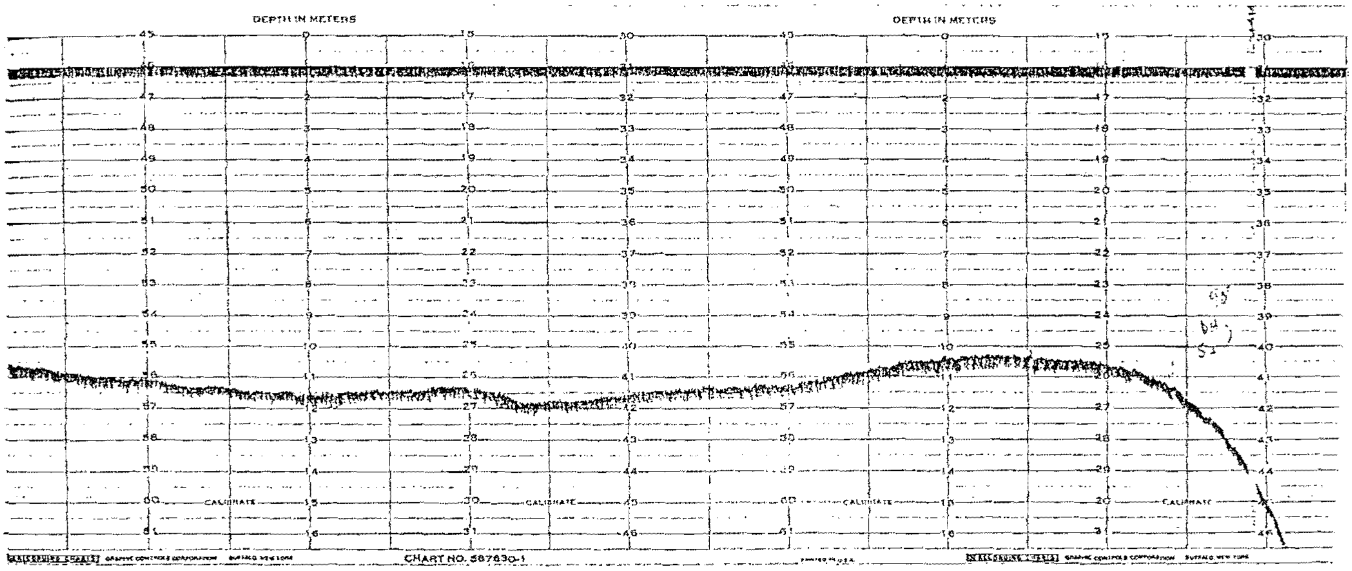


Figure 9.1b Location of Pelorus Channel Samples

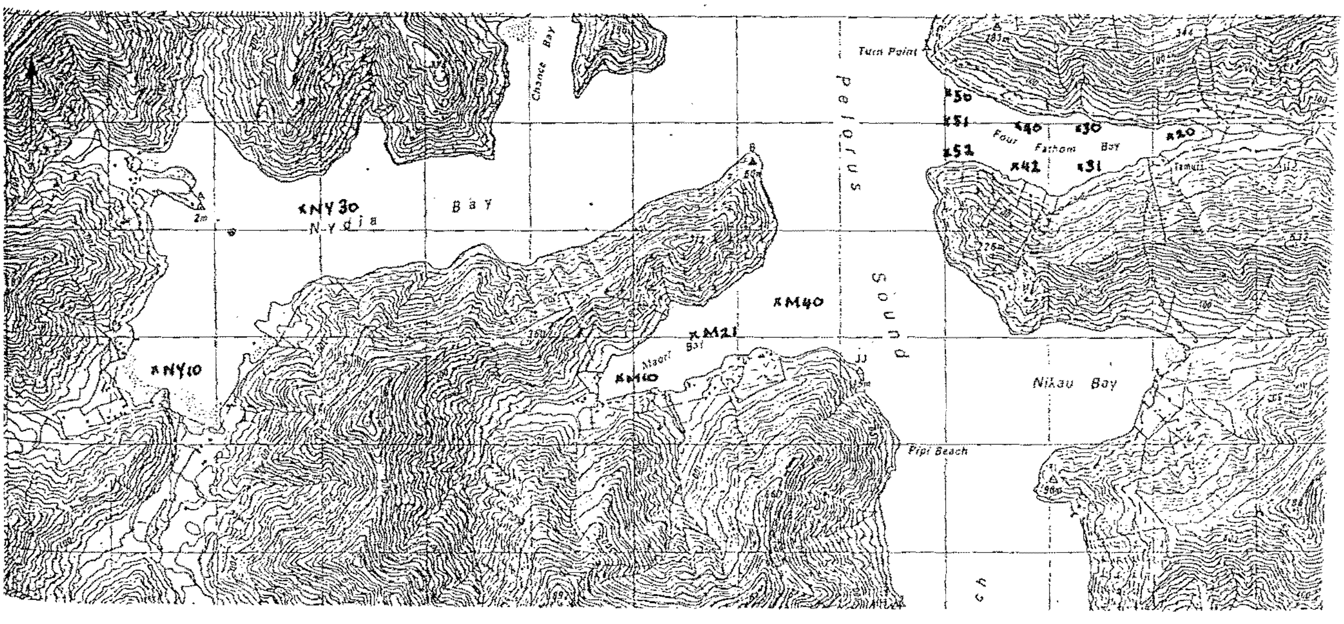


Figure 9.2

Four Fathom Bay Sediments, Pelorus Channel

Figure 9.2a

Four samples drawn from northern side of bay, with distances from bayhead as labeled. Trend of fining apparent in sediments from baymouth towards bayhead.

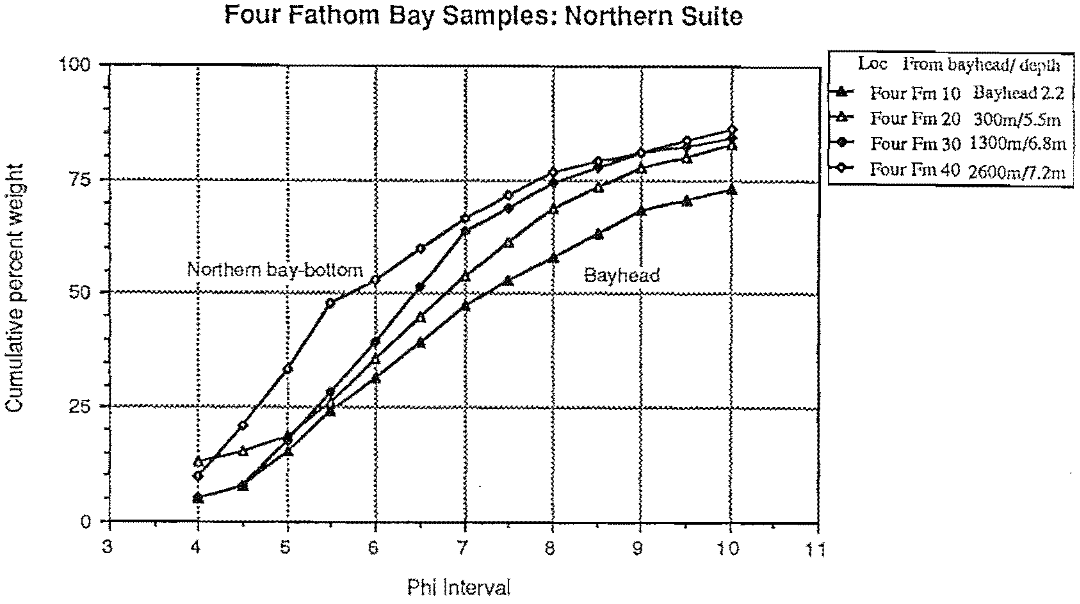
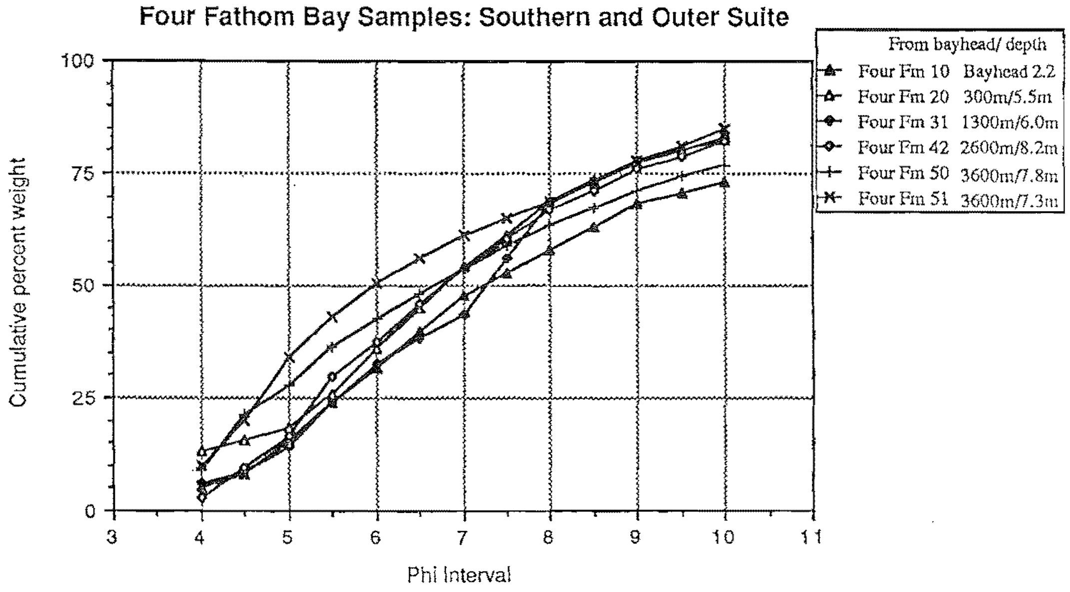


Figure 9.2b

Samples from south of Four Fathom Bay. While the suite are seen to be enclosed within an envelope delimited by the finest and coarsest samples found in the northern suite, the southern suite does not show any systemmatic trend along the baylength. There is evidence for across-bay as well as along-bay patterns in sediments.



Discussion

Four Fathom sediments are notably homogeneous with only minor differences between samples. The fining sequence in the northern suite into the bayhead suggests a trapping of fine material, and this correlates with a high organic content in bayhead samples (see samples FFO1 and FFO2, Figure 5.10a, which were taken from inshore of sample 10). That no sequence can be identified in the southern samples, but that they are consistently fine, suggests that a fining sequence also exists from north to south across the bay (i.e. a transverse zonation), probably related to the tidal gyre of waters flowing past the baymouth in the Pelorus Channel. The coarseness of sample 40, 1000 m up the bay from the mouth, relates to an observed tidal flow along the baysides.

Other Pelorus and Kenepuru Sound Sites

In Figures 9.3a to d the grain-size curves of a series of samples from other bays in the Pelorus and Kenepuru Sounds are presented. Samples 10 and 20 from the Four Fathom inner suite are replotted for comparison.

Nydia Bay

Nydia Bay is a large bay 6km long branching off the western side of Pelorus Channel. It has at its head a 2km long alluvial flat with a mean gradient of 1:40 which includes terrace remnants referred to in Chapter 5. Two large catchments in the southern bayhead drain (19.2 km^2), and discharge onto a broad intertidal surface of gentle gradient. Steep catchments in the north drain a further (4.4 km^2), and streams discharge at low water across gravelly deltas onto low water "aprons" of mud lying at gentle gradients. The axial long profile of the bay drops to 12.5m in the bay centre, a gradient of 1:475. Like Four Fathom Bay, the baymouth centre is flanked by a deep (28 m) channel.

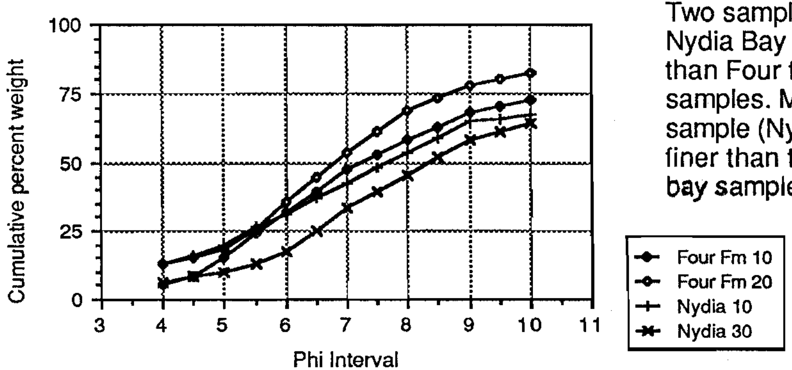
Two samples from the bayhead are plotted on Figure 9.3a. Nydia 10 was located at Map 3 GR 758 038, and Nydia 30 at GR 765 050. The inner sample (Nydia 10) was closest to the southern deltas and in an equivalent position to Four Fathom 10. The Nydia sample is fractionally finer. In the mid-bay sample (Nydia 30), the sediment is finer yet again, with a median size in the clay range (8.4ø).

Like Four Fathom Bay, Nydia Bay appears to function as a repository for finer sediments. The large bayhead catchments act as a sediment source,

Figure 9.3

Pelorus Sound Sediments Sub-regional Variations

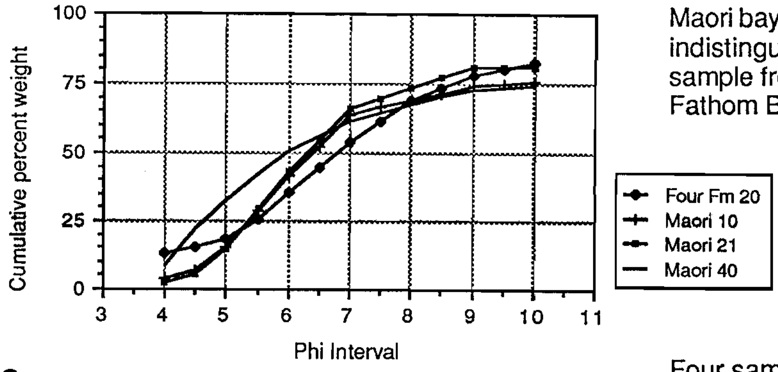
Fig 9.3a



Nydia Bay: In/Mid and Four Fathom Inner

Two samples from Nydia Bay plot finer than Four fathom samples. Mid bay sample (Nydia 30) is finer than the upper bay sample (Nydia 10).

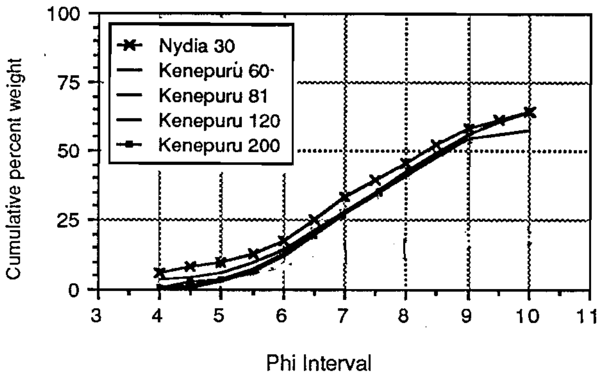
Fig 9.3b



Maori Bay Axial Transect and Four Fathom Inner

Three samples from Maori bay are indistingusihable from sample from Four Fathom Bay

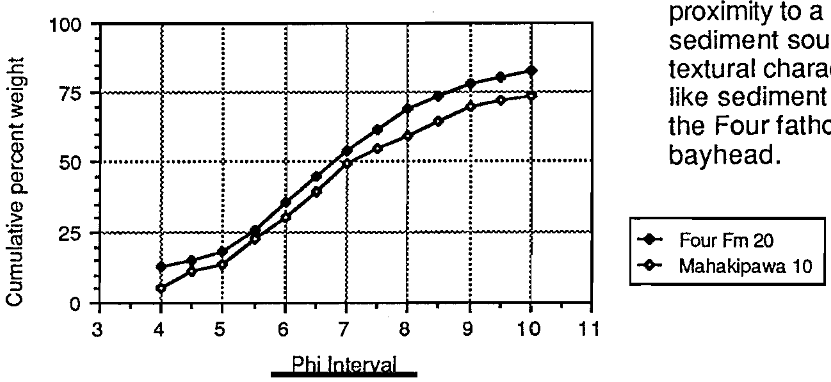
Fig 9.3c



Kenepuru Sound and Mid Nydia Bay

Four samples from Kenepuru Sound are the finest presented here. Kenepuru sediment are indistinguishable, despite the spatial separation of these samples. The Sound is interpreted as a trapping environment, and one in which little sedimentary fractionation takes place.

Fig 9.3d



Mahakipawa Arm Inner and Four Fathom Inner

Mahakipawa Arm sediment sample, despite its inner sounds location and proximity to a major sediment source, has textural character very like sediment found in the Four fathom bayhead.

especially for suspended silt, and this may account for the higher silt content, 55% in the inner 10 compared to 45% in the mid-bay 30 samples. A pattern is apparent in which parts of larger embayments have notably finer sediments than in their outer (mouth) areas, and finer in their middle reaches than at their bayheads.

Maori Bay

In Figure 9.3b three samples taken from Maori Bay (Map 2, GR 810 040) are plotted with Four Fathom 20 for comparison. The form of Maori Bay is similar to Four Fathom but with larger catchments on its southern flanks. The bayhead alluvial flat is 600m long with a gradient of 1:10. Baymouth depth is 8m with an axial gradient of 1:280 in a bay length of 2.25km. Marginal bay-mouth channels are not so prominent as above.

Bay bottom sediments are barely distinguishable from those in southern Four Fathom Bay.

Kenepuru Sound

Nydia Bay sample 30 is the finest yet identified and this is replotted on Figure 9.3c along with four samples from Kenepuru Sound. Kenepuru sample 60 was taken from a position in mid-sound 2km north-east of Portage at Map 4 GR 978 022. The site is 6km down the Sound from the bayhead with a catchment area of 32.3km^2. Water depth was 7m, giving a long-sound profile gradient of 1:830. At the Sound head an alluvial flat extends 5km inland with a gradient over the lower 1.5km of 1:75.

Sample 81 was recovered from 5m of water in the middle of Waitaria Bay, northern Kenepuru, at GR 968 035. Kenepuru sample 120 was taken south of Weka Point at GR 941 005 in 24m of water in the deep channel referred to in Chapter 8. Sample 200 was taken at GR 883 002 from 25 m of water 1km due west from Schnapper Point in the lower Kenepuru, 5km from its confluence with the Pelorus Channel. The axial distance over which the samples extend is 14km and Figure 9.4c shows them to be indistinguishable over the entire length and fractionally finer than the Nydia 30 sample.

The uniformity of these samples is significant. It suggests that minimal sedimentary fractionation takes place along the axis of Kenepuru Sound and consequently illustrates the hypothesis, discussed in Chapter 5, that in a trapping environment fractionation between grain-size grades would diminish. No further interpretations of sediment dynamics can be made of the Kenepuru offshore other than that the highly dispersive character of fine sediments (Median size is between 8.0 and 8.5ø, or clay) leads to a very uniform distribution.

Mahakipawa Arm

The Mahakipawa is a gently sloping arm of the inner Pelorus with a low water depth at the sample location of 2m. Its proximity to the inflow of the Pelorus River, a deeply embayed plan form, and a catchment area of 47.7km^2, might be expected to result in a differentiation in sedimentary texture from that found elsewhere in the Sound. In Figure 9.3d, a mid-bay sample from the Mahakipawa Arm (Map 2 GR 780 913) is plotted with Four Fathom sample 20.

The Mahakipawa sample is fractionally finer than the sample from the bayhead of Four Fathom, silt content being identical at just over 70% with 25% clay as against 15% clay in Four Fathom. Boyce (1971) reported on a suite of samples taken in this inner Pelorus sub-region, including samples in the Havelock Estuary. His evidence suggests a fining trend up the Mahakipawa Arm which would conform generally to the observations in Four Fathom and Nydia Bays. Silty-sand deposits are found at low water on the Cullens Creek and Oruaputaputa deltas (see Map 2) reflecting the fluvial source.

The dominant feature of Pelorus Sound samples presented here is the relative uniformity in sediment texture between sites. Differentiation within embayments decreases with grain-size. Some differentiation can be observed in response to the additive effect of streams and reworking by tidal currents.

Grain Size Distributions: Queen Charlotte Sound

Samples taken from the inner and northern bays of the Queen Charlotte Sound are located in Figure 9.4

Grove Arm

The Grove Arm is a 5.5km long inlet at the head of Queen Charlotte Sound, the morphology of which was described in Chapter 6, and the long profile is shown in Figure 8.1a. Samples are plotted with other inner Queen Charlotte samples on Figure 9.5.

Figure 9.4
Queen Charlotte Sound Sediment Sample Locations

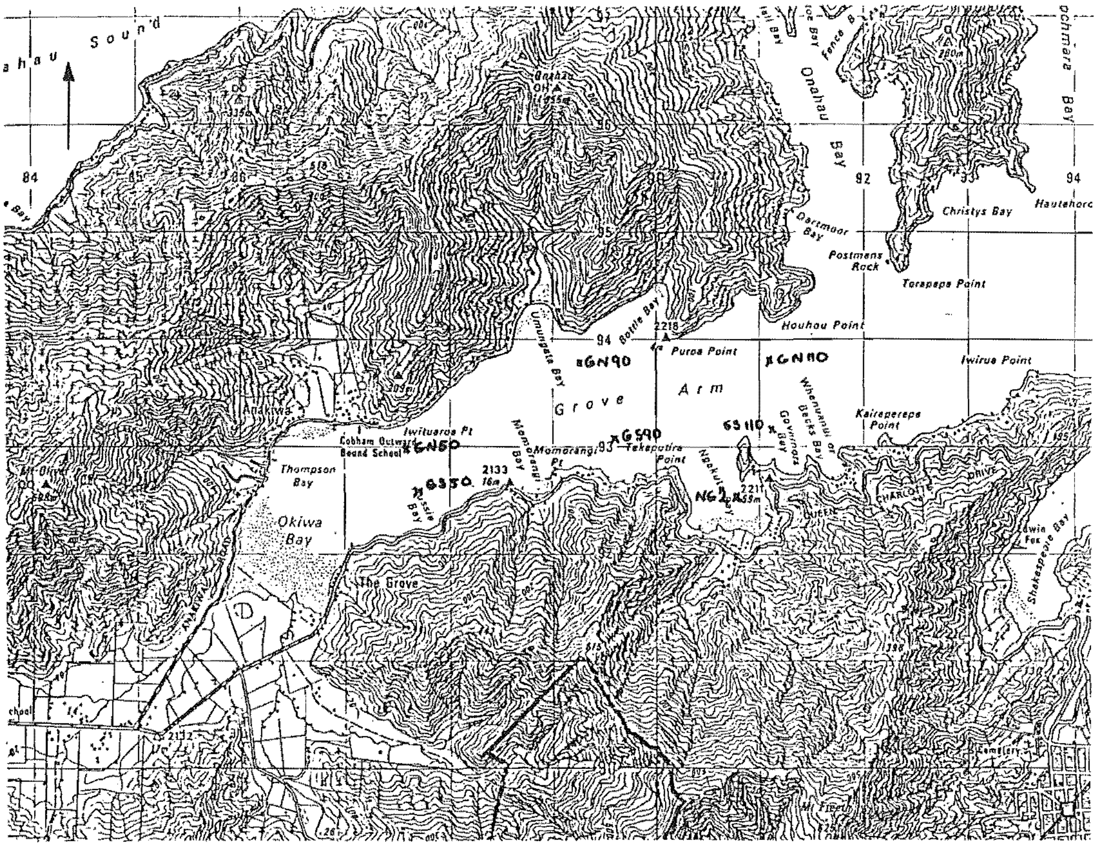


Figure 9.5

Queen Charlotte Sound Sediments, Inner and Northern Bays

Figure 9.5a

Grove 50 and Grove 90 samples were paired from north and south sides of the Sound, the 50 pair towards the bayhead. Sediments fine down the Sound into deeper water. The Grove samples are shown to be enclosed within an envelope defined by the Four Fathom samples from Pelorus Sound

Grove Arm (Queen Charlotte) and Four Fathom Samples

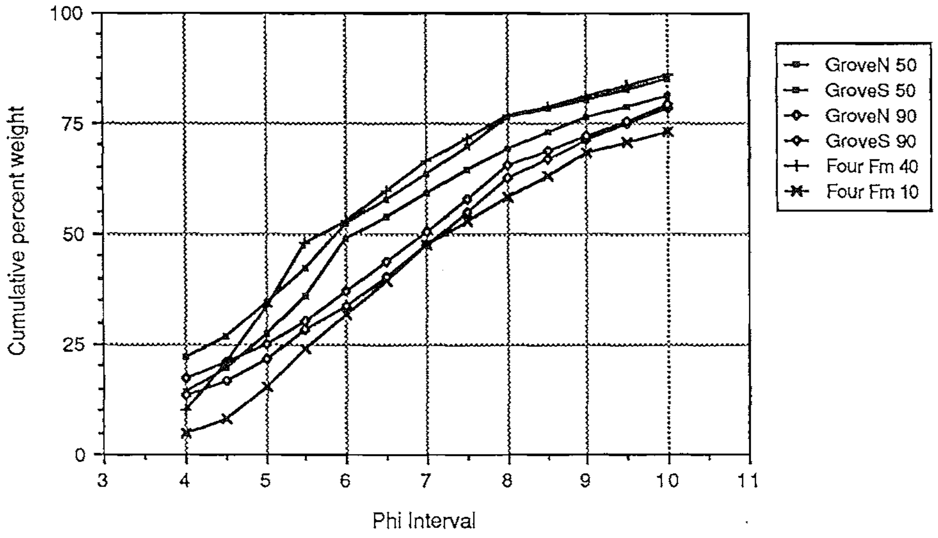
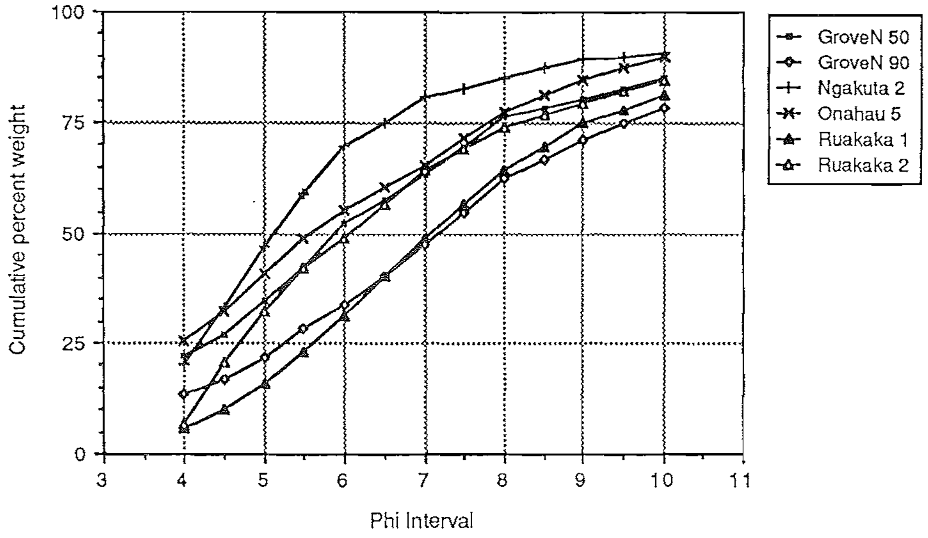


Figure 9.5b

Sediments in bay-bottoms of northern Queen Charlotte embayments are measurably similar to those in the Sound head at in the Grove Arm.

Queen Charlotte: Grove (Inner) and Marginal Bays



TheseGrove N50 and S50 were taken equidistant from the shore and from each other on the north and south respectively. Sample Grove N 50 was recovered from 11m depth, GS 50 from 16m. This reflects the asymetrical cross profile of the arm, with the thalweg following a line one third of the width on the southern side. This bathymetry extends from Okiwa to past Ngakuta Bay (i.e. Map GR 870 923 to GR 910 933), where the bottom character becomes flatter and the profile symetrical. GN 90 and GS 90 were both taken in 22m of water. The long-profile gradient is 1:150 between the line of 50 and 90.

Figures 9.5a and 9.5b present four samples from the Grove Arm of Queen Charlotte and four samples from marginal bays of the Sound. Samples GN 50 and GS 50 are very similar with median grain-sizes of 5.8ø and 6.1ø respectively, or medium to fine silt. Samples GN 90 and GS 90 have medians of 7.2ø and 7.0ø respectively, or very fine silt. The trend of fining is towards deeper water. The high organic content of the Grove Arm samples was shown in Figure 5.10a. In Figure 9.5a the Grove sample curves are shown to fall in an envelope between the finest (FF10) and coarsest (FF 40) samples from Four Fathom Bay. Thus both in grain-size and organic content, the inner Queen Charlotte and the marginal bays of the Pelorus are seen to be markedly similar.

Marginal Bay, Queen Charlotte

Figure 9.5b shows grain size curves from a number of marginal bays.

Ngakuta Bay (Map 4, GR 905 927) flanks the Grove Arm in the vicinity of the Grove "90" samples, one of which is plotted on Figure 9.5b. Ngakuta Bay is backed by a moderately larger catchment ($5.9km^2$) compared to most Grove Arm bays and has a steep nearshore pro-delta sloping to a flat bay-bottom. Onahau and Ruakaka Bays are situated on the north of Queen Charlotte Sound.

The Ngakuta sample is very silty with only 10% clay compared to 22% in the Grove Arm outside the bay. The marginal bay is dominated by stream inflow of silt and no "backwater" trapping of clay is apparent in this sample. Sites in the northern, more enclosed portion of the bay at GR 909 927 were found to have a markedly higher clay content.

Sample Onahau 5 plotted on Figure 9.5b came from a depth of 22m. Two samples from the bay-bottom of Ruakaka Bay are shown also, sample Ruakaka 1 from 33m and sample Ruakaka 2 from 20m, further inside the bay. The Onahau sample is shown to be similar to sample Grove N 50 although with fractionally more coarse silt and 12% more sand. The Onahau sample was taken in Fence Bay at GR 917 968 in the baymouth of the minor embayment. Steep gradients characterise the nearshore of these northern Queen Charlotte bays, and a bay long profile gradient in Fence Bay of 1:25 is related to this higher sand content. Offshore sites with steep gradients are found to be sandy, even when tidal currents are not strong. This is attributed to a factor related to the angle of repose of fine sediments.

Ruakaka samples were taken on the flat bay-bottom, clear of the nearshore slope. While the sample within the bay (Ruakaka 2) is very like Grove N 50, the outer bay sample (1) is almost identical to Grove N90, apart from a small difference in sand content. This suggests a uniformity between inner Queen Charlotte sediments and those in the deeper parts of the marginal bays.

Grain-Size Distributions: Tory Channel

Figure 9.6 identifies the locations of samples drawn from the Tory Channel sub-region. Figure 9.7 presents the grain-size distributions of samples drawn from the bays flanking Tory Channel.

Maraetai Bay is 1.6km long and 850m wide at its mouth with two small alluvial fans 500m long in the bayhead having catchments smaller than 2km^2. Bay mouth depth is 13m giving a long gradient of 1:125. Opua Bay is much longer (4km) with a width at the mouth of 800m, and a larger catchment area (total catchment 11.9km^2). Depths in bay-mouths of Tory Channel were discussed in Chapter 8. The mean long-profile gradient of the inner half of Opua Bay is 1:130. Hitaua Bay is morphologically similar to Maraetai bay.

Deep Bay is a small embayment 1500m long on the north of Tory Channel. It has a markedly shallow (1m at LW) bay-mouth mound and a deeper region behind with depths up to 7m.

Samples Maraetai 02 and 10 were taken within 700m of the bayhead and are similar to the curve of sample Opua 20, also taken in a bayhead location.

Samples Opua 20 and 30 were taken from axial positions along the bay length, the former 1000m from the bayhead, and the latter 1900m. The two samples plot within 5% of each other at each Phi interval over their size range indicating a highly uniform distribution of very fine silt in the mid-bay area. The

Figure 9.6
Tory Channel Sediment Sample Locations

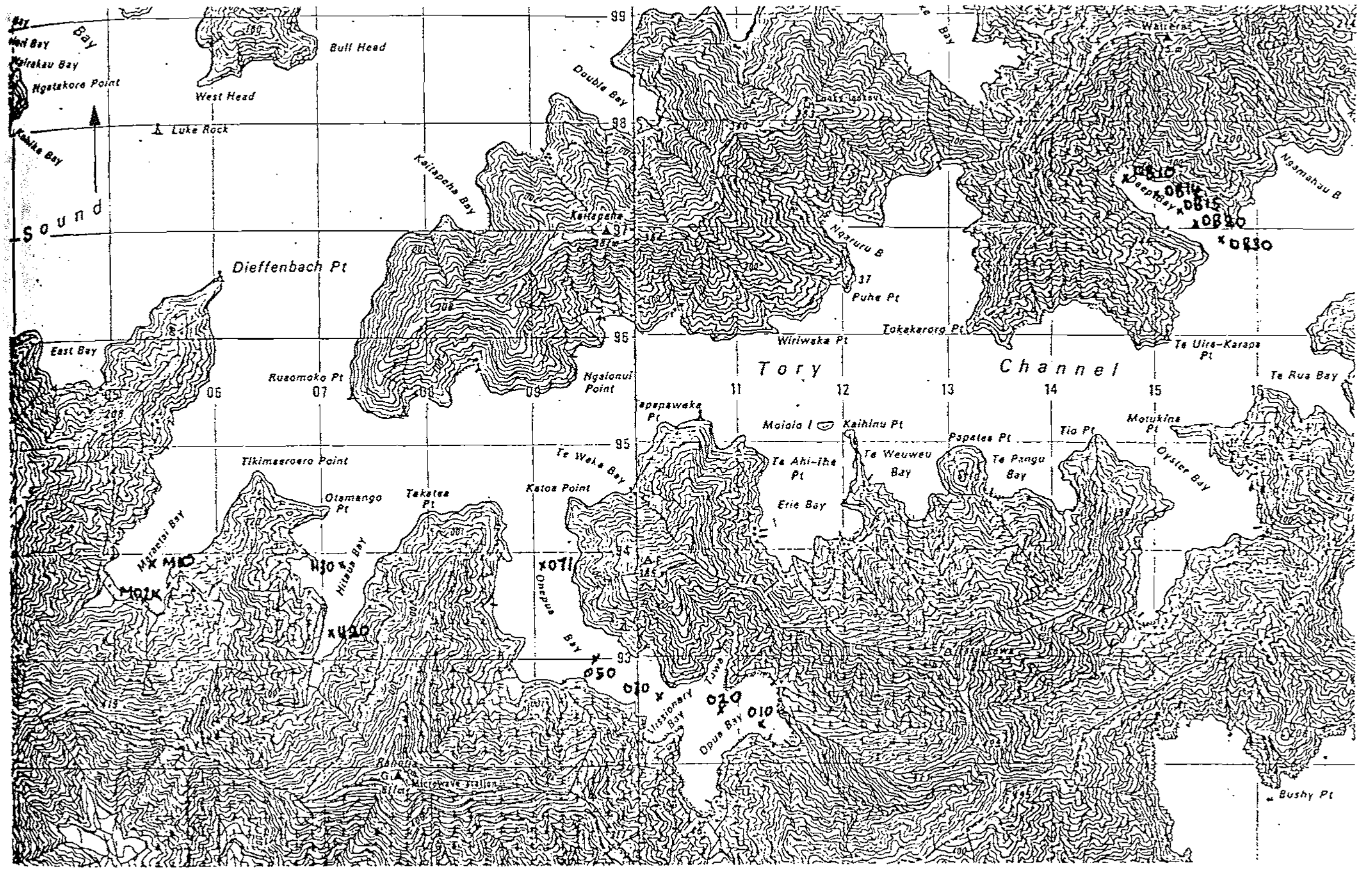


Figure 9.7

Tory Channel Sediments, Marginal Bays, and comparison with other sub-regions

---

Figure 9.7a

Three goups of sediment curves are identified. Mid Opua Bay samples are finest, while bayhead samples from Opua are similar to those in Maraetai Bay. Hitaua and Deep Bays have marginally coarser sediments.

Tory Channel Bays: Inner and Mid-Bay Samples

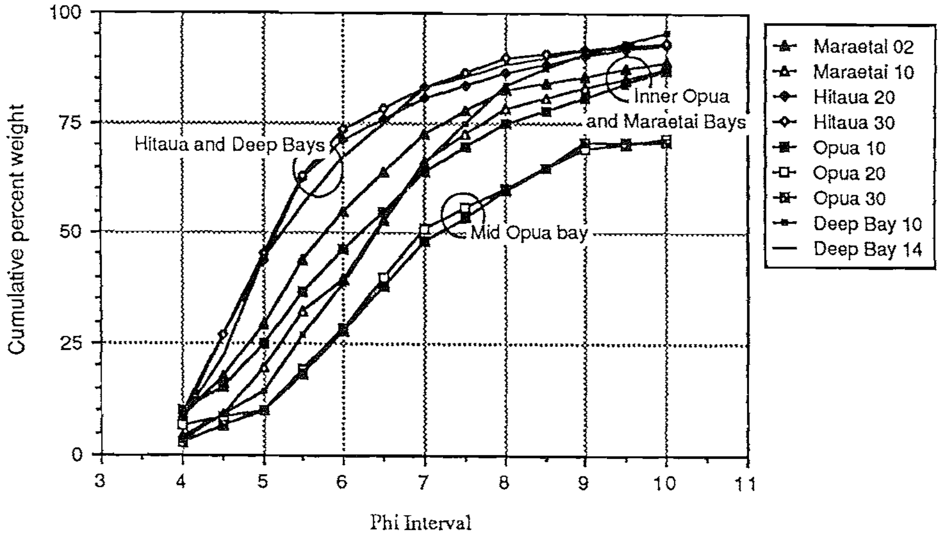
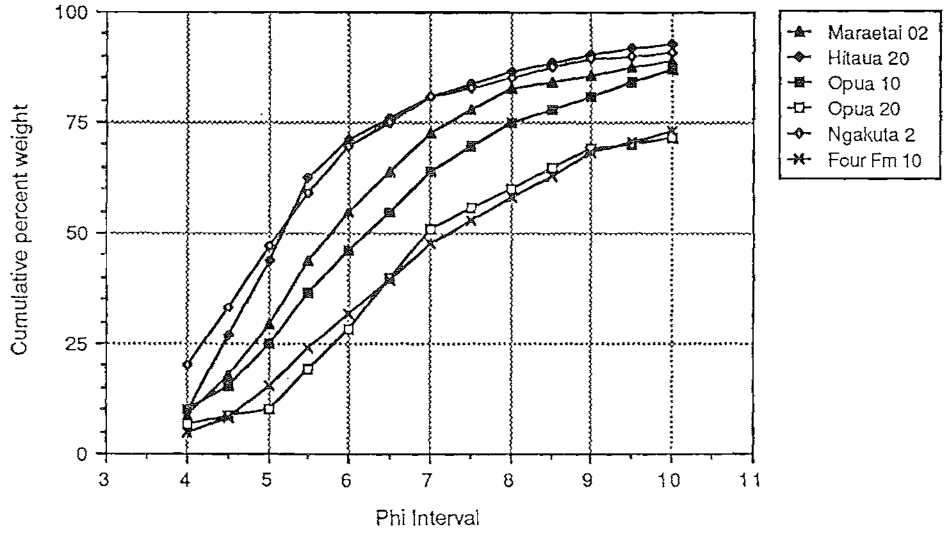


Figure 9.7b

Sediments in Tory Channel bays are compared to those in Grove Arm and Four Fathom Bay. Ngakuta Bay, a silty marginal bay of the Grove Arm, has a curve like that in Hitaua Bay. This is the coarse bound to the regional sediment envelope. Samples in Opua Bay are as fine as those in the inner parts of Four Fathom Bay. Sub-regional differences, and differences within bays, are more significant than differences between sub-regions.

Tory Channel Bays : Relation to other sub-regions



similarity in these samples (independently analysed) also serves as an index of the reproducibility of the analytical method. Both samples are distinctly finer than sample Opua 10, taken from the bayhead.

Samples Hitaua 20 and 30 were taken from situations proximal to stream deltas which could account in part for the dominance of coarse silt (4-6ø, 65%) compared to a value of 45% or 30% for the Maraetai samples.

Deep Bay samples 10 and 14 were taken at 7m depth. The sample immediately behind the baymouth accumulation (14) is silty like those in Hitaua Bay while the sample nearest the bayhead (Deep Bay 10) is finer and similar to that found in the head of Opua Bay (Opua Bay 10).

Tory Channel and Other Regions: Comparison

Figure 9.7b enables the comparison of samples taken from Tory Channel, Queen Charlotte Sound and Pelorus Sound. Samples with high silt content such as Hitau 20 are seen to be almost identical to the silty (stream dominated) sample in Ngakuta Bay of the Grove Arm. Other samples are seen to be contained in an envelope between these and the finest Tory Channel samples, Opua 20 and 30. These fine samples are texturally similar to the inner samples of Four Fathom Bay in Pelorus Sound. No samples in Queen Charlotte Sound are significantly finer than Opua 20 or Four Fathom 10. Samples from the two longest catchments of Pelorus Sound, Kenepuru Sound and Nydia Bay, have the finest grain-sizes identified.

Offshore Sediments: Summary

Offshore sediments have been identified with median grain-sizes between 5.0ø and 8.5ø. Very fine samples (i.e. clays, median >8ø) are found only in Pelorus and Kenepuru Sounds, while in Queen Charlotte Sound and Tory Channel medians are between 5ø and 7ø. Comparisons between embayments of similar dimensions in Tory Channel and Pelorus Sound (Opua Bay, Four Fathom Bay) show that the variation in samples within bays exceeds the variation between sub-regions. Therefore, the patterns of sub-regional differentiation in textural class identified in Figure 5.4 do not indicate that embayment sediment dynamics differ between the sub-regions. Rather, the patterns of sub-regional differences and embayment similarity point to two scales of sediment patterning.

The broader scale pattern lies in the relative abundance of fine material over sand in the Pelorus System, especially as compared to Tory Channel samples. In equivalent bay-mouth positions (cf Maraetai Bay, Four Fathom Bay), the sediments on bay-mouth mounds are dominantly sandy in Tory Channel and dominantly silty in the Pelorus Channel. In part, this is attributed to tidal scour as the tidal streams in Tory Channel exceed recorded velocities in the Pelorus Channel (Nautical Almanac, 1982). However, it is also apparent that there is a higher availability of fine sediments in the Pelorus Sound, explained by Carter (1976) as being attributable to the inflow of the Pelorus River.

However, at the embayment scale it can be seen that these external hydraulic and source area effects do not have an overriding control on the patterns of trapping and sediment reworking within marginal bays. Rather, embayment dynamics are fundamentally similar throughout the inner Sounds.

In the following section, further analysis is made of the textural components of embayment sediment dynamics.

Sediment Texture in Marginal Embayments

In Chapter 8, the bottom form was used as an initial index of sediment dynamics. Channels sites were subject to tidal currents while baymouth sites adjacent to channels show evidence of tidal scour but to a variable degree. Tidal influences could be read from channel forms extending into marginal bays also, but due to variable sub-bottom form bottom morphology was an ambiguous index of hydraulic control in embayments.

Grain-size evidence shows that Pelorus Sound sites have lower sand contents and Kenepuru Sound sites higher clay contents, but that marginal bays were found to contain a full range of the sediment sizes which were available in a sub-region- sand, silt, and clay. In order to recognise patterns in the offshore textures within marginal bays, reference is made to the "deposit-repository" concept referred to in Chapter 5.

A "repository" was shown to be a coastal site which contained a number of "deposits". The deposits have their own grain-size populations, but within the repository, deposits can be recognised as being complements of each other. Given that in the Pelorus Sound, "source area" effects apparently give rise to a higher available population of fine silts and clays in the offshore, while in the bays of Tory Channel coarse silts predominate, the analysis of grain-size patterns is best accomplished between samples in the "complementarity" approach. The plots in

Figures 9.8a-d are examples of such an approach, and are referred to here as "complementarity curves".

The x axis dimension in each is the distance from the bayhead to the site of a given axial profile sample. The y axis is an arithmetic percentage axis. At each "distance point" a sample is plotted as a vertical string of points, one point for each phi interval in the grain-size distribution, and each y-elevation corresponding to the cumulative percent value of that phi interval. The result is a plot which enables the recognition of the proportion of each sample in a given size grade as it varies along the length of a bay.

The first example is Opua Bay, Figure 9.8a. Samples plotted are Opua 10, 20, 30, 50 and 71. Three elements of the pattern are significant. First, the dominance of silt at the bayhead; secondly, the notable increase in clay and the decrease of sand in the inner-mid bay region and thirdly, the overall coarsening of the samples, especially in sand and coarse silt, towards the bay-mouth.

The second example is also from Tory Channel. Deep Bay is a narrow bay, as noted earlier, with a bay-mouth accumulation whose morphology has been related to both antecedent fluvial form and to hydraulic reworking and deposition. Figure 9.8b shows the variation in sediment grain-size along the bay axis. Clay content is 15% in the bayhead, and sand content diminutive. Silt comprises over 80%. However, with the transition towards the bay-mouth bar an increase in sand content is matched by a decrease in silt and clay.

A third example is shown from Four Fathom Bay in the Pelorus Sound. While sand content is diminutive throughout, the expression of complementary repository fractionation is seen to take place in the silt size range. The fining up-bay pattern noted in the previous section in this northern suite of samples is apparent. However, the relatively more subtle pattern of repository fractionation compared to the Tory Channel examples is also apparent.

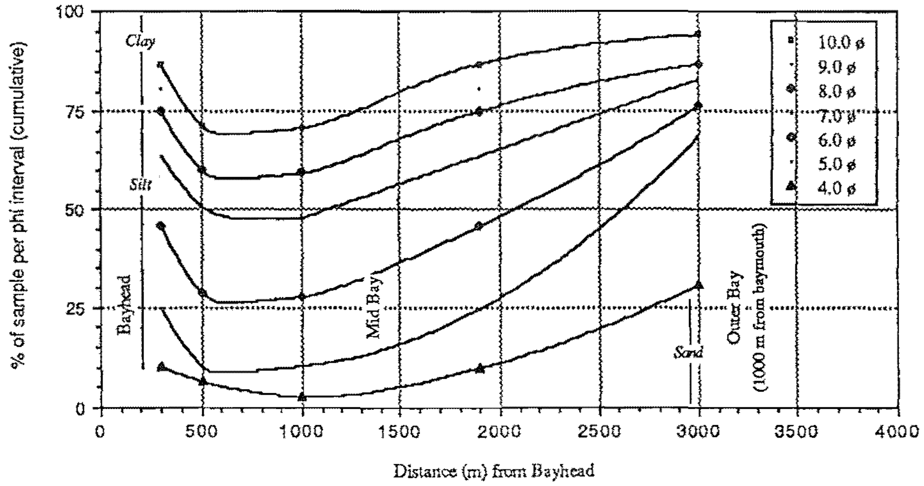
Figure 9.8d shows a fourth example of the complementarity curves for Bottle Bay. The bay is a small (1km long) embayment in the inner Queen Charlotte, Map 4 GR 898 942. Sand content is high in the bayhead and is associated with proximity to a stream, and generally diminishing towards the bay-mouth. Clay content increases over the length. However, a marked mid-bay deviation shows an increase in sand content with a correlative decrease in clay.

Figure 9.8

Embayment Axial Sediment Variation: "Complementarity Plots"

Figure 9.8a

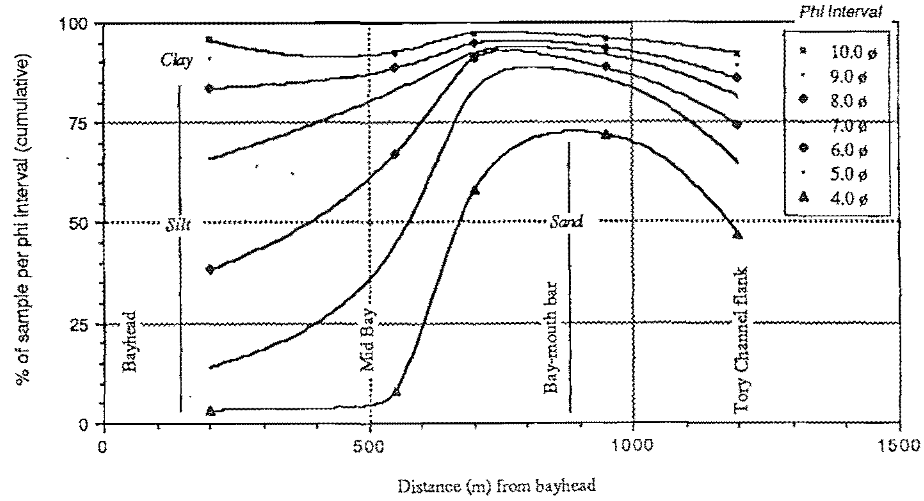
BAY AXIS: Opua Bay (Tory Channel)



Sediments vary along the axis of the bay, with a relative exchange of fine for coarse material in response to sediment supply or hydraulic reworking. Concentration of fine materials in the middle reaches of Opua Bay is interpreted as evidence of a mobility trap operating to retain and concentrate the finer materials. Silt-rich sediments in the bay-head are related to stream inflows, and to the retention of this material in a confined coastal site.

Figure 9.8b

BAY AXIS: Deep Bay (Tory Channel)

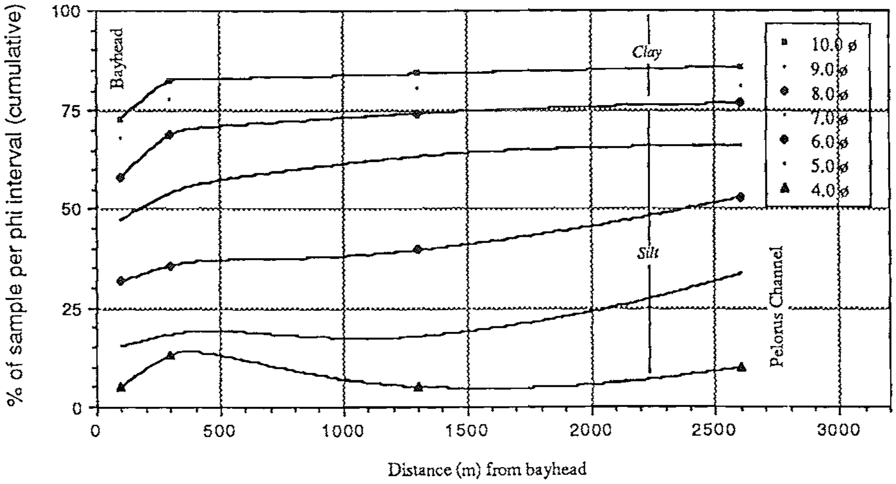


Deep Bay sediments reflect the influence of strong tidal scour on the shallow bay-mouth mounds. This scour is reflected in the sandy composition of sediments.

Figure 9.8

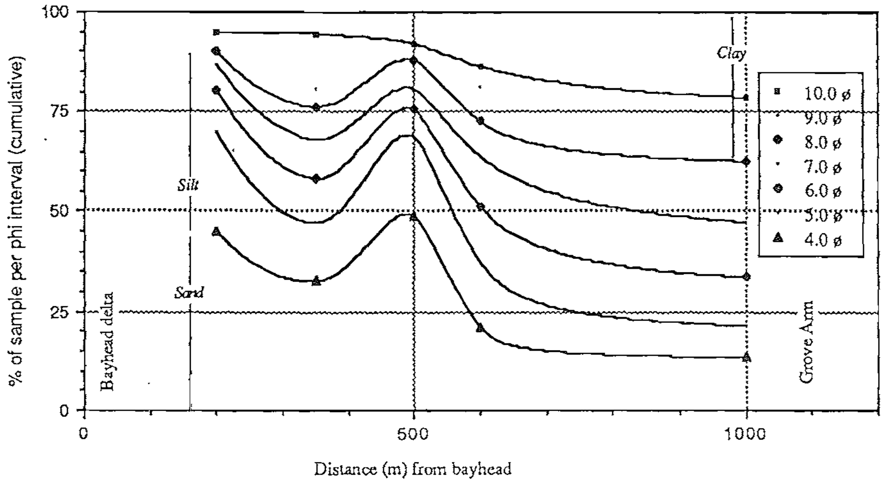
Embayment Axial Sediment Variation: "Complementarity Plots"

Figure 9.8c BAY AXIS: Four Fathom Bay (Pelorus Sound) North



Axial profile of sediments on northern axis of Four Fathom Bay shows pattern of spatial uniformity. Two elements of the pattern are slight increases of sand in the bay mouth, and slight increase in the clay content in the bayhead.

Figure 9.8d BAY AXIS: Bottle Bay (Queen Charlotte)



Bottle Bay is a minor embayment with a broad mouth. Tidal currents extend an influence into the bay. Coarse grain-sizes in the mid-bay region are attributed to tidal scour.

Interpretation

Longitudinal grain-size variations within embayments point to a number of significant controls acting on the redistribution of sediments in the offshore domain. The first stems from the source area influence of bayhead streams. Silt contents in the bayhead of Opua Bay and Bottle Bay - as in Nydia Bay - are attributed to the influence of stream inflows. Conversely, bays with restricted bayhead catchments (e.g. Deep Bay) are found to have relatively less bayhead differentiation between silt and clay fractions. In combination, the factors of bayhead enclosure and stream inflow appear to act in concert to produce a *morphologic* trap in the offshore for materials entering sites with low tidal energy.

The second control relates to the hydraulic capacity of tidal currents to fractionate and redistribute materials. The action of tidal currents is constrained by embayment morphology, but in more deeply embayed locations sedimentary evidence points to a zone convergence in the mid-bay region. This is apparent in the Opua Bay complementarity curve. In the mid-bay region, tidal currents diminish and suspended material (especially fine material) would appear to be subject to a *mobility* trap.

In the outer bay regions tidal currents are able to disperse fine material leaving a lag of sandy material as found in Deep Bay. Between the outer bay and the mid-bay locations there can be recognised an equivalent complementarity to that observed on the shoreline systems between an agglomerative and a dispersive sediment behaviour. The latter were associated with the higher energy levels of the relative mobility spectrum.

Discussion

The recognition of a range of offshore sedimentary behaviours in evidence drawn from morphologic and textural sources gives an index of both the scales and the the broad-scale mechanisms which are acting on sediment dispersal in the offshore domains.

Evidence of the relatively homogeneous distribution of sediment thickness in the offshore domains indicated the effectiveness of hydraulic processes acting at the broadest scale to redistibute fine materials within the Sounds. This pattern of uniformity has been confirmed by the textural patterns in which similarities between morphologically similar sites in different sub-regions were recognised. At the scale of the Sounds as a whole, the inlets are seen to act as an undifferentiated repository for catchment derived sediments.

The detectable differences in sediment thickness between sub-regions were correlated to a trapping behaviour found in larger embayments as observed specifically in Kenepuru Sound and Nydia Bay. These patterns also were confirmed by sediment texture, with the finest materials being found in these two areas.

The key differentiation between sites is at the scale of embayments and differences can be seen between marginal bays according to their levels of tidal currents. It is possible to recognise a systematic pattern in embayment sedimentary behaviours.

A Morphologic Index of Embayment Sedimentary Behaviour.

The morphometric Embayment Index proposed in Chapter 6, where a range of sites was identified according to their relative length and bay-mouth widths could be used as a gauge of marginal bay sedimentary behaviour.

In "indentations" defined as bays in which the width is over twice the depth sedimentary dispersal behaviour could be expected to reflect the mobility conditions of the next largest inlet within which it is found. Consequently, a broad embayment flanking Kenepuru Sound will reflect the morphologic trapping character of that Sound as a whole. An indentation flanking a more exposed reach (mid Queen Charlotte or Pelorus Channel) will conform to the more dispersive character of the broader site, depending on tidal conditions.

In shallow to moderately embayed locations, trapping behaviour will be a response to the penetration of tidal flow into the embayment. The index of this in bottom morphology would be recognised in the incision of tidal channels; the index in sediment texure would include local coarse silt and sandy areas, as seen in Bottle Bay.

In more deeply embayed locations both a mobility and a morphologic trap could be expected to develop. The distinction between the traps is recognised in the deposit-repository relationships in the finer (mud) fractions. Clay concentration is correlated with mobility trapping and the relationship of clay content to organic content (Chapter 5) suggests that sites which develop mobility trapping conditions may also evidence ecological differences.

The longer-term responsiveness of sites to sediment delivery is the most significant question from the viewpoint of prediction. The framework of ordered response identifies those factors which are likely to determine both short-term and long-term effects.

A Summary Model

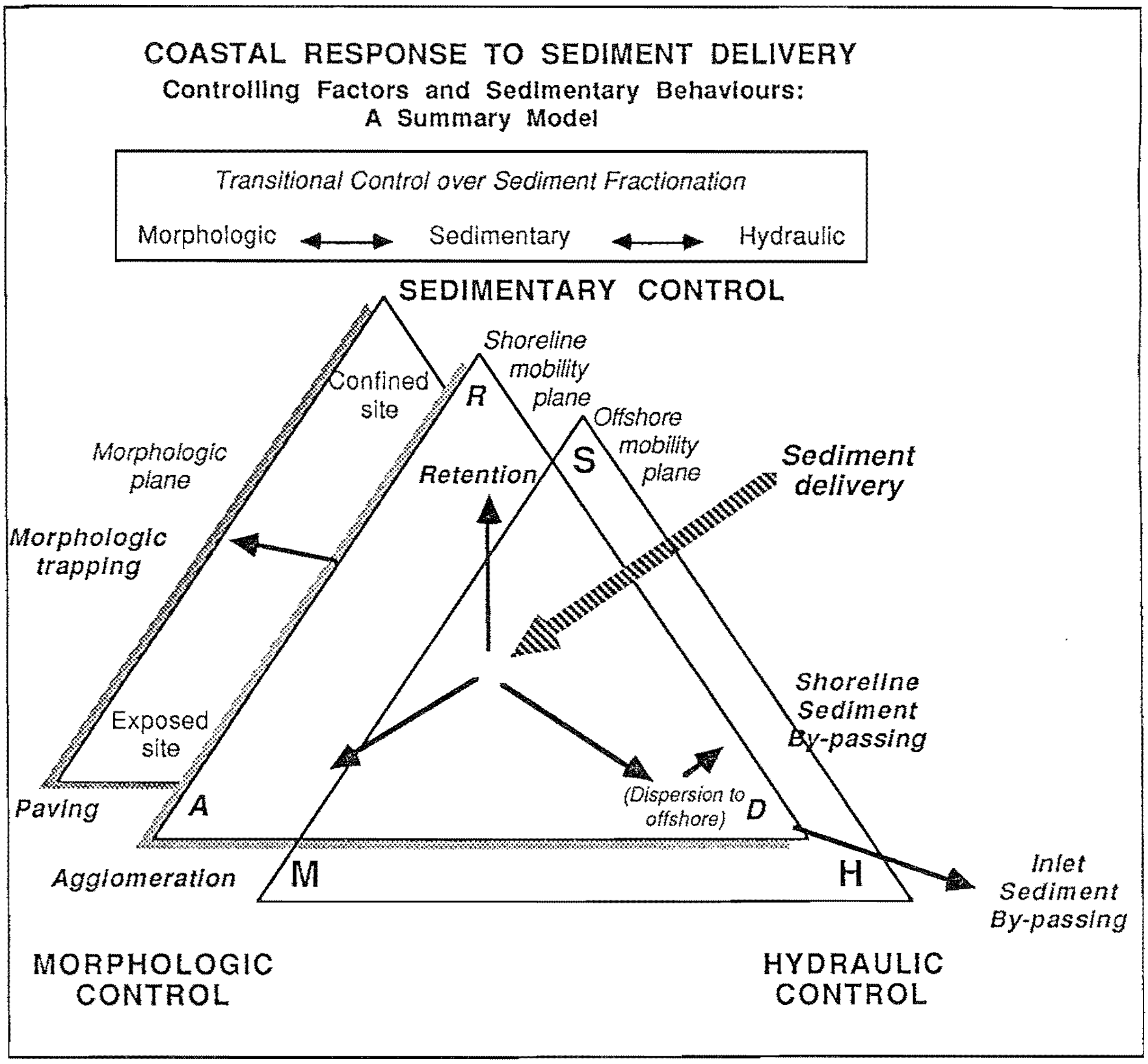
The patterns of offshore sediment texture have confirmed the patterns of embayment behaviour proposed in the Embayment Framework on Figure 8.16. At bayhead and mid-bay locations the patterns of sediment behaviour are retentive - in the inner locations due to confined morphology, in the mid locations apparently due to a mobility trap. Outer bay locations are liable to be under tidal hydraulic control and the absence of sediments in scoured locations illustrates the nature of transitional control defined in that diagram.

The coherence between the retention-agglomeration-disperion plane framework and the Ordered Response Model was explained in Chapter 6. The unifying concept between the general model and its two local expressions for the shoreline and the offshore domains was *transitional control*. In Figure 9.9, a summary model shows the manner in which the morphologic plane and the mobility planes for shoreline and offshore behaviour can be related. The figure shows the manner in which it is sediment fractionation, according to the exercise of transitional control, that determines the coastal response to sedimentation.

The manner in which a coastal system responds to sedimentation is thus recognised through the investigation of the fate of several sedimentary fractions of differring mobility.

Figure 9.9

Coastal Response Framework:
An Operational Statement of the Ordered Response Model



The investigation of coastal response to sediment delivery entails recognising the relationship between the various controls acting on the coast. These have been divided in Figure 9.9 into three planes of action, as developed in previous chapters.

The morphologic frame determines the boundary conditions of shore and offshore behaviour.

The shoreline mobility plane is that to which all sediment is delivered on the coast. The framework shows in what manner the shore responds to sediment delivery by adopting one of a number of mobility behaviours. Within the shore, three are identified: retention, agglomeration, and dispersion.

In the offshore mobility plane, material is seen to be under the control of either morphology, sediments or hydraulics, or a transitional relationship between them.

Chapter 10

Conclusions

This thesis has been concerned with the nature, development, and functioning of the coastal system of the Marlborough Sounds. Focus was directed to questions of catchment sediment delivery and of the response to sedimentation of the shore and offshore domains of this sheltered coast. Because of the scale at which the investigation was conducted, and in particular because it entailed the study of catchment, shore and offshore linkages it became necessary to develop a perspective on the region and for a coastal sedimentation that differed from that presented in the literature. Expressions of this perspective were the development of a new model of coastal response and the adoption of a Realist approach to investigation.

The intepretation of sediment dynamics in the landscape required a consideration of the Quaternary history of the region and aspects of historic and contemporary catchment landuse practices. Some regard had been given to catchment-coast linkages in literature, but this had been restricted to considerations of the mechanisms of delivery of fine sediments at specific sites.

It was observed that both catchments and the coastal domains contained a wide size range of sediment particles and that these were delivered to different parts of the coastal domains. On this basis, the proposition was advanced that the key to understanding coastal sedimentation in the Marlborough Sounds lies in the recognition of the fate of several sedimentary fractions. A task for this chapter is to evaluate this proposition.

This chapter is comprised of three sections and proceeds from the specific to the general aspects of the investigation. The first section is a review of the principal findings about the Marlborough Sounds landscape, coastal form, coastal sediments and their distributions. The second section is a review of the investigative framework with an evaluation of the utility of the Ordered Response Model as a framework within which to study coastal sedimentation. The third section takes a broader perspective on the investigation and its implications.

Principal Findings of the Investigation

The section examines first, the specific findings of each part of the investigation and the implications of them for coastal sedimentation in the region; and secondly, the scope for future research.

Specific Findings

Geomorphology: New sub-bottom evidence of terraces.

Previous physiographic descriptions of the Marlborough Sounds landscape have noted the drowned river valley formation of the embayed coastal landscape. Key elements of explanation of land form involved reference to the tilting of a regional structural block with subsequent reversal of drainage of rivers that shaped overall physiography. No evidence was found to justify the view that tilting has relevance to the interpretation of coastal or bathymetric form.

A focus on smaller-scale aggradational forms in landscape has shown specific value as a source of evidence. Terrace remnants in the Pelorus Sound are more extensive than previously mapped and are to be found in bayheads throughout the Pelorus Sound. A significant finding has been the identification of submarine terraces that correlate well with these subaerial remnants. Incised terrace remnants in the sub-bottom of Nydia Bay correlate with terrace remnants in marginal bays as far north as Tawero Point. Patterns of incision in these terrace remnants point to a new source of evidence for the late Quaternary river patterns in the Pelorus region.

Submarine morphology in Pelorus Sound has been correlated to submarine form in Tory Channel. Accumulation forms found in bay mouths which had not previously been explained were accounted for by a model of stream incision of the channel axis before drowning. An origin attributable entirely to tidal currents was rejected on the grounds of bay mouth marginal channels which have an analogy to forms in the Pelorus Sound, and the origin of which is apparently fluvial. A corollary to this explanation was the recognition of Quaternary cutting of the Cook Strait entrance to the channel and a subsequent reversal of drainage through the channel - but without a tectonic mechanism.

Catchment Sediment Delivery: Redirection of focus to type of sediment delivered

The catchment sediment delivery regime is only partly documented. A correlation between catchment behaviour and sediment delivery to the coast is most apparent in cases of:-

a) Long-term deep-seated hillslope instability,
b) Disturbance of hillslope detrital materials, both historically (gold-mining), and in contemporary times (roading, track construction, hillslope excavations), and,
c) Disturbance of hillslope drainage (culverts, slippage into streams).

A key difference between modes of sediment delivery is found in the nature of material which is delivered to the shore. This distinction may be more important than the specific landuse practice involved or in the timing of delivery. While catchments were subject to widespread clearance by fire in the historical period (1850-1910), it has not been established that this in itself radically modified catchment sediment delivery. However, the disturbance of hillslope detrital materials in which there are direct transfers of material of a wide size range to the shore has had measurable effects at shoreline sites.

Modelling Coastal Response

Analysis of coastal response to sedimentation identified three primary controls which determine coastal response to catchment-derived sediments:

a) Morphological character of the receiving environment
b) Size range of material delivered to the coast
c) Energy level of the local coastal site

The prime features of this coast were identified as the low energy character of the shore line, the mixed size range of materials and the enclosed form of both shoreline and offshore sites. The conceptual framework developed provided a means by which to evaluate the mechanisms and scale at which sediment trapping occurred on such a coast.

A new model was developed (the Ordered Response Model) that identified the functional linkages between the controls acting on the coast and the manner in which the coast responds to these controls. Trapping behaviours were identified at two distinct orders and the recognition that certain elements of control were subordinate to others was a key by which field investigation could be tied to the analysis of coastal behaviour. The model is evaluated in the following section.

Analysis and Interpretation of Coastal Sediments and the Processes of Fractionation

Coastal Sediments

Mean grain-sizes in sampled shoreline accumulations fell into the coarse sand and fine granule grades, while the median sizes of nearshore and offshore samples were mostly silt. Such a clear differentiation takes place between intertidal and subtidal domains that their investigation as separate systems was warranted.

Patterns of sorting in shoreline sediments reflected a good sorting in unimodal very coarse sand and fine gravel samples, but poorer sorting in those samples with a finer mean i.e. in the coarse to medium sand grades. This poorer sorting was attributable to the higher sand content. The transition from poor to well sorted samples took place with the winnowing of fine and medium sand from the granule population. In finer submarine samples no strong correlation was obtained between mean size and the sorting parameters. This was attributed to the relatively lower sensitivity of cohesive sediments to hydraulic sorting.

The sand fraction in submarine samples diminished with increasing depth away from the shore. Exceptions were identified in scoured bay-mouth locations, especially in Tory Channel, where a well-sorted fine fraction was present with a mud admixture. These sites were subject to tidal scour. Organic content in offshore samples was correlated to clay content. The highest organic contents were found to depend not on the sub-region of sampling (e.g. Pelorus Sound) but on the type of depositional site.

The investigation of sedimentary fractionation highlighted two particular aspects of control acting on an enclosed and low energy environment in which a wide size range of materials was available. These were:

1. The transitional relationships which exist when energy levels are sufficient to achieve only partial mobility of a sediment population and accomplish only part of the reworking that might be expected in higher energy settings, and,

2. The effects of trapping behaviours at a range of scales which led to the retention of materials at sites that under higher energy conditions, or less enclosed topography, might be expected to be dispersed or by-passed.

Shoreline Sediment Fractionation

The principal coastal control on both sediment fractionation and shoreline responsiveness to sediment inflow, was shown to stem from sediment relative mobility. A primary fractionation takes place at the shore of sediments delivered to the coast from catchment sources. The outcome of these processes of fractionation depends on the mobility characteristics of sediment materials and the morphology characteristics of the shoreline site.

Sediment delivery was shown to have least effect on sites which exhibit a dispersive behaviour. These were identified as steep-shore sites at which the sediment delivered was most liable to be by-passed to the nearshore. However, due to the limited capacity of the shore to redistribute materials the relatively immobile sediment fractions are retained even at dispersive sites with the resulting formation of rubble and ramp shores.

Sites which exhibit a retentive behaviour were identified with those of low intertidal gradient, such as are found in bayheads. It is at these sites where the principal stream inflows occur and consequently these are the shoreline sites most sensitive to catchment-delivered sediments.

On these shores, a distinctive intertidal accumulation form was identified. The recognition of clastic waves as a distinctive shoreline bedform, that has not been identified in the coastal literature, is a significant finding of this study. The forms warrant further investigation.

Factors identified as preconditions for their development were low wave energy, mixed sand and gravel composition, and tidal translocation of the wave working zone across a gently sloping intertidal surface. The significance of low wave energy and mixed materials lies in the variation in particle transport rates that occurs in a heterogeneous mix of particles. This leads to interparticle interactions and the development of kinematic relationships between the clastic constituents of the wave. The significance of the tidal translocation across the gently sloping surface is that the forms are subject alternatively to drowning and working by swash zone processes. This enables the waves on the rising tide to sweep material up the form and deposit it on the lee slope. This lee slope deposition is what leads to the migration of the forms up the beach.

Sedimentary fractionation takes place with this migration and also leads to the development of a distinctive intertidal stratigraphy.

Offshore Sediment Fractionation

Analysis of sub-bottom seismic profiles showed that the inner and middle reaches of Pelorus Sound to have a mean bottom sediment thickness of 7.33m. Sediment was not thickest in the inner reaches of the Sound, however, but in the deeper marginal embayments. Relationships between the bottom and sub-bottom form pointed to the recognition of embayments as acting as partially independent sedimentary systems to the axial inlets.

The significance of trapping within embayments was confirmed by the sediment textural analyses. Sub-regional variations between Pelorus Sound, Queen Charlotte Sound and Tory Channel offshore sediments were identified, but these were not so significant as variations within the embayments themselves. A distinctive pattern of axial variation in sediments between bayhead and baymouth was identified. This pointed to three controls acting on sediment redistribution.

First, tidal currents are a primary control in baymouth and channel locations. Secondly, in the middle reaches of more deeply embayed sites a trapping behaviour was identified in which a concentration of fine-grained material takes place. Thirdly, at bayhead locations stream inflows were dominant.

These patterns have implications for the response of offshore sites to sediment delivery. First, sites at which tidal currents predominate are governed by conditions within the broader channel or Sound. Kenepuru Sound was shown to act as a sediment trap as a whole, and consequently all sites in this Sound will show a retentive behaviour. In strongly tidal sites (Pelorus Channel, Tory Channel) the effects of fine sediment delivery are dispersed.

Secondly, the finding of what has been referred to as a mobility trap in the middle reaches of deep (long) embayments, but not in smaller indentations, indicates that the retention of fine materials in these embayments is accentuated by hydraulic processes. Sediment discharges into these bays, even on the bay-sides, are liable to be retained in the bay.

Thirdly, bayhead locations in all but the smallest shoreline indentations are inherently trapping environments due to site morphology. This observation highlights the importance to coastal dynamics of the sediment delivery from small catchments for any location in the Sounds.

The concept of sediment fractionation provided the link by which the relationships between the catchments, the shoreline, and offshore sediment behaviour could be considered in a coherent way. The interpretation of sediment behaviour in each domain, and the connections between domains, was accomplished through the recognition of fractionation by reltive mobility, or by its analogue, grain size. The limitations of grain size as a measure of mobility are recognised (Winkelmolen, 1982); but within a broader framework of interpretation suficient pattern has been recognised to identify the scale at which trapping behaviours take place.

The proposition was advanced, that the key to understanding coastal sedimentation in the Marlborough Sounds lies in the recognition of the fate of several sedimentary fractions. In the light of these findings of this investigation this proposition can be considered confirmed.

Recommendations for Future Research

There is scope for further investigation of four specific aspects from this thesis.

1. The Ordered Response Model has the potential for operationalisation as a framework for the investigation of coastal processes in a wide range of coastal problems. The recognition of orders in control and the specification of the linkages between these by feedback loops are its particular attributes. If operationalised from a Realist perspective, the model has good potential to suggest hypotheses which could be tested by "crucial experiments" (Aronson, 1984).

2. Clastic Waves, as an intertidal bedform of mixed material low energy tidal shores evidence a range of sediment behaviours which warrant focussed investigation. In particular, their stratigraphic record of medium-term (historical) catchment behaviour offers a most interesting potential means to investigate catchment sedimentation.

3. Offshore sediment trapping has been shown to be controlled not only by inlet hydrodynamics (Carter, 1976) but by embayment hydrodynamics also. A

specific investigation of patterns of tidal flow within bays and of the flow patterns generated by local streams would explain the mechanisms that determine the observed patterns of sediment grain-size and that operationalise the "mobility trap" concept.

4. The pattern of terrace systems identified in bayheads of Pelorus Sound and the probable sub-bottom correlatives of these surfaces point to an unexplored source of evidence of Quaternary changes in a landscape in which few dates for landscape development are available. The "Nydia surface" in particular has potential and correlative surfaces in Kaiuma Bay and Tennyson Inlet could tie local findings into the Pelorus and the Rai Valley geomorphology.

Evaluation of the Investigative Framework

Beyond the details of specific findings about the coastal landscape of the Marlborough Sounds this has been a study of frameworks and models used to investigate, explain and interpret the Sounds and coastal sedimentation. At each stage in the study it has been apparent that there have been or could be a number of different views adopted to interpret the form and functioning of catchments, the behaviour of coasts, the fractionation of sediments, and the form and texture of the shore and offshore domains.

In reviews of literature on both the form of the landscape in Chapter 2 and the analysis of sediment grain-size distributions in Chapter 5, it was seen that the adoption of an explanatory model so influences the manner in which questions are asked about the problem that it can condition the evidence expected and the conclusions which are reached.

In the case of both the interpretation of the Marlborough Sounds as a tilting earth block, and the interpretation of sediments as expressing either source area or hydraulically sorted characteristics, the central issues are the scales of investigation. The essentially Davisian reasoning which gave rise initially to the "tilted block model" did not coincide well with the scale at which evidence could be sought to validate the model. In retrospect, however, the model served the useful function of stimulating research to contemplate alternative explanations - and in this regard a particular value of models in any investigation is highlighted.

It was shown in Chapters 4 and 5 that differences in interpretation of sediment grain-size distribution could be resolved in large part by a reconsideration of the scale of variability at which different levels of explanation could be applied. It was in the light of this observation, that scale was central to the explanation of coastal sedimentary behaviour, that the "ordering principle" was adopted in Chapter 4, that gave rise to the Ordered Response Model.

The three key aspects of the Ordered Response Model were the ordering of controls and response, the recognition of transitional control, and the identification of three functions of the coastal system.

Independent Controls, Interdependent Controls and Coastal Response

The Ordered Response model sought to identify the key controls acting on different sites on a variable coast by identifying different aspects of coastal response with controls interacting at different levels. Certain coastal reponses (either morphologic or sedimentary) were seen to be dominated by higher order or independent coastal controls, namely the initial morphology and the nature of sedimentary materials available or delivered to the coast. Other responses were seen as being at a lower order, in which case behaviour was dependent on the local hydraulic factors and the mobility of sediments.

In the case of shoreline sedimentary behaviour, it was found useful to restate the general form of the Ordered Response Model in a local form. This highlighted the relative mobility of sediments within a low energy shore on which was to be found a wide size range of sediment particles. As a consequence of examining variations in relative mobility it was shown that the morphologic trap and the mobility trap were expressions of a general sediment trapping behaviour. The two traps are related, but reflected different levels of particle mobility. The relative mobility concept was shown to be an expression of the concept of Transitional Control.

Futhermore it was shown that when the model was operationalised within one specific region of coastal behaviour - the retentive shore - the recognition of sediment trapping at several orders became a useful concept by which to explain a distinctive sediment behaviour found on those shores. The demonstration that the Ordered Response Model could be operationalised at more than one scale served as evidence that the initial ordering principle has a general applicability.

Transitional Control

The existence of three independent controls on coastal behaviour had been recognised by Krumbein (1961).

In the development of a model of sedimentary control McLean and Kirk (1969) had taken two of these elements (energy and sediments) and illustrated that control could stem from either a source area or an hydraulic source. By incorporating the morphologic element into this model, in the ordered response framework, it was possible to account also for the factors which determined source area effects. A further outcome was the recognition of transitional control.

Transitional control was defined in Chapter 4 as an expression of the variation in coastal behaviour. The principal control on a site can transit from morphologic, to sedimentary to hydraulic domination.

In terms of shoreline behaviour transitional control was recognised in terms of relative particle mobility. When the essentially immobile components of shore form were distinguished from the more mobile elements, it was possible to conceive of the morphologic frame of the shore as acting as a trap for certain sedimentary fractions. On steep shores the trap acts only on the coarsest sediment fractions. The particles, having aligned with the surface of a shoreline ramp, become essentially immobile and therefore under the control of morphologic rather than hydraulic factors. On more gently graded shores the trapping effect of morphology was seen to retain a wide range of particulate sizes. Coincident with trapping behaviour is a decline in relative mobility. On shoreline sites dominated by morphologic trapping relative mobility is low. This led to the recognition that there is a complementarity between morphologic trapping and relative mobility, and therefore between the morphologic and the mobility traps. These two behaviours were therefore seen to be end-members of a continuum of trapping behaviours.

One particular challenge of shoreline classification and modelling on a variable shore, especially one which includes elements with markedly different responsiveness to shore process, is to identify a coherence between the model for the mobile components (for example, the shore profile of the beach) and the less mobile elements (a ramp, or shore platform). The concept of transitional control is a means by which this coherence can be obtained, and its operational expression is in relative mobility.

On the retentive shoreline transitional control is expressed between morphology and mobility in a different sense. While for shoreline ramps the investigation was of the mobility of individual particles, on the retentive shore the key expression of mobility is of collective particle mobility. In retentive situations the control on shoreline functioning is not so much dominated by external morphology or hydraulic factors, as by *sediment* factors. The interparticle interaction that leads to the collective morphology referred to as a clastic wave is an expression of the intermediate form of transitional control.

Sediments that are sufficiently mobile to by-pass the shoreline trap enter the offshore domain. The control over these fractions is principally hydraulic and as a consequence the patterns of sediment texture reflect the hydraulic domination.

It was a significant discovery to identify the extent to which sub-bottom morphology was reflected in bottom form. This pointed to an element of morphologic control in coastal response and to the fact that the geometry of the inlets reflects antecedent morphology at least as strongly as hydraulic geometry.

These apparently contradictory observations - that offshore sedimentation would appear to be controlled both by morphology and by hydraulics - are reconciled by the distinction made in the ordered response model between a morphologic trap and a mobility trap.

These findings highlighted a significant difference in the operationalised expression of ordered response in the shoreline and in the offshore domain. The general framework of ordered response makes the distinction between the morphologic trap and the mobility trap.

In the shoreline domain the importance of the relative mobility of sediments delivered to the shore was found to be the crucial factor in determining shoreline response. As a result, the ordered response model was locally restated in terms of the relative mobility model. This highlighted the relationship between morphologic and mobility trapping as a continuum.

In both the shoreline and offshore domains it was found useful to restate the general form of the Ordered Response Model in a framework adapted to the domain in question. As a result of the interactions which were seen to occur between independent controls and interdependent response within the model it was possible to distinguish in each domain a set of constraining factors imposed by morphology and a set of factors imposed by mobility. Three end-member behaviours were identified at each plane: retention (attributed to morphologic trapping), agglomeration (attributed to mobility trapping) and dispersion.

When the two "local" expressions of the Ordered Response Model i.e.: the Relative Mobility Framework (shoreline) and the Embayment Framework (offshore) are considered together the result is a recognition of three planes of sediment behaviour. One is controlled by morphology, one by sediment relative mobility, and one by sediments under hydraulic domination. The three planes can be visualised to float one above the other, and the linkage between them is exercised by transitional control. With diminishing mobility particles pass from the higher to the lower planes and become trapped in a mobility or a morphologic frame. With increasing mobility, material is sequentially dispersed from each plane until, as pictured in the Embayment mobility model, it is by-passed from the inlet system altogether.

The finding that the Ordered Response Model, and its local restatements, can be linked in a number of ways is evidence of a general coherence in the manner in which coastal processes are stated in the model. That the frameworks have been used to investigate a diverse range of coastal processes and have led to the identification of a number of new relationships and patterns is evidence of its practical usefulness.

These two grounds - coherence and practical usefulness - were the two criteria specified in Chapter 4 as being those upon which a model was to be validated from a Realist standpoint.

The Broader Perspective: Implications

A move by geomorphologists towards a functional perspective in the study of coasts has taken place in recent years (Pethick, 1984). A consequence has been a growing understanding of the processes which govern coastal change but also there has been a trend towards the definition of investigative problems in a narrow and mechanistic manner. There appears to be a need to retain a perspective of landscape function at multiple and particularly larger scales of scientific inquiry in order to balance this trend.

This investigation of the coastal system has endeavoured to maintain a functional theme, but at a scale which crossed the boundaries between a number of coastal domains and demanded a consideration of the landscape functioning as a whole. This entailed taking a study at a scale referred to as the catchment-coast approach. The means by which the links between domains were investigated was by explicit reference to conceptual frameworks. This approach was adopted on two grounds.

One was the complexity and variability of the coastal landscape. Coastal investigation (and geomorphic investigation) had previously been completed only in limited parts of the region. In the absence of a wider perspective it was an open question as to what would constitute a representative study site. It was seen, on consideration, that an investigation which sought to identify the controlling factors of variability between sites would be the first step towards a coherent coastal analysis.

The second reason why the framework approach was adopted stemmed from the more fundamental proposition put in Chapter 4 - that while the expressions of coastal control could be observed in the field, the controls which determine coastal functioning could be conceived of only within a theoretical framework and not in a strictly empirical view of the system. This viewpoint was identified in that chapter as a Realist perspective on science, and the criteria upon which models proposed within this perspective were to be judged are grounded in coherence and practical usefulness. Models are the tools by which the investigator gains access to the underlying controls (to "reality") that govern the empirical system.

This section briefly considers the consequences of taking a catchment-coast and Realist approach to the investigation of landscape functioning.

In taking a broader catchment-coast approach in contrast to more local, site-specific investigations one of the more interesting findings is the range of problems uncovered for future investigation. Specific ones noted above were the mechanisms of clastic wave migration, the relative mobility of shoreline ramps, and the dates and details of terrace surfaces in the Pelorus Sound and Tory Channel. In contrast to a narrowly focussed investigation a regional approach may not lead to a resolution of all the problems it uncovers. However, the identification of topics for further investigation could be regarded as one of the primary objectives of field investigations.

There are, however, compensations in the broader approach to the links between parts of the landscape. In this landscape more than many others the coastal forms and processes relate to subaerial factors. At the broadest scale the inlet dimensions are determined by antecedent landscape factors and this extends in detail to the relationships identified between remnant terrace systems found in catchments and underlying muds on the seabed. The level of confidence which could have been given to a terrace interpretation of sub-bottom form, without correlative subaerial investigation, would have been markedly lower. Neither the literature of this region nor that of many others shows evidence of the joint consideration of terrestrial and submarine morphology with reference to Quaternary form. Stopping at the water's edge has weaknesses both for scientific investigation and landscape management.

The patterning of offshore sediments in confined areas - notably deeply embayed marginal bays and in the Kenepuru Sound as a whole - suggests that the offshore system functions to trap material delivered to it not only at the scale of the Sounds as a whole (Carter, 1976) but also as a series of internal traps. The focus on variations in sediment within and between sub-regions gave a spatial perspective to the problem which had specific benefits in identifying the significant scales of variation.

One of the demands of treating the shoreline as a whole was to recognise the manner in which a coherence could be recognised between shoreline types of radically different textures, forms and sensitivities to hydraulic reworking. Rather than treating a number of shoreline types as behaviourally distinct the approach taken has been to identify the fundamental relationships which give rise to similarities and distinctions between them. The concept of transitional control, determined by the interaction between sediment traps at a range of scales, and expressed in the relative mobility of coastal materials was the outcome of looking at a varied shore as a continuous rather than a segmented landform system.

Had this investigation been conducted in the absence of a conceptual framework the various components of the study - geomorphic background, catchment behaviour, and the coastal form and sediments - would have appeared to be largely unrelated in other than a very general spatial sense. It might well be argued that if the primary objective of scientific investigation is the acquisition of empirical facts, then the most direct way to do so is by a reductionist dissection of the landscape into its smallest parts with specialist investigation of each part independently. Such a view is not coherent with the objective of science to develop general principles, and is not the view taken here. Not only has taking a view of the landscape parts as related given rise to some specific empirical findings which have practical usefulness, but it has also led on to the recognition of a more coherent relationship between parts of the landscape, and between models and reality.

The Realist perspective seems to be well suited as a starting point for investigations of landscape functioning when the scale of analysis is broader than the analysis of specific mechanisms of change. The process-response approach (Krumbein, 1963) has specific utility at these smaller scales but has been found to be limited when an historical element is involved in which the boundary conditions of process-response are progressively modified (King, 1970).

While the empirical response to landscape complexity may be to introduce an element of probability into a deterministic model (i.e. to form a stochastic model), the realist approach is to focus on the relationships of boundary structures to their modifying processes. Unlike a structuralist approach to scientific thought the Realist approach seeks to identify the manner in which agents (process-response behaviours)act within structures and also modify structures. It is this perspective which has been illustrated in the Ordered Response Model and proven to have practical utility in terms of recognising both the relationships between mobile sediment accumulations and their immobile environment together with the relationships between tidal processes and offshore sediment distribution, and with the underlying landscape form.

Considerations of theory are frequently a subordinate component of geomorphic investigations. "Whenever anyone mentions theory to a geomorphologist, he instinctively reaches for his soil auger" (Chorley, 1978). However, as Chorley noted geomorphology is that science which has for its *object* of study the geometrical features of the earth's terrain; but that each generation of geomorphologists has redefined both the scales and processes under investigation to best accord with the contemporary *aims* of the science (Chorley, 1978, p1).

It is interesting to find that in Chorley's view (1978, p9), the "most obvious result of the rise of Realist theory in geomorphology has been to accelerate the existing tendencies towards studying landforms on more restricted scales of space and time." Yet proponents of Realism in science at large (Aronson, 1984) find that the key to theory confirmation within the perspective lies in the testing of hypotheses across categories in as broad a framework as possible.

These considerations have relevance to the broadest issues of investigation.

This study arose in the context of a landuse and water management debate. Not only the empirical findings, but also the model frameworks and the manner in which these have been validated have relevance to the management issues arising. It will be recalled that the criteria upon which the model were to be validated, were those of coherence and practical usefulness.

This reasoning bears directly on the observation of Chorley (1978) above, that Realist thinking in geomorphology has led to the exploration of environmental dynamics over shorter time spans and in smaller spaces. However, the value of a Realist perspective would appear to be only partially exploited by investigation at the smallest scale.

This investigation has taken the opportunity to view the operation of a coastal system at a broader scale. The explanation of pattern within the system did not begin with a direct investigation of detailed mechanisms, although the operation of the system at small as well as large scales is inherent in the ordered response framework. The view taken was that where the bounds on the operation of sub-components of the system could be identified then a description of the system could be achieved. This view was inherent in the concepts of a morphologic and a mobility trap neither of which was defined on fundamentally physical grounds. The proposition that the coast has three functions comprised of a morphologic transform, a sediment transform, and an energy transform is a functional statement (although not a functionalist statement) which resides in the conceptual rather than the empirical domain.

This study has shown that in this region as much as in any other in New Zealand, there is a direct connection between catchment factors and coastal factors. This relationship arises from the geomorphic form of the landscape and is reflected in its functioning at all time scales, from the Quaternary to contemporary processes.

The role of human activity in the historical and the contemporary behaviour of catchments is only partially understood but whatever changes have been induced have been constrained, and continue to be constrained by the framework of the landscape. The natural character of this coast has been shown to be determined neither by morphologic, nor by hydraulic, nor by sedimentary factors alone, but by a transitional control which exists between these factors. Therefore, the analysis of any questions pertaining to sedimentation on this coast must be made within a framework which considers the enclosed form of the landscape and its low levels of coastal energy.

In the consideration of coastal response to sediment delivery two factors are of primary importance. The first is the nature of sediment delivery from catchment sources - and delivery not only in terms of volume discharge but also in terms of the grain-size range of materials delivered. The second is the nature of trapping behaviours which the coastal system can be seen to display.

In this investigation it has been shown that trapping within the coastal system is occurring at two orders: one which stems from the morphologic form of the embayed coast; another which can be attributed to the low energy regimes of waves and tidal currents which are found within such a coast. The means by which the scales and mechanisms of these traps were identified was by reference to the grain-size characteristics of the sedimentary materials and their distribution within the coastal domains.

In all cases, however, it was not on criteria of grain-size but of sediment particulate and collective mobility on which the fractionation took place. At a range of scales it was seen that material redistributed from one location to another did not leave the coastal system but was retained. The natural character of this coastal landscape is one in which there is a nested hierarchy of trapping behaviours and these various behaviours can be seen to be determined by factors operating at different orders of control within the hierarchy.

It is found, therefore, that the key to understanding coastal sedimentation in the Marlborough Sounds lies in the recognition of the redistribution of several sedimentary fractions within an ordered whole.

Acknowledgements

This work was made possible by support and assistance from many individuals and institutions.

First of all, grateful thanks are expressed to Dr. R. M. (Bob) Kirk for his supervision. His support and help throughout the investigation were invaluable. Appreciation is also extended to Professor W. B. Johnston and to other members of the staff of the Department of Geography, University of Canterbury.

Financial support was provided by the University Grants Committee through a Post-Graduate Scholarship. Equipment was made available through the University Grants Committee and through the University. The Marlborough Catchment Board also provided financial and practical support. Particular thanks are due to Mr. Ron Sutherland and Mr. Ross McArthur for facilitating the project and for ongoing support and encouragement.

Practical support was given by the Marlborough Harbour Board with echosounding and sampling. Thanks specifically to Captains Don Jameson and Ken McKenzie for their assistance in every way. Help with diving was provided by Messrs. Jim Mace, John Meredith-Young and Alex Johnson of Ministry of Agriculture and Fisheries, Nelson. Their help went beyond the call of duty.

Help and advice concerning the substance of this thesis has been contributed by a number of people. For their knowledge of the landscape of the Sounds, Ron Sutherland and Will Esler were of inestimable assistance, and the long and enjoyable debates with both on every aspect of the landscape of the Sounds remains a highpoint of the times in Marlborough. Dr. Lionel Carter and Mr. Jack Irwin, Division of Marine and Freshwater Research, D.S.I.R. gave generous access to raw data and were helpful at all times, as was Mike Laffan, Soil Bureau, Nelson. Prof. Jane Soons and Dr. Eric Pawson read drafts of some chapters and their comments and discussion were of particular value. Trevor Hoey's help with field geomorphology and his fastidious attention to detail in reviewing ideas was invaluable.

For the preparation of field equipment, I would like to thank Peter Tyree, Ray Begg and Walter Gallagher. For help in the field, thanks to Paul Sowman, Trevor Hoey, Tim Frazer, Peter Kingsbury, Sandy Manderson, Peter Noble, Jenny Oakley, Andrew Bedford and Ray Begg. Andrew Mulligan as an excellent co-diver shared the cold side of the Sounds. Assistance with draughting provided by

Tony Shatford and Alastair Dyer, and the helpfulness in every way of Anna Maloney and Linda Harrison, Bill Cutts, Irene Franks, John MacDonald and other technical staff of the Geography Department is gratefully acknowledged.

For their support during fieldwork, I would like to thank Ron and Lorraine Sutherland, Sue and Mark Giles, Lindsay and Joy Turner and clan of Blenheim, Paul and Joanne Sowman and Mr. and Mrs. Ken McKenzie of Picton. Their kindness made all the difference.

It was the Sounds people who brought the landscape alive. I give my particular thanks to Ann and Bill Esler with whom I had the pleasure of exploring the Sounds from Anakiwa. To Jeff and Frances Hauschild and clan of Momorangi, who took me into their home and helped in every way; to Peter Brady and Jenny Jones of Mahakipawa, adventurers; to the generosity and good company of Dave and Pam Speedy of Mistletoe Bay; Mr. and Mrs. Kenward of Bythells Bay, Ross and Sylvia McArthur of the Grove, and Diarmid and Isabell Jennings of The Rock, Mahau, for keeping in touch with the way the Sounds used to be. The Sewell family first introduced me to Ngawhakawhiti, a place at the right end of the world. Fieldwork in rain and shine with Jenny Oakley, 'Poss' Bedford, and Tim Frazer is memorable.

This time at University would not have been the same without the abiding enthusiasm of my fellow students, especially over the years with Laurie Brown, Richard Curtis (and Nicki) and Mahbub. A good natured atmosphere has always been a hallmark of the student community in the Geography Department, added to each year by the undergrad and grad students with whom I have had the pleasure to work.

My tribute to Bob Kirk not only as a supervisor, but as an educator in the best tradition. Lastly, my thanks to my parents, for everything.

References

Adams, C.W. (1901) The Marlborough Sounds. in *N.Z. Official Yearbook,* 1901. Government Printer Wellington.

Adams, J. (1985) Large-scale tectonic geomorphology of the Southern Alps, New Zealand. In, M. Morisawa and J.T. Hack (Eds) *Tectonic Geomorphology. Proceedings of the 15th Annual Binghampton Geomorphology Symposium.* Allen and Unwin. New York.

Allen, J.R.L. (1984) *Sedimentary structures - their character and physical basis.* Elsevier. Oxford. 1256pp.

Aronson, J.L. (1984) *A Realist philosophy of science.* The Macmillan Press Ltd. London. 278pp.

Bagnold, R.A. (1941) *The physics of blown sand and desert dunes.* Methuen and Co. Ltd. London. 265pp.

Bagnold, R.A. and O. Barndorff-Nielsen (1980) The pattern of natural size distributions. *Sedimentology* 27:199-207.

Barndorff-Nielsen, O. (1977) Exponentially decreasing distributions for the logarithm of particle size. *Proceedings of the Royal Society of London* A353:401-419.

Beck, A.C. (1964) *Geological map of New Zealand. Sheet 14, Marlborough Sounds.* New Zealand Geological Survey, Wellington.

Bloom, A.L. (1969) *The Surface of the Earth.* Prentice-Hall, New Jersey. 147pp.

Bowie, I.J.S. (1963) *Land utilisation in the Marlborough Sounds.* Unpublished MA Thesis, Department of Geography, University of Canterbury, Christchurch, New Zealand. 98pp.

Bowman, D. and V. Goldsmith (1983) Bar morphology of dissipative beaches: An empirical model. *Marine Geology* 51:15-33.

Boyce, A.G. (1971) *Coastal depositional environments of the inner Marlborough Sounds.* Unpublished MA Thesis, Department of Geography, University of Canterbury, Christchurch, New Zealand. 112pp.

Bradley, W. and G. Griggs (1976) Form, genesis and deformation of central California wave cut platforms. *Bulletin of the Geological Society of America* 87: 433-19.

Brailsford, B. (1981) *The Tattooed Land - the Southern Frontiers of the Pa Maori.* A.H. and A.W. Reed, Wellington. 262pp

Bridge, J.S. (1981) Hydraulic Interpretation of Grain-Size distributions using a physical model for bedload transport. *Journal of Sedimentary Petrology* 4:1109-1124.

Brown, L.J. (1981a) Water well data, Northern Marlborough. *Department of Scientific and Industrial Research, New Zealand Geological Survey Report* 93. 126pp.

Brown, L.J. (1981b) Late Quaternary geology of the Wairau Plain, Marlborough, New Zealand. *New Zealand Journal of Geology and Geophysics* 24:477-490.

Brunsden, D. and J.B. Thornes (1979) Landscape sensitivity and change. *Institute of British Geographers Transactions* , 4ns:463-483.

Bruun, P. (1978) *Stability of tidal inlets - theory and engineering.* Elsevier Scientific, Amsterdam. 510pp.

Buick, T.L (1900) *Old Marlborough.* Hart and Keeling, Wellington. 478pp

Buller and McManus (1972) Simple metric sedimentary statistics used to recognise different environments. *Sedimentology* 18:1-21.

Burns, D.A. (1977) Distribution of planktonic diatoms in Pelorus Sound, South Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research* 11: 275-95.

Campbell, I.B. (1979) Occurrence of Kawakawa tephra near Nelson. *New Zealand Journal of Science* 22:133-6.

Campbell, I.B. (1986) New occurrences and distribution of Kawakawa tephra in the South Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 29:425-435.

Campbell, I.B. (Ed.) (1985) *Proceedings of the Soil Dynamics and landuse Seminar* New Zealand Soil Scientists and Soil Conservators Association. Blenheim, New Zealand. 20-24 May, 1985. 412pp.

Campbell, I.B. and M.R. Johnston (1982) *Nelson and Marlborough.* pp285-298. In Soons, J.M. and M.J. Selby (Eds) *Landforms of New Zealand.* Longmans, Wellington. 392pp.

Carling, P.A. and N.A. Reader (1982) Structure, composition and bulk properties of upland stream gravels. *Earth Surface Processes and Landforms* 7:349-365.

Carter, L. (1976) Seston transport and deposition in Pelorus Sound, South Island, New Zealand . *New Zealand Journal of Marine and Freshwater Research* 10: 263-282.

Chappell, J. (1983) A revised sea level record for the last 300,000 years from Papua New Guinea. *Search* 14:99-101.

Chorley, R.J. (1962) Geomorphology and general systems theory. *US Geological Survey Professional Paper 500 B.*

Chorley, R.J. (1978) Bases for theory in geomorphology. pp 1-13 in C. Embleton, D. Brunsden, and J.K.C. Jones (Eds) *Geomorphology: Present Problems and Future Prospect* Oxford University Press. 281pp.

Chorley, R.J., R.P. Beckinsale, and A.J. Dunn (1973) *The history of the Study of Landforms or the development of Geomorphology Vol.2: The Life and Work of William Morris Davis.* Methuen and Co. Ltd. London.

Church M. and R. Kellerhals (1978) On the statistics of grain-size variation along a gravel river. *Canadian Journal of Earth Science* 15:1151-1160.

Church, M. (1979) *On experimental method in geomorphology.* pp563-580 In Burt, T.P. and D.E. Walling (Eds) *Catchment Experiments in Fluvial Geomorphology*

Collins, B.W. (Ed.) (1974) *Bold Coasts Annotated Reprints of Selected Papers on Coastal Geomorphology 1916-1969. By the late Sir Charles Cotton.* A.H. and A.W.Reed, Wellington. 354pp.

Cotton, C.A. (1913) The Tuamarina Valley: A Note on the Quaternary History of the Marlborough Sounds district. *Transactions of the New Zealand Institute* 45:316-322.

Cotton, C.A. (1914) Preliminary notes on the uplifted east coast of Marlborough. *Transactions of the New Zealand Institute* 46:286-294.

Cotton, C.A. (1916) The Structure and Later Geological History of New Zealand. *Geological Magazine Decade* 6: 249, 314-320.

Cotton, C.A. (1917) Block Mountains in New Zealand. *The American Journal of Science 4th series* 44:249-293.

Cotton, C.A. (1918) The outline of New Zealand. *The Geographical Review* 6:320-40.

Cotton, C.A. (1949) *Geomorphology: An Introduction to the Study of Landforms.* Whitcombe and Tombs Ltd. 494pp.

Cotton, C.A. (1952) Cyclic resection of headlands by marine erosion. *Geological Magazine* 89:221-5.

Cotton, C.A. (1954) Submergence of the lower Wairau Valley. *New Zealand Journal of Science and Technology,* Section B 35:364-9.

Cotton, C.A. (1955) *New Zealand Geomorphology. Reprints of selected papers 1912-1925. Wellington,* New Zealand University Press. 281pp.

Cotton, C.A. (1955) Solifluxion and periglacially modified landforms at Wellington, New Zealand. *Transactions of the Royal Society of New Zealand* 82:1001-31.

Cotton, C.A. (1956) Rias Sensu Stricto and Sensu Lato. *Geographical Journal* Vol.122.

Cotton, C.A. (1957) Geomorphic contrasts in Central New Zealand. *Tidjschrift Koninklijk Nederlandsch Aardrijkskundig Genootschap. Leiden* 74:248-53.

Cotton, C.A. (1967) Plunging cliffs and Pleistocene Coastal Cliffing in the Southern Hemisphere. *Melanger de Geographie offerts a M. Omer Tuilippe, Vol.1. Gembloux: J. Du Carlot, SA.* 1:37-59.

Cotton, C.A. (1969) Skeleton Islands of New Zealand and elsewhere. *Earth Science Journal* 3:61-76.

Cotton, C.A. and M.T. Te Punga (1935) Fossil gullies in the Wellington Landscape. *New Zealand Geographer* 2:72-75.

Crawford, J.C. (1874) Did the great Cook Strait River flow to the north-west or to the south-east? *Transactions of the New Zealand Institute* 7:448-51.

Crown Study (1976) *A strategy for the conservation and development of the Marlborough Sounds.* Ministry of Agriculture and Fisheries, New Zealand Forest Service, Department of Lands and Survey, Ministry of Works and Development. Government Printer, Wellington. 147pp.

Davies, J.L. (1980) *Geographical variation in coastal development.* Longman. London. 204pp.

Davis, R.D. and W.T. Fox (1972) Coastal processes and nearshore sand bars. *Journal of Sedimentary Petrology* 42:401-412.

Davis, W.M. (1915) The principles of geophysical description. *Annals of the American Association of Geographers* 5: 61-105.

Dieffenbach, E. (1850) *First report to the New Zealand Company on the physical condition and natural history of Queen Charlotte's Sound, Cloudy Bay, Tory Channel, Port Nicholson and the surrounding country Supplementary Information Relative to New Zealand. London,1850* In, Bowie, (1963) *Land utilisation in the Marlborough Sounds.* Unpublished MA Thesis, Department of Geography, University of Canterbury, Christchurch, New Zealand. 98pp.

Dyer, K.R. (1979) *Estuarine hydrography and sedimentation.* Cambridge University Press, Cambridge. 230pp.

Eden, D.N. (1983) *A late Quaternary history of the Awatere and Wairau Valleys, Marlborough, New Zealand.* Unpublished Ph.D thesis, Geology Department, Victoria University of Wellington.

Ehlrich, R. (1983) Size analysis wears no clothes, or have moments come and gone? *Journal of Sedimentary Petrology* 53:1

Esler, W.R.(1984) *Aspects of the Quaternary Geology of the Marlborough Sounds* Unpublished dissertation, B.Sc.(Hons) Geology, Victoria University of Wellington. 62pp.

Eyles, G.O. (1985) *The New Zealand Land Resource Inventory Erosion Classification* Water and Soil Miscellaneous Publication 85 Ministry of Works and Development Wellington 61pp.

Fieller, N.R.J., D.D. Gilbertson and W. Olbricht (1984) *Skew log-laplace distribution to interpret particle size data from shoreline environments.* Sheffield School of Probability and Statistics Research Report 235. 7pp.

Fieller, N.R.J., D.D. Gilbertson and W. Olbricht (1984) A new method for environmental analysis of particle size distribution data from shoreline sediments. *Nature* 311:648-651.

Fleming, C.A. (1978) *The Geological History of New Zealand and its Life.* Auckland University Press, Auckland. 141pp.

Folk, R.L. (1962) Of skewness and sands. *Journal of Sedimentary Petrology* 32:145-146.

Folk, R.L. (1966) A review of grain size parameters. *Sedimentology* 6:73-93.

Folk, R.L. (1974) *Petrology of Sedimentary Rocks* Hemphills, Austin, Texas. 182pp.

Folk, R.L. and W.C. Ward (1957) Brazos River Bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27:3-26.

Folk, R.L., P.B. Andrews and D.W. Lewis (1970) Detrital sedimentary rock classification and nomenclature for use in New Zealand *New Zealand Journal of Geology and Geophysics* 13: 937-68

Gage, M (1980) *Legends in the rocks - an outline of New Zealand Geology.* Whitcoulles, Wellington.425pp.

Gibb, J.G. (1979) *Late Quaternary shoreline movements in New Zealand.* Unpublished Ph.D. Thesis, Victoria University of Wellington, 334pp.

Giles, S.M., M.P. Tuchy and P.E.H Gregg (1985) *Soil erosion / soil fertility investigations in the Marlborough Sounds.* pp 110-117. In Campbell, I.B. (Ed.) *Proceedings of the Soil Dynamics and Land Use Seminar*, Blenheim, May 1985. 412pp.

Grant-Taylor, T.L. (1978) *Southwest Wellington and North Eastern Marlborough.* pp 470-1 In Suggate, R.P. (1978) *The Geology of New Zealand.* Government Printer, Wellington. 2 Vols. 820pp.

Grant-Taylor, T.L. and N.de B. Hornibrook (1964) The Makara faulted outlier and the age of Cook Strait. *New Zealand Journal of Geology and Geophysics* 7: 299-313.

Grave, J.T.C., B.T. Grothans and R. Ehrlich (1978) Non-normal size frequency distributions of sand from divided-laminae. *Journal of Sedimentary Petrology* 48:1193-1202.

Greenwood, B. and R.G.D. Davidson-Arnott (1979) Sedimentation and equilibrium in wave-formed bars: a review and case study. *Canadian Journal of Earth Science* 16:312-332.

Gregory. D (1986) *Realism* p387 in R.J. Johnson (Ed) *The Dictionary of Human Geography*, 2nd Edition. Basil Blackwell, Oxford.

Griffiths, J.C. (1967) *Scientific method in analysis of sediments.* McGraw-Hill New York. 505pp.

Haner, B.E. (1984) Santa Anna River: An example of a sandy braided floodplain system showing sediment source area imprintation and selective sediment modification. *Sedimentary Geology* 381:47-261.

Harms, J.C., J.B. Southard and R.G. Walker (1982) *Structures and Sequences in clastic rocks.* S.E.P.M. Short Course No.9.

Harris, S.A. (1958) Probability curves and the recognition of adjustment to depositional environment. *Journal of Sedimentary Petrology* 28:151-163.

Heath, R.A. (1974) Physical Oceanographic Observations in Marlborough Sounds. *New Zealand Journal of Marine and Freshwater Research* 8: 691-708

Heath, R.A. (1976) Tidal variability of flow and water properties in Pelorus Sound, South Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research*10: 283-300

Heath, R.A. (1976a) Broad classification of New Zealand inlets with emphasis on residence time. *New Zealand Journal of Marine and Freshwater Research* 10: 429-444.

Heath, R.A. (1976b) Factors controlling the entrance cross-sectional area of four inlets. *New Zealand Journal of Marine and Freshwater Research* 10: 725-35.

Hector, J. (1872) Report on Gold Mines in the Province of Marlborough. *New Zealand Geological Survey Reports of Geological Explorations* 7:119-29.

Hein, F.J. and R.G. Walker (1977) Bar evolution and development of stratification in the gravelly braided Kicking Horse River, British Columbia. *Canadian Journal of Earth Science* 14:562-570.

Henderson, J. (1918) Notes on the Geology and Mineral Occurrences of the Wakamarino Valley. *New Zealand Journal of Science and Technology* 1:11-26.

Henderson, J. (1924) The post Tertiary history of New Zealand. *Transactions of the New Zealand Institute* 55: 580-99.

Henderson, J. (1929) The faults and geological structure of New Zealand. *New Zealand Journal of Science and Technology* 11: 93-97.

Henderson, J. (1935) Notes on the Geology of the Marlborough Goldfields. *New Zealand Geological Survey 29th Annual Report,* pp11-21.

Hewitt, A (1982) *Mapping the average annula surface water resource of the Marlborough Sounds.* Report of the Water and Soil Division, Ministry of Works and Development, Nelson.

Hjulström, F. (1935) Studies of the morphological activity of rivers as illustrated by the River Fyris. *Bulletin of the Geological Institute, University of Uppsala* 25:221-527.

Hobday, D.R. and N. L. Banks (1971) A coarse-grained pocket beach complex, Tanafjord (Norway). *Sedimentology* 16:129-134.

Huntingdon, E (1931) *Early days in the Marlborough Sounds .* Unpubl MA thesis, University of New Zealand, Wellington.

Ibbeken, H. (1983) Jointed source rock and fluvial gravels controlled by Rosin's Law: A grain-size study in Calabria, South Italy. *Journal of Sedimentary Petrology* 53: 1213-1231.

Inman, D. and R. Bagnold (1963) Littoral processes. In, Hill, M.N. (Ed.) *The Sea, 3*:507-25. Interscience, New York.

Inman, D.L. (1940) Sorting of sediments in the light of fluid mechanics. *Journal of Sedimentary Petrology* 19:51-70.

Inman, D.L. and R.T. Guza (1982) The origin of swash cusps on beaches. *Marine Geology* 49:133-148.

Irwin, J. (1975) Queen Charlotte Sound Bathymetry. 1:50,000. *New Zealand Oceanographical Institute Chart, Miscellaneous Series 22.*

Jobberns, G. (1935) The physiography of Northern Marlborough, New Zealand. *Journal of Science and Technology* 16:349-539.

Jobberns, G. (1936) *A Study of the major structural features and the shoreline of the northern part of the South Island of New Zealand: with especial reference to the raised shore platform in the north-east.* Unpublished D.Sc. thesis, University of New Zealand.

Johnson, D.W. (1919) *Shore Processes and shoreline development.* New York.

Johnston, A., J. Mace and M. Laffan (1981) The saw, the soil, and the Sounds. *Soil and Water* 17: 4-9. Ministry of Works and Development, Wellington.

Kennedy, S.K., R. Ehrlich and T.W. Kana (1981) The non-normal distribution of intermittent suspension sediments below breaking waves. *Journal of Sedimentary Petrology* 51:1103-1108.

Keunen, Ph.H. (1959) Experimental abrasion. 3. Fluvatile action on sand. *American Journal of Science* 257:172-190.

Kinako, P.D.S. and C.H. Gingham (1980) Heather burning and soil erosion on upland heaths of Scotland. *Scotland Journal of Environmental Management* 10: 279-284.

King, C.A.M. (1970) Feedback relationships in geomorphology. *Geografiska Annaler* 52A:147-159.

Kingsbury, P. (1987) *Engineering Geology Investigations, Havelock Area, Marlborough.* Unpublished M.Sc. Thesis, Geology, University of Canterbury.

Kirk, R.M. (1980) Mixed sand and gravel beaches: morphology, processes and sediments *Progess in Physical Geography* 4:189-210

Krank, K. (1981) Particulate matter grain-size characteristics and flocculation in a partially mixed estuary. *Sedimentology* 28:107-114.

Krumbein, W.C. (1934) Size frequency distribution of sediments. *Journal of Sedimentary Petrology* 4: 65-77.

Krumbein, W.C. (1936) The use of quartile measures in describing and comparing sediments. *American Journal of Science* 32:98-111.

Krumbein, W.C. (1961) *The analysis of observational data from natural beaches.* U.S. Army Corps of Engineers Beach Erosion Board Technical Memorandum 130. 57pp.

Krumbein, W.C. (1963) A geological process-response model for analysis of beach phenomena. *U.S. Army Corps of Engineers Bulletin of the Beach Erosion Board,*17. 15pp.

Laffan, M.D. (1980) Some observations of regoliths and landslides in the Marlborough Sounds. *New Zealand Soil News* 28:96-102.

Laffan, M.D. and B.K. Daly (1981) *Soil resources of the Marlborough Sounds and implications for exotic production forestry.* Soil Bureau District Office Report NS11. Department of Scientific and Industrial Research, New Zealand. 22pp.

Langbein, W.B. and L.B. Leopold (1968) River channel bars and dunes - Theory of Kinematic Waves. *U.S. Geological Survey Professional Paper* 422-L. 20pp.

Lauder, G.A. and R.M. Kirk (1985) *Sedimentation, land-use and coastal stability in the Marlborough Sounds* pp118-135 In Campbell, I.B. (Ed.) *Proceedings of the Soil Dynamics and Land Use Seminar*, Blenheim, May 1985. 412pp.

Lauder, W.R. (1970) The ancient drainage of the Marlborough Sounds-Note. *New Zealand Journal of Geology and Geophysics* 13:747-9.

Lawrence, P. (1967) New Zealand region: Bathymetry, 1:6,000,000. *New Zealand Oceanographical Institute Chart, Miscellaneous Series* 15.

Lensen, G.J. (1962) *Sheet 16 Kaikoura. Geological map of New Zealand.* 1:250,000. New Zealand Geological Survey, Wellington.

Lensen, G.J. (1976) Sheets N28D, O28C, and N29B Hillersden (1st Ed.). Sheets O28D, P28A, and P28C Renwick (1st Ed.). *Late Quaternary Tectonic Map of New Zealand,* 1:50,000. Department of Scientific and Industrial Research, Wellington.

Leroy, S.D. (1981) Grain-size and moment measures: a new look at Karl Pearson's ideas on distribution. *Journal of Sedimentary Petrology* 51: 625-630.

Lewin, J. (1983) Changes of channel pattern and flood plains. pp 303-320 In, Gregory, K.J. (Ed) *Background to Paleohydrology* . John Wiley and Sons. 486pp.

Lewis, D.W. (1982) *Practical Sedimentology* Apteryx Books. Christchurch.

Lewis, K.B. and D.C. Mildenhall (1985) The late Quaternary seismic, sedimentary, and palynological stratigraphy beneath Evans Bay, Wellington Harbour. *New Zealand Journal of Geology and Geophysics* 28:129-152.

Lewis, K.B. and J.S. Mitchell (1980) *Cook Strait Sediments.* New Zealand Oceanographical Institute Coastal Chart Service 1:200,000.

Lowry, (1943) *Queen Charlotte Bathymetric Chart.* 1:25,000 New Zealand Navy

Mahmood, K. (1973) Lognormal size distribution of particulate matter. *Journal of Sedimentary Petrology* 43:1161-1166.

Maltby, E. (1980) The impact of severe fire on *Colluna* moorland in the North York Moors *Bulletin of Ecology* 11:683-708.

Marine Division, Ministry of Transport (1987) *New Zealand Nautical Almanac Part 1.* Ministry of Transport, Wellington. 86pp.

May, J.P. (1981) *Chi(X)* A proposed standard parameter for settling tube analysis of sediments. *Journal of Sedimentary Petrology* 451: 607-610.

McKay, A. (1879) The district between Kaituna Valley and Queen Charlotte Sound. *New Zealand Geological Survey Report of Geological Exploration* 1878-79, 12 :86-97.

McKay, A. (1890) On the Mahakipawa goldfield. *New Zealand Geological Survey Report of Geological Exploration. 1888-89,* 20 : 36-44.

McKay, W.A. (1899) Report on the District East and South of Clova Bay, Pelorus Sound. *Appendix to the Journals of the House of Representatives of New Zealand* C-9:31-3.

McLaren, P. (1981) An interpretation of trends in grain size measures. *Journal of Sedimentary Petrology* 51: 611-624.

McLean, R.F. and R.M. Kirk (1969) Relationship between grain size sorting and foreshore slope on mixed sand and shingle beaches. *New Zealand Journal of Geology and Geophysics* 12:138-55.

McManus, D.A. (1982) Phi and sediment size analysis: Discussion. *Journal of Sedimentary Petrology* 52: 1011-1026.

McQueen, D.J., G.J Churchman, M.D Laffan and J.B. Whitton (1986) *Soil properties as indicators of soil erodibility and fine sediment production in the Marlborough Sounds* pp 92-109. In Campbell, I.B. (Ed.) *Proceedings of the Soil Dynamics and Land Use Seminar*, Blenheim, May 1985. 412pp.

Middleton, G.V. (1976) Hydraulic interpretation of sand size distributions. *Journal of Geology* 84:405-426.

Modriniak, N. and E. Marsden (1938) Experiments in geophysical survey in New Zealand. *Department of Scientific and Industrial Research Memoir* 14.

New Zealand Department of Lands and Survey (1981) *New Zealand Topographical Maps* 1:50,000. NZMS 260 Sheets 026, 027, P25, P26, P27, Q26, Q27. Edition 1.

New Zealand Hydrographic Survey (1962) *Marlborough Sounds 1:100,000 Hydrographic Chart* NZ615 Government Printer Wellington.

New Zealand Hydrographic Survey (1972) *Queen Charlotte Sound 1:36,000 Hydrographic Chart* NZ6153 Government Printer Wellington.

New Zealand Lands and Survey (1982) *Marlborough Sounds 1:100,000.* NZMS 301. Edition 1.

New Zealand Lands and Survey (1984) *Map of New Zealand 1:2,000,000.* NZMS 266. Edition 1.

New Zealand Meteorolgical Service (1977) G14200 *Picton. Data* period July 1974-Aug 1976. Wellington, New Zealand.

New Zealand Soil Bureau (1968) A general survey of the Soils of the South Island, *New Zealand Soil Bureau Bulletin* 27. Department of Scientific and Industrial Research, New Zealand.

Newton, C.G.C. (1977) *The sedimentary dynamics of Tory Channel.* Unpublished MA thesis, Department of Geography, University of Canterbury, Christchurch, New Zealand. 243pp.

Norrman, J. (1964) Lake Vattern Investigations on shore and bottom morphology. *Geografiska Annaler, Haffe* 1-2:1-238.

Novak, D. (1973) *Predicting coarse sediment transport: The Hjulstrom Curve Revisited. pp13-25 .* In Morrisawa, M. (Ed): *Fluvial Morphology.* Proceedings, 4th Annual Geomorphology Symposium. Published in Geomorphology S.U.N.Y. Binghampton.

O'Loughlin, C.L, L.K. Rowe and A.J. Pearce (1978) Sediment yield from small forested catchments, North Westland, Nelson, New Zealand. *Journal of Hydrology (New Zealand)* 17:1-15.

O'Loughlin, C.L. (1985) *Influences of exotic plantation forest on slope stability-implications of forest management in the Marlborough Sounds.* pp313-328. In. Campbell, (Ed) *Proceedings of the Soil Dynamics and Land Use Seminar,* Blenheim, May 1985.

Officer, C. B. (1959) On some offshore seismic refraction profiles in the Cook Strait, Tasman Bay, and Golden Bay areas of New Zealand. *New Zealand Journal of Geology and Geophysics* 2 : 350-54.

Owen, E.E.(1956) New Zealand about 1911-a land transformed. *Unpublished MA thesis, University of New Zealand , Auckland.*

Parker, G. and P.C. Klingeman (1982) On why gravel bed streams are paved. *Water Resources Research* 18: 1409-1423.

Parker, G., H. Stefan and S. Dhamotharan (1982) Mobile experiments on mobile, paved gravel bed streams. *Water Resource Research* 18: 1395-1408.

Paton, B.R. (1982) *Sawmill pioneers in the Pelorus.* Unpublished Dissertation for the Diploma of Parks and Recreation. Lincoln College, New Zealand.

Pethick, J. (1984) *An Introduction to Coastal Geomorphology.* Edward Arnold, London. 260pp.

Pirajno, F. (1979) Geology, Geochemistry and Mineralisation of the Endeavour Inlet Antimony-Gold Prospect, Marlborough Sounds, New Zealand. *New Zealand Journal of Geology and Geophysics* 22:227-37.

Ponder, W.F. (1986) *A Labyrinth of Waterways: The Forgotten Story of New Zealand's Marlborough Sounds.* Wenlock House, Wellington.

Pritchard, D.W. (1952) Estuarine hydrography. *Advances in Geophysics.* 1:243-80.

Rae, S. (1981) *Pelorus and Marlborough Sounds Surface Water Resource Survey 1980-81.* Report to Marlborough Catchment Board.

Reineck, H.E. and I.B. Singh (1970) *Depositional Sedimentary Environments.* Springer-Verlag, New York. 549pp.

Richards, K.J. (1982) *Rivers: Form and Process in Alluvial Channels.* Methuen, London. 358pp.

Riddell, R. (1986) *Coastal Photomaps, Marlborough Sounds.* Aerial Surveys Ltd., Nelson.

Russell, R.J. (1967) Origin of Estuaries. p93-9 In G.H. Lauff (Ed.) *Estuaries,* American Association for the Advancement of Science, Publication 83, Washington.

Rutland, J. (1894) Traces of ancient Maori occupation in the Pelorus District, Middle Island, New Zealand. *Journal of Polynesian Society* 3:220-32.

Rutland, J. (1897) On the ancient pit dwellings of the Pelorus District, South Island, New Zealand. *Journal of Polynesian Society* 6:76-83.

Schumm, S.A and R.J. Chorley (1985) *Geomorphology.* Methuen, London.

Schwarzacher, W. (1975) *Sedimentation Models and Quantitative Stratigraphy.* Developments in Sedimentology 19 . Elsevier Scientific , Oxford.

Selby, M.J. (1982) *Hillslope materials and processes.* Oxford University Press, Oxford.

Sengupta, S. (1975) Size-sorting during suspension transportation - log-normality and other characteristics. *Sedimentology* 22:257-273.

Shea, J.H. (1974) Deficiencies of clastic particles of certain sizes. *Journal of Sedimentary Petrology* 44: 985-1003.

Shearer, J. (1982) *Water Quality Management Plan.* Unpublished report. Marlborough Sounds Catchment and Regional Water Resources Board, New Zealand. 54pp.

Sherriff, J.M. (1983) *The genesis and development of bay barriers in the northwest Marlborough Sounds* Unpublished M.Sc. Thesis, Geography, University of Canterbury 171pp

Slaymaker, O. (1987) *Sediment and solute yield in British Columbia and Yukon: their geomorphic significance reexamined* pp 925-945 in V. Gardiner (Ed) *International Geomorphology* (1986) Part 1 John Wiley and Sons Ltd.

Sly, P.G., R.L. Thomas and B.R. Pelletier (1983) Interpretation of moment measures derived from water-lain sediments. *Sedimentology* 30:219-233.

Sonu, C.J. (1969) Collective movement of sediment in littoral environment. *Proceedings of the 11th Conference on Coastal Engineering. London, England* Sept. 1968. American Association of Civil Engineers, 2 Vols., 1795pp.

Sonu, C.J. (1972) Bimodal composition and cyclic characteristics of beach sediment in continuously changing profiles. *Journal of Sedimentary Petrology* 42: 852-857.

Soons, J.M. (1968) Raised submarine canyons: A discussion of some New Zealand examples. *Annals of the American Asociation of Geographers* 58: 606-13.

Soons, J.M. and M.J. Selby (Eds) (1982) *Landforms of New Zealand.* Longmans, Wellington. 392pp.

Spencer, D.W. (1963) The interpretation of grain size distribution curves of clastic sediments. *Journal of Sedimentary Petrology* 33: 180-190.

Statham, I. (1974) The relationship of porosity and angle of repose to mixture proportion in assemblages of different sized materials. *Sedimentology* 21:149-162.

Stevens, G. (1958) The Wellington Fault. *Transactions of the Royal Society of New Zealand* 85: 633-46.

Stevens, G.R. (1974) *Rugged Landscape: The Geology of Central New Zealand.* A.H. and A.W. Reed, Wellington. 286pp

Stevens, G.R. (1980) *New Zealand Adrift. The theory of continental drift in a New Zealand setting.* A.H. and A.W. Reed, Wellington. 442pp.

Suggate, R.P. (1965) *Late Pleistocene geology of the northern part of the South Island, New Zealand.* New Zealand Geological Survey Bulletin 77. 91pp.

Suggate, R.P. (1982) *The Geological Perspective.* p1-13. In, Soons, J.M and M.J. Selby (Eds.)*Landforms of New Zealand.* Longmans, Wellington. 392pp.

Suggate, R.P.(1963) The Alpine Fault. *Transactions of the Royal Society of New Zealand, Geology* 2: 105-129.

Suggate, R.P., G.R. Stevens and M.T. Te Punga (Eds.) (1978) The Geology of New Zealand. *Government Printer, Wellington. 2 Vols. 820pp.*

Sundborg, Å (1965) The river Klaralvern. A study of fluvial processes. *Geografiska Annaler* 38:125-316.

Swift, D.J.P., J.R. Schubel and R.E. Sheldon (1972) Size analysis of fine-grained suspended sediments: a review. *Journal of Sedimentary Petrology* 42:122-34.

Tanner, W.F. (1960) Florida Coast classification. *Gulf Coast Association of Geologists Society* 10: 259-266.

Tanner, W.F. (1964) Modification of sediment distributions. *Journal of Sedimentary Petrology* 34: 156-164.

Tanner, W.F. (1974) Advances in near-shore physical sedimentology: a selected review. *Shore and Beach* 42.

Te Punga, M.T. (1964) Relict red-weathered regolith at Wellington. *New Zealand Journal of Geology and Geophysics* 7:314-339.

Te Punga, M.T. (1984) *Seven climatic cycles in New Zealand during the last half-million years.* Report G79, New Zealand Geological Survey, Department of Scientific and Industrial Research.

Tinkler, K.J. (1985) *A short history of Geomorphology.* Groom Helm, London. 314pp.

United States Army (1977) *Shore Protection Manual Volume* U.S. Army Coastal Engineering Research Centre ,Virginia. 2 Vols.

Visher, G.S. (1969) Grain size distributions and depositional processes. *Journal of Sedimentary Petrology* 39:1074-1106.

Vitaliano, C.J. (1968) Petrology and structure of the South-eastern Marlborough Sounds, New Zealand. *New Zealand Department of Scientific and Industrial Research Geological Survey Bulletin* 74. 40pp.

Wellman, H (1956) Structural outline of New Zealand. *New Zealand Department of Scientific and Industrial Research, Report* 121, 36pp.

Wentworth, C.K. (1922) A scale of grade and class terms for clastic sediments. *Journal of Geology* 30: 377-392.

Whitehouse, I. (1984) Erosion in the east South Island high country- a changing perspective. *Tussock Grasslands and Mountain Lands Institute Review* 42:2-23.

Whitton, J.S., M.D. Laffan and I.B. Campbell (1985) *Clay mineralogy of some soils from Marlborough and Nelson. pp26-48.* In, Campbell, I.B.(Ed) *Proceedings of the Soil Dynamics and Landuse Seminar* 412pp.

Williams, P.W. (1980) *From forest to suburb: the Hydrological Impact of man in New Zealand.* pp103-124. In, G. Anderson (Ed.) *The Land our Future; essays on land use and conservation. 324pp.*

Wilson, G. (1962) *Linkwater- a history.* Express Printing Works, Blenheim. 159pp.

Winkelmolen, A.M. (1971) Rollability, a functional shape property of sand grains. *Journal of Sedimentary Petrology* 41: 703-714.

Winkelmolen, A.M. (1982) Critical remarks on grain parameters with special emphasis on shape. *Sedimentology* 29: 255-265.

Winslow, J.H. (1966) Raised submarine canyons: An exploratory hypothesis. *Annals of the American Association of Geographers* 56: 634-72.

Winslow, J.H. (1968) Stopping at the waters edge: Reason or habit? A reply. *Annals of the American Association of Geographers* 56: 614-34.

Wischmeir, W.H. and D.D. Smith (1960) A universal soil-loss equation to guide conservation farm planning *7th International Congress on Soil Science Transactions* 1:418-425.

Wolman, D.E. (1983) The sediment delivery problem *Journal of Hydrology* 65: 209-237.

Wolman, M.G. and J.P. Miller (1960) Magnitude and frequency forces in geomorphic processes. *Journal of Geology* 68:54-74.

Wyrwoll, K-H. and G.K. Smyth (1985) On using the log-hyperbolic distribution to describe the textural characteristics of aeolian sediments. *Journal of Sedimentary Petrology* 55: 471-478.

Zenkovich, V.P. (1967) *Processes of Coastal Development.* Oliver and Boyd, Edinburgh and London. 738pp.

Zotov, V.P. (1938) Some correlations between vegetation and climate in New Zealand. *New Zealand Journal of Science and Technology* 19:474-487.

Appendices

Appendix 1: Maps, Charts and Air photographs used in the investigation

Appendix 2: Sediment Analysis: Equipment and Formulae

Appendix 3: Shoreline Sediment Samples: Location and analysis

Appendix 4: Submarine Sediment Samples: Location and analysis

Appendix 1
Maps, Charts and Air Photographs

Topographic Maps

1:50,000 New Zealand Map Series 260 Sheets 026, 027, P25, P26, P27, Q26, Q27. Edition 1 *New Zealand Department of Lands and Survey (1981)*

1:100,000 Marlborough Sounds 1:100,000. NZMS 301. Edition 1. *New Zealand Department of Lands and Survey (1981)*

1:250,000 New Zealand Map Series 262 Sheet 9. Edition 1 *New Zealand Department of Lands and Survey (1981)*

Marine Charts and Maps

1:100,000 Marlborough Sounds 1:100,000 Hydrographic Chart NZ615 *New Zealand Hydrographic Survey (1962)*

1:36,000 Queen Charlotte Sound 1:36,000 Hydrographic Chart NZ6153 *New Zealand Hydrographic Survey (1972)*

1:25,000 Queen Charlotte Sound Bathymetry *Lowry,(1943)*

1:50,000 Queen Charlotte Sound Bathymetry (Contoured Map) *Irwin,(1975)*

Geology

1:63,360 Geological map of New Zealand. Sheet 14, Marlborough Sounds. *Beck,(1964)*

Marine Sediments

1:200,000 Cook Strait Sediments. *Lewis and Mitchell (1980)*

Air Photographs

1943 Marlborough Sounds Survey No. 257 ,
Runs 641 to 669
F 8.25", Altitude 11,000'
Survey and Land Information, Blenheim/Nelson

1958, 60 Marlborough Sounds Survey No. 1208 ,
Runs 2899 to 2930
F 8.25", Altitude average11,000'
Survey and Land Information, Blenheim/Nelson

1973-4 Marlborough Sounds-Pelorus Bridge Survey No. 3684, 3781
1566 A-M, 1571 N-P, 1570 Q-S
F 8.25", Altitude 17,000' - 18,000'

Appendix 2
Sediment Analysis, Equipment and Formulae

Mean

Inclusive Graphic Mean (Folk and Ward, 1957)

$Mz_{ø} = (ø16 + ø50 + ø84) \; / \; 3$

where ø16, ø50 and ø84 are the phi sizes corresponding to the cumulative percentiles 16%, 50% and 84%.

Median

$Md = ø50$

Sorting

Shore samples

Inclusive Graphic Standard Deviation (Folk and Ward, 1957)

$s_{i}\,ø = (ø84 - ø16) / 4 + (ø95 - ø5) / 6.6$

Submarine samples

Phi Quartile Deviation (Krumbein,1936)

$QD_{ø} = (ø75 - ø25) / 2$

Skewness

Inclusive Graphic Skewness (Folk and Ward, 1957)

$SK_{iø} = (ø84 - ø50) / (ø84 - ø16) - (ø50 - ø5) / (ø95 - ø5)$

Kurtosis

Graphic Kurtosis (Folk and Ward, 1957)

$K_{gø} = (ø95 - ø5) / 2.44 \, (ø75 - ø25)$

Rapid Sediment Analyser Technical Details

RAPID SEDIMENT ANALYSER INFORMATION SHEET

INTRODUCTION

The University of Waikato Rapid Sediment Analyser system consists of three main components; a settling tube (for pebble-fine sand size particles), a Shimadzu Centrifugal Particle Size Analyser (for finer sizes), and an Apple II Plus computer. This sheet will cover only the output from the Apple computer. Results of a particle size analysis, irrespective of the source of the data, can be processed.

The settling tube can produce a result in terms of the settling velocity as well as particle size, whereas the other routines consider only particle size. The output for both settling velocity and particle size appear similar but there are some important differences.

SETTLING VELOCITY

Settling velocity is analysed in terms of the Chi parameter discussed by May (1981). This can be defined as follows:

$CHI = -\log2\ (s/so)$

where so = standard settling velocity of 1m/s

and s is the standardised settling velocity given by

$s = sm + (k) * (20-t) * sm$

where k is a temperature correction factor given by

$sm > 0.177 \quad k = 0$

$0.002 > sm > 0.177 \quad k = -0.00555 * \ln(sm) - 0.00961$

$sm < 0.002 \quad k = 0.025$

The resulting Chi values are for spherical quartz grains falling through pure water at 20 degrees Celcius. It is therefore possible to compare the Chi results for different sediments under different conditions.

The output for the settling velocity analysis consists of 3 main parts. The first of these consists of three plots; the velocity distribution and the cummulative frequency on both arithmetic and probability ordinates. This allows a rapid visual comparison between samples - the paper used at Waikato University is sufficiently transparent to enable printouts to be superimposed and viewed simultaneously. All plots have the settling velocity in terms of Chi on the X axis. The labelling of the X axis is determined by the program from the range of values covered by the sample and the available space on the print out. This means that the resulting values printed may not always be 'nice' values.

The second part of the output consists of a summary of the data acquired by the system. There are five columns of data; the settling velocity in Chi units, the settling velocity in cm/s, the cummulative weight in water (gm), the interval frequency and the cummulative frequency (%). Finally there is the 'total weight' of sediment for that run. This is included since the last Chi value printed may not coincide with the Chi value of the last sediment to reach the bottom. Hence not all of the sediment would be included in the analysis. A comparison between the 'total weight' and the cummulative weight will show if this has occurred. Note that all weights are weight in water and have not been corrected to weight in air.

The final part of output is the results of the statistical analysis of the data acquired. The data output consists of the first four moments of the distribution of Chi values. These represent the mean, sorting, skewness and kurtosis respectively. No verbal classification of these parameters has been included.

PARTICLE SIZE

Particle size is analysed in terms of the Phi parameter which is defined as follows:

$PHI = -\log2\ (d)$

where d = grain diameter in millimetres

The program uses the Gibbs et al. (1971) equation to convert the settling velocity distribution to a particle size distribution. This is done by determining the settling velocity for the required Phi values, and then obtaining the cummulative weight for that velocity. The equation used is as follows:

$$V = \frac{-3 \ast U + SQR\,(9 \ast U \ast U + G \ast R \ast R \ast W \ast (S - W) \ast (0.015476 + 0.19841 \ast R))}{W \ast (0.011607 + 0.14881 \ast R)}$$

where V = velocity (cm/s)
U = water dynamic viscosity (poise)
G = acceleration due to gravity (cm/s2)
R = radius of a sphere (cm)
W = water density (g/cm3)
and S = particle density (g/cm3)

To allow a wide range of sediment types to be processed, the density correction factors proposed by Komar (1981) are employed. Therefore the results are for equivalent spheres with the user specified density (normally Quartz).

The output for the particle size analysis also consists of three parts; a group of plots, a summary of the data and a statistical analysis. The plots are essentially the same as the settling velocity plots except that the X axis is now the particle size in Phi units. The summary of data is similar, but there are a few differences. Firstly the first two columns now represent the particle size in Phi units and millimetres. The other columns are the same, but since the Phi parameter does not necessarily coincide with the Chi parameter, the numerical values will be different. Further it is possible for the final cummulative weight to be different from the corresponding value in the settling velocity analysis. The other major difference is that a summary of the size composition of the sediment in terms of gravel, sand, silt and clay is included. Due to round-off errors the sum of the percentages may not always equal 100%.

The statistical section is significantly different. In addition to a summary of the first four moments, the printout includes the results of an analysis using the graphical method of Folk and Ward (1957). This method was used to derive the mean, median, sorting, skewness, and kurtosis. The descriptive term derived by Folk (1968) for these last three parameters is also given. 'C' refers to the C statistic defined by Passega (1957) and represents the coarsest 1% of the sample. The descriptive terminology of Folk (1968) is also applied to the second moment (sorting) derived by the moment method.

REFERENCES

FOLK, R. L. 1968: Petrology of Sedimentary Rocks. Hemphill's Austin, Texas. 170p.

FOLK, R. L. and WARD, W. C. 1957: Brazos River Bar - a study of the significance of grain size parameters. Journal of Sedimentary Petrology 27: 3-27

GIBBS, R. J. , MATTHEWS, M. D. and LINK, D. A. 1971: The relationship between sphere size and settling velocity. Journal of Sedimentary Petrology 41: 7-18

KOMAR, P. D. 1981: The applicability of the Gibbs Equation for grain settling velocities to conditions other than Quartz in water. Journal of Sedimentary Petrology 51: 1125-1132

MAY, J, P. 1981: CHI (X) - A proposed standard parameter for settling tube analysis of sediments. Journal of Sedimentary Petrology 51: 607-610

PASSEGA, R. 1957: Texture as characteristic of clastic deposition. American Association Of Petroleum Geologists Bulletin 41: 1952-1984

Appendix 3
Shoreline Sediment Samples
Locations and Analysis

Shoreline Sediment Samples

Analysis # RSA	Location	Sample Label	Grid Ref NZMS 260 P 27	Content		Summary Grain Size Parameters					Graphic Moments of Grain Size		
				Gravel %	Sand %	Mean ø	Mode ø	D 35 ø	Median ø	D 65 ø	Sorting ø	Skewness Dimensionless	Kurtosis
001	Grove Arm	N/8A/1N	906 923	52.18	47.81	-1.06	-0.75	-1.21	-1.03	-0.85	0.52	-0.13	1.08
002	Grove Arm	N/8A/2N	906 923	49.63	48.66	-1.01	-0.75	-1.17	-1	-0.08	0.49	-0.02	1.14
003	Grove Arm	N/8A/2T	906 923	6.9	93.9	-0.14	0.25	-0.34	-0.13	0.07	0.56	-0.03	1.16
004	Grove Arm	N/8A/3N	906 923	4.2	95.79	0.35	0.25	0	0.24	0.54	0.86	0.19	1.12
005	Grove Arm	N/8A/3T	906 923	2.34	97.66	0.46	0.25	0.04	0.31	0.68	0.86	0.26	0.99
006	Grove Arm	M/7A/MS	886 927	21.59	78.4	-0.72	-0.5	-0.86	-0.7	-0.57	0.4	-0.06	1.11
007	Grove Arm	R/7A/MS	875 922	50.6	49.39	-1.03	-0.75	-1.17	-1.01	-0.86	0.42	-0.11	1.08
008	Grove Arm	R/7A/MB	875 922	15.85	84.14	-0.56	-0.5	-0.73	-0.57	-0.4	0.45	0	1.07
009	Grove Arm	T/7A/MB	882 924		100	-0.19	0	-0.31	-0.2	-0.08	0.29	0.02	1
010	Grove Arm	T/7A/AM	882 924	29.71	70.28	-0.68	-0.75	-0.93	-0.72	-0.49	0.59	0.1	1.07
011	Grove Arm	T/7A/MB(U)	882 924	0	100	-0.07	0	-0.21	-0.1	-0.02	0.34	0.17	1.05
012	Grove Arm	I/7A/UB	935 936	59.32	43.67	-1.14	-1	-1.25	-1.1	-0.94	0.43	-0.19	1.04
013	Grove Arm	I/8A/M	935 936	26.76	73.23	-0.79	-0.5	-0.92	-0.76	-0.62	0.39	-0.15	1.09
014	Grove Arm	I/7A/BM	935 936	2.88	97.11	0.06	-0.5	-0.31	-0.12	0.13	0.75	0.38	1.17
015	Grove Arm	I/7A/2B	935 936	17.79	82.2	-0.67	-0.5	-0.81	-0.67	-0.53	0.38	0	1.03
016	Grove Arm	I/7A/2S	935 936	40.84	59.15	-0.93	-0.75	-1.07	-0.9	-0.74	0.46	-0.11	1.1
017	Grove Arm	I/7A/UI	935 936	77.99	22	-1.3	-1	-1.43	-1.26	-1.12	0.4	-0.2	1.01
018	Grove Arm	G/7A/M	872 921	3.65	96.34	0.01	0.25	-0.14	0.02	0.18	0.49	-0.46	1.25
019	Grove Arm	G/7A/T	872 921	25.42	74.57	-0.74	-0.5	-0.89	-0.72	-0.57	0.45	-0.07	1.13
020	Grove Arm	OI/7A/M	874 921	14.43	85.56	-0.53	-0.25	-0.69	-0.52	-0.35	0.46	-0.04	1.08
021	Grove Arm	GN/7A/M	883 925	11.7	88.29	-0.53	-0.5	-0.68	-0.53	-0.37	0.41	-0.01	1.04
022	Grove Arm	B/7A/M	884 925	15.15	84.84	-0.65	-0.5	-0.78	-0.65	-0.53	0.35	0	1.02
023	Grove Arm	S/7A/M	881 924	29.19	70.81	-0.78	-0.5	-0.94	-0.78	-0.62	0.43	-0.05	1.09
024	Aussie Bay	A/7A/CM	878 923	7.05	92.94	-0.09	0	-0.28	-0.1	0.1	0.63	0.06	1.39
025	Aussie Bay	A/7A/M	878 923	6.5	93.49	0.12	0	-0.21	0.1	0.42	0.8	0.06	0.93
026	Grove Arm	W/8A/14.8	945 937	41.43	58.56	-0.94	-0.75	-1.07	-0.92	-0.79	0.4	-0.1	1.08
027	Grove Arm	W/8A/11	945 937	47	53	-0.99	-0.75	-1.14	-0.97	-0.81	0.44	-0.07	1.09
028	Kahikatea	K/8A/M	033 957	41.85	58.14	-0.95	-0.75	-1.08	-0.93	-0.79	0.4	-0.13	1.08
029	Lochmara	LL/8A/M	943 969	33.3	66.69	-0.87	-0.75	-0.98	-0.85	-0.71	0.38	-0.09	1.09
030	Kahikatea	K3/8A/U	034 953	87.46	12.53	-1.56		-1.78	-1.55	-1.34	0.47	0.02	0.75

Analysis # RSA	Location	Sample Label	Grid Ref NZMS 260 P 27	Content		Summary Grain Size Parameters					Graphic Moments of Grain Size		
				Gravel %	Sand %	Mean ø	Mode ø	D 35 ø	Median ø	D 65 ø	Sorting ø	Skewness Dimensionless	Kurtosis
031	Kahikatea	K/8A/B	033 958	52.97	47.03	-1.08		-1.24	-1.04	-0.84	0.56	-0.1	1.05
032	Kahikatea	KC/8A/B5	034 951	79.26	20.73	-1.4		-1.56	-1.36	-1.17	0.48	-0.1	0.91
033	Kahikatea	KP/8A/B	033 949	55.3	44.7	-1.09		-1.25	-1.06	-0.88	0.54	-0.05	1.14
034	Kahikatea	KW/8A/M	033 949	28.88	71.11	-0.78		-0.94	-0.79	-0.63	0.44	0.04	1.17
035	Kahikatea	KP/8A/U	033 952	21.73	78.26	-0.29		-0.6	-0.26	0.11	0.95	-0.06	1.01
036	Monkey	MW/8A/M	020 950	15.27	84.72	-0.47		-0.64	-0.45	-0.27	0.57	-0.13	1.3
037	Outer Q.C.	QO/8A/U	025 955	47.31	52.68	-1.01		-1.35	-0.97	-0.82	0.46	-0.16	1.15
040	Momorangi	M/27N/T(T)	886 927	11.17	88.82	-0.49	-0.25	-0.62	-0.46	-0.33	0.41	-0.13	1.16
041	Momorangi	M/27N/T(M)	886 927	13.72	86.27	-0.41	-0.25	-0.63	-0.42	-0.22	0.62	0.12	1.3
042	Momorangi	M/27M/T(S)	886 927	13.68	86.31	0.13	0.25	-0.4	0	0.37	1.06	0.15	0.84
043	Momorangi	M/27N/PS(U)	886 927	4.21	95.79	1.16	1.5	0.93	1.19	1.43	0.8	-0.17	1.42
044	Momorangi	M/27N/CUSP	886 927	35.67	64.32	-0.86	-0.75	-1.01	-0.85	-0.69	0.46	-0.08	1.11
045	Momorangi	M/27N/CUSP(BE	886 927	14	86	-0.44	-0.5	-0.64	-0.43	-0.21	0.54	-0.05	1.08
046	Momorangi	MS/x/S	886 927	42.41	57.58	-0.96	-0.75	-1.09	-0.93	-0.79	0.43	-0.15	1.16
047	Momorangi	MS/x/U	886 927	3.97	96.02	0	0.25	-0.23	0.02	0.25	0.57	-0.06	0.93
048	Momorangi	M/6O/50/1	887 927	16.15	83.84	-0.47	-0.25	-0.68	-0.46	-0.26	0.53	-0.04	0.98
049	Momorangi	M/6O/50/2	887 927	61.02	38.97	-1.16	-1	-1.38	-1.15	-0.94	0.61	0	1.03
050	Momorangi	M/6O/50/3	887 927	4.31	95.68	-0.16	-0.25	-0.4	-0.19	-0.04	0.6	0.17	1.15
051	Momorangi	M/6O/50/4	887 927	8.15	91.84	0.27	0	-0.25	0.07	0.48	1.07	0.27	0.98
052	Momorangi	M/6O/50/5	887 927	31.62	68.37	-0.76	-0.5	-0.95	-0.71	-0.51	0.62	-0.09	1.12
056	Momorangi	M/6O/TPCW1(1)	888 927	12.82	87.17	-0.18	-0.25	-0.5	-0.24	0.03	0.83	0.16	1.27
056	Momorangi	M/6O/TPCW1(2)	888 927	14.09	65.9	-0.21	-0.25	-5	-0.25	0	0.81	0.12	1.26
057	Momorangi	M/6O/TPCW1(3)	888 927	14.19	85.81	-0.22	0	-0.52	-0.25	0	0.8	0.11	1.18
057	Momorangi	M/6O/TPCW2	888 927	33.53	66.46	-0.82	-0.75	-0.98	-0.83	-0.66	0.45	-0.01	1.13
058	Momorangi	M/6O/TPCW3	888 927	20.68	79.31	-0.56	-0.5	-0.76	-0.55	-0.34	0.57	0	1.06
059	Momorangi	M/6O/TPCW4	888 927	11.03	88.96	0.13	0	-0.33	-0.03	0.3	0.89	0.21	0.96
065	Bythells	BY/15D/A	938 927	33.28	66.71	-0.69	-0.5	-0.97	-0.69	-0.41	0.75	0.04	1.08
066	Bythells	BY/15D/B	938 927	4.86	95.13	-0.31	-0.25	-0.43	-0.3	-0.16	0.39	-0.01	1.21
067	Bythells	BY/15D/C	938 927	56.55	43.44	-1.11	-1	-1.28	-1.08	-0.89	0.53	-0.09	1.06
068	Bythells	BY/15D/D	938 927	18.05	81.94	-0.45	-0.25	-0.69	-0.45	-0.22	0.64	0.02	1.1

Appendix 3 continued(Samples 070-110)

Analysis # RSA	Location	Sample Label	Grid Ref NZMS 260 P 27	Content		Summary Grain Size Parameters					Graphic Moments of Grain Size		
				Gravel %	Sand %	Mean ø	Mode ø	D 35 ø	Median ø	D 65 ø	Sorting ø	Skewness Dimensionless	Kurtosis
070	Bythells	BY/15D/F	938 927	51.91	48.08	-1.01	-1	-1.21	-1.02	-0.82	0.58	0.06	1.15
071	Double Bay	DBM/4O/1	825 942	38.79	61.2	-0.82	-0.75	-1.06	-0.84	-0.62	0.7	0.11	1.32
072	Double Bay	DBM/4O/4	825 942	25.48	74.51	-0.66	-0.75	-0.87	-0.67	-0.47	0.57	0.03	1.2
075	Ngakuta	NGA/?/60/1	906 923	21.76	78.23	-0.52	-0.5	-0.77	-0.55	-0.32	0.75	0.14	1.42
076	Ngakuta	NGA/?/60/2	906 923	38.19	61.8	-0.71	-0.75	-1.06	-0.81	-0.54	0.9	0.25	1.43
077	Ngakuta	NGA/x/60/3	906 923	7.82	92.17	0.31	-0.25	-0.35	-0.04	0.52	1.15	0.4	0.84
078	Ngakuta	NGA/x/90/1	907 923	26.25	73.74	-0.3	-0.5	-0.83	-0.56	-0.2	1.14	0.3	1.18
079	Ngakuta	NGA/x/90/2	907 923	15.93	84.07	-0.07	-0.25	-0.44	-0.15	0.14	1.09	0.08	1.55
080	Ngakuta	NGA/x/20/1	907 923	23	76.99	-0.28	-0.25	-0.67	-0.37	-0.02	1.2	0.12	1.26
090	Wedge Point	WP/8A/S	945 937	2.68	97.31	0.71	1.25	0.55	0.89	1.12	0.79	-0.33	0.93
091	Wedge Point	WP/8A/U	945 937	3.77	96.22	0.08	-0.25	-0.38	-0.14	0.26	0.82	0.36	0.8
092	Wedge Point	WP/8A/T	945 937	65.76	34.23	-1.19	-1	-1.32	-1.15	-1.01	0.42	-0.16	1.04
093	Wedge Point	W/8A/7S	945 937	0	100	1.44	1.5	1.18	1.41	1.67	0.72	0	1.17
094	Wedge Point	W/8A/7G	945 937	19.8	81.1	-0.66	-0.5	-0.81	-0.64	-0.48	0.45	-0.05	1.11
095	Wedge Point	WG/8A/M	945 937	0.18	99.81	0.07	0	-0.12	0.02	0.19	0.47	0.19	1.2
096	Wedge Point	W/8A/8	945 937	18.64	81.36	0.02	0.5	-0.1	0.24	0.48	1	-0.27	1.01
097A	Wedge Point	WP/8A/T	945 937	0	100	1.09	1	0.94	1.06	1.19	0.31	0.12	1.02
097B	Grove Arm	I/8A/S	934 035	5.94	94.05	0.97	1.75	0.9	1.41	1.65	1.15	-0.48	0.76
098	Grove Arm	RO/8A/M	933 933	18.56	81.43	-0.43	-0.25	-0.64	-0.39	-0.17	0.64	-0.09	1.06
099	Grove Arm	C/8A/M	928 933	10.3	89.69	-0.17	0	-0.39	-0.15	0.08	0.65	-0.03	1.06
100	Grove Arm	R/8A/T	929 933	19.84	80.15	-0.2	-0.75	-0.7	-0.35	0.2	1.01	0.13	1.02
101	Ngakuta	NG/8A/1F	907 923	3.15	96.84	0.55	0	-0.06	0.3	0.83	1.13	0.31	0.93
102	Ngakuta	NG/8A/T	907 923	39.26	60.73	-0.84	-0.75	-1.08	-0.82	-0.58	0.66	-0.03	1.06
104	Lochmara	LG/8A/6	935 958	33.54	66.45	-0.83	-0.75	-0.98	-0.8	-0.61	0.57	-0.15	1.24
106	Lochmara	LG/8A/T	935 958	38.93	61.06	-0.89	-0.75	-1.06	-0.88	-0.7	0.49	-0.04	1.1
107	Lochmara	L2/8A/M	935 958	24.92	75.07	-0.33	-0.75	-0.79	-0.42	0.05	0.91	0.15	0.88
108	Lochmara	LL/8A/U	935 958	9.35	90.46	-0.1	0.25	-0.32	-0.05	0.18	0.74	0	1.15
110	Kahikatea	KC/8A/U	033 949	60.74	39.25	-1.12	-1.25	-1.62	-1.29	-0.86	0.95	0.32	0.88

Analysis # RSA	Location	Sample Label	Grid Ref NZMS 260 P 27	Content Gravel %	Content Sand %	Summary Grain Size Parameters Mean ø	Mode ø	D 35 ø	Median ø	D 65 ø	Graphic Moments of Grain Size Sorting ø	Skewness Dimensionless	Kurtosis
115	Kahikatea	KH/8A/S	033 950	0.38	99.61	2.49	2.25	2.28	2.44	2.63	0.42	0.17	0.95
121	Aussie	A/7A/CT	878 923	52.05	47.94	-1.05	-0.75	-1.19	-1.02	-0.87	0.48	-0.14	1.21
123	Aussie	A/7A/CP	878 923	93.34	6.65	-1.73	-1.25	-2.02	-1.79	-1.55	0.42	0.29	0.78
124	Momorangi	M/7A/T	886 927	32.67	67.32	-0.84	-0.75	-0.97	-0.81	-0.64	0.55	-0.15	1.31
125	Iwirua	I/7A/BT	935 937	21.61	78.38	-0.72	-0.5	-0.86	-0.72	-0.58	0.39	-0.01	1.12
126	Aussie	A/7A/WT	878 923	15.03	84.96	-0.62	-0.5	-0.74	-0.61	-0.47	0.37	-0.07	1.03
127	Grove Arm	R/7A/T	929 933	27.87	72.12	-0.76	-0.5	-0.87	-0.64	-0.44	0.69	-0.28	1.16
128	Grove Arm	R/7A/T	929 933	43.88	56.11	-0.96	-0.75	-1.1	-0.94	-0.8	0.41	-0.06	1.09
141	Grove Arm	OI/7A/T	881 926	17.67	82.32	-0.65	-0.5	-0.81	-0.66	-0.51	0.4	0.04	1.02
142	Grove Arm	GROIN/7A/T	880 921	29.74	70.25	-0.8	-0.5	-0.94	-0.79	-0.63	0.45	-0.1	1.17
143	Grove Arm	SN/7A/T	879 921	44.5	55.49	-0.95	-0.75	-1.13	-0.93	-0.74	0.53	-0.05	1.07
144	Grove Arm	T/7A/T	880 922	29.57	70.42	-0.8	-0.75	-0.95	-0.8	-0.64	0.41	0	1.1
150	Kenepuru	K/5F/1		20.16	79.83	-0.21	-0.5	-0.65	-0.31	0.05	1.02	0.14	1.14
151	Kenepuru	K/5F/2		79.05	20.94	-1.46	-1.25	-1.69	-1.44	-1.22	0.55	0.05	0.86
152	Kenepuru	K/5F/3		26.98	73.01	-0.74	-0.5	-0.9	-0.71	-0.54	0.47	-0.11	1.03
155	Kenepuru	K/5F/6		52.96	46.03	-1.1	-0.75	-1.23	-1.05	-0.88	0.5	-0.2	1.1
156	Kenepuru	K/5F/6		15.08	84.91	-0.54	-0.5	-0.75	-0.59	-0.39	0.5	0.1	1.11
157	Kenepuru	K/5F/7		42.48	57.51	-0.42	-1.25	-1.24	-0.73	-0.09	1.43	0.3	0.72
158	Kenepuru	K/5F/8		78.4	21.59	-1.48		-1.75	-1.46	-1.22	0.56	0.04	0.72
162	Kenepuru	K/3F/1		24.5	75.49	-0.71	-0.5	-0.88	-0.71	-0.54	0.44	-0.03	1.04
163	Kenepuru	K/3F/2(2)		44.45	55.54	-0.94	-0.75	-1.15	-0.92	-0.69	0.61	0.05	1.06
164	Kenepuru	K/3F/3		41.02	58.97	-0.93	-0.75	-1.07	-0.91	-0.77	0.41	-0.49	1.06
165	Kenepuru	K/3F/4		8.92	91.07	-0.24	0	-0.44	-0.23	-0.04	0.6	0.03	1.22
167	Kenepuru	K/3F/6		42.72	57.27	-0.95	-0.75	-1.09	-0.93	-0.78	0.43	-0.08	1.07
168	Kenepuru	K/3F/7		33.31	66.68	-0.79	-0.5	-0.97	-0.72	-0.47	0.81	-0.08	1.24
170	Kenepuru	K/5F/13		25.14	74.85	-0.26	-0.25	-0.67	-0.26	0.18	1.16	-0.02	1
173	Mahau Sd	MHD/CANOE	777 830	72.97	27.02	-1.3	-1	-1.46	-1.26	-1.09	0.48	-0.1	0.99
174	Mahau Sd	MHD/CANOE	777 830	44.3	55.69	-0.86	-1	-1.24	-0.85	-0.46	0.9	0.05	0.89
175	Ngakuta	Nga/14A/CW1/1	907 923	71.61	28.38	-1.29	-1	-1.45	-1.25	-1.08	0.49	-0.11	0.98
176	Ngakuta	NGA/14A/CW1/1	907 923	29.74	70.25	-0.75	-0.5	-0.93	-0.74	-0.55	0.52	-0.03	1.1

				Content		Summary Grain Size Parameters					Graphic Moments of Grain Size		
Analysis # RSA	Location	Sample Label	Grid Ref NZMS 260 P 27	Gravel %	Sand %	Mean ø	Mode ø	D 35 ø	Median ø	D 65 ø	Sorting ø	Skewness Dimensionless	Kurtosis
177	Ngakuta	NGA/14A/CW1/3	907 923	14.59	85.4	-0.28	0	-0.52	-0.26	-0.01	0.7	-0.03	1.1
178	Ngakuta	NGA/14A/CW2/1	907 923	33.33	66.66	-0.68	-0.25	-0.96	-0.61	-0.35	0.77	-0.09	1
179	Ngakuta	NGA/14A/CW2/2	907 923	67.05	32.94	-1.22	-1	-1.38	-1.18	-1.02	0.47	-0.13	1.02
180	Ngakuta	NGA/14A/CW2/3	907 923	18.9	81.09	-0.57	-0.5	-0.75	-0.57	-0.37	0.51	-0.03	1.03
181	Ngakuta	NGA/14A/CW3/2	907 923	26.54	73.45	-0.55	-0.25	-0.82	-0.53	-0.26	0.71	-0.02	0.99
182	Ngakuta	NGA/14A/E.Stm (	910 923	3.14	96.85	-0.29	-0.25	-0.45	-0.3	-0.15	0.41	0.07	1.12
183	Ngakuta	NGA/14A/E.Stm (	910 923	71.23	28.76	-1.32	-1	-1.5	-1.28	-1.08	0.53	-0.07	0.92
184	Ngakuta	NGA/14A/CW2/4	907 923	5.76	94.24	-0.28	-0.25	-0.46	-0.29	-0.1	0	0.05	1.05
185	Ngakuta	NGA/14A/CW3/1	907 923	11.7	88.3	-0.5	-0.5	-0.66	-0.51	-0.34	0.46	0.06	1.14
186	Aussie	A/12A/1	878 923	10.4	89.59	0.59	1.5	0.02	0.61	1.18	1.14	-0.03	0.77
187	Aussie	A/12A/2	878 923	18.67	81.32	-0.65	-0.5	-0.8	-0.64	-0.5	0.42	-0.04	1.06
189	Aussie	A/12A/4	878 923	7.87	92.12	0.42	-0.5	-0.26	0.19	0.92	1.16	0.24	0.74
191	Aussie	A/12A/6	878 923	15.1	84.89	0.25	-0.25	-0.37	0.06	0.75	1.22	0.17	0.81
192	Aussie	A/12A/7	878 923	25.73	74.26	-0.14	-0.25	-0.71	-0.29	0.21	1.17	0.15	0.87
194	Aussie	A/12A/9	878 923	73.86	26.13	-1.37	-1	-1.53	-1.3	-1.11	0.52	-0.12	0.89
195	Aussie	A/12A/10	878 923	10.91	89.09	-0.04	0	-0.45	-0.16	0.14	0.96	0.29	1.32
196	Aussie	A/12A/11	878 923	9.56	90.43	0.56	-0.25	-0.23	0.15	0.75	1.4	0.38	0.89
197	Aussie	A/12A/12	878 923	59.59	40.4	-1.15	-1	-1.34	-1.13	-0.92	0.55	-0.07	1.02
198	Umungata	Umu/13A/1	887 943	4.74	95.25	0.05	0	-0.24	-0.04	0.22	0.74	0.24	1.29
199	Umungata	Umu/13A/2	887 943	71.79	28.2	-1.35	-1	-1.53	-1.3	-1.09	0.55	-0.07	0.89
200	Umungata	Umu/13A/3	887 943	59.63	40.36	-1.13	-1	-1.29	-1.11	-0.93	0.49	-0.07	1.04
201	Umungata	Umu/13A/4	887 943	12.32	87.67	-0.47	-0.25	-0.61	-0.44	-0.29	0.46	-0.13	1.15
202	Umungata	Umu/13A/5	887 943	29.08	70.19	-0.71	-0.5	-0.92	-0.71	-0.51	0.56	-0.01	1.08
203	Umungata	Umu/13A/6	887 943	51.81	48.18	-1.06	-0.75	-1.23	-1.02	-0.84	0.53	-0.12	1.03
204	Umungata	Umu/13A/7	887 943	27.26	72.73	-0.7	-0.5	-0.89	-0.69	-0.5	0.52	-0.12	1.06
205	Double Bay	1(1)	825 942	44.24	55.75	-0.95	-0.75	-1.13	-0.93	-0.74	0.56	-0.05	1.14
206	Double Bay	1(2)	825 942	20.28	79.71	-0.04	-0.75	-0.62	-0.17	0.35	1.08	0.15	0.82
207	Double Bay	2(1)	825 942	7.07	92.92	0.59	1.5	0.09	0.73	1.21	1.11	-0.14	0.75
208	Double Bay	2(2)	825 942	16.33	83.66	0.21	-0.5	-0.49	0.1	0.93	1.18	0.11	0.73
209	Double Bay	2(3)	825 942	39.88	60.11	-0.75	-0.75	-1.1	-0.82	-0.54	0.94	0.19	1.32

				Content		Summary Grain Size Parameters					Graphic Moments of Grain Size		
Analysis # RSA	Location	Sample Label	Grid Ref NZMS 260 P 27	Gravel %	Sand %	Mean ø	Mode ø	D 35 ø	Median ø	D 65 ø	Sorting ø	Skewness Dimensionless	Kurtosis
210	Double Bay	2(4)	825 942	32.65	67.34	-0.59	-0.5	-0.95	-0.67	-0.37	0.91	0.18	1.23
211	Double Bay	3(1)	825 942	19.37	80.62	0.04	0.75	-0.5	0	0.54	1.14	0.07	0.87
212	Double Bay	3(2)	825 942	25.87	74.12	-0.49	-0.5	-0.83	-0.58	-0.3	0.85	0.13	1.34
213	Double Bay	4(1)	825 942	21.8	78.19	0.01	-0.25	-0.51	-0.06	0.54	1.33	0.07	0.92
214	Double Bay	4(2)	825 942	28.13	71.86	-0.4	-0.75	-0.89	-0.65	-0.34	0.96	0.37	1.23
215	Double Bay	4(3)	825 942	45.56	54.43	-0.85	-1	-1.17	-0.92	-0.65	0.85	0.23	1.32
216	Double Bay	5(1)	825 942	24.4	75.59	-0.18	-0.5	-0.78	-0.48	-0.09	1.17	0.39	1.16
217	Double Bay	5(2)	825 942	22.97	77.03	-0.41	-0.5	-0.81	-0.58	-0.29	0.87	0.29	1.24
218	Double Bay	6(1)	825 942	36.36	63.63	-0.76	-0.75	-1.03	-0.79	-0.55	0.87	0.18	1.62
219	Double Bay	6(2)	825 942	18.7	81.29	-0.03	-0.5	-0.63	-0.31	0.1	1.22	0.35	1.16
220	Double Bay	6(3)	825 942	43.6	56.39	-0.8	-0.75	-1.21	-0.86	-0.53	1.06	0.73	1.14
221	Double Bay	A(1)	825 942	25.19	74.8	-0.31	-0.75	-0.82	-0.55	-0.15	0.99	0.3	0.9
222	Double Bay	A(2)	825 942	11.76	88.23	0.52	1.5	-0.05	0.72	1.17	1.18	-0.26	0.83
223	Double Bay	A(3)	825 942	43.83	56.17	-0.6	-1.25	-1.24	-0.81	-0.28	1.26	0.28	0.91
224	Double Bay	B(1)	825 942	35.06	64.93	-0.62	-0.75	-1	-0.67	-0.3	1.01	0.12	1.1
225	Double Bay	C(1)	825 942	15.25	84.74	-0.19	-0.5	-0.59	-0.32	0.01	0.88	0.22	1.08
240	Bythells	BythNS A1	938 927		100	2.64		2.37	2.61	2.86	0.58	0.11	0.93
241	Bythells	BYTH A2	938 927		100	2.91		2.66	2.85	3.09	0.5	0.18	0.85
242	Bythells	BYTH A3	938 927		100	2.91		2.66	2.93	3.19	0.58	-0.04	0.82
243	Bythells	BYTH C1	938 927		100	2.62		2.42	2.59	2.77	0.46	0.15	1.04
244	Bythells	BYTH NS C2	938 927		100	2.58		2.3	2.47	2.72	0.53	0.3	0.93
245	Bythells	BYTH C3	938 927		100	2.47		2.16	2.4	2.69	0.65	0.18	0.94
246	Bythells	BYTH C4	938 927		100	2.55		2.21	2.53	2.87	0.83	-0.08	1.03
247	Bythells	BYTH D1	938 927	1.58	98.1	1.64		1.18	1.79	2.36	1.44	-0.14	0.79
248	Bythells	BN D2	938 927		10	2.14		1.89	2.41	2.89	1.27	-0.29	0.89
249	Bythells	BN STM MTH	938 927		100	1.45		0.79	1.35	2	1.23	0.11	0.79
250	Bythells	BN STM 75	938 927		100	2.05		1.7	2.24	2.73	1.21	-0.22	0.81
251	Bythells	BN J 50	938 927		100	2.21		1.91	2.33	2.71	1.03	-0.2	0.98

Pelorus Sound Offshore Samples

Location	Sample Label	Grid Ref NZMS 260 P/27	Depth m	Content Sand %	Silt %	Clay %	Summary Grain Size Parameters 25th % ø	Median ø	75th % ø	QD ø	Nonlithic content Shell %	Organics %
Four Fathom Bay	F 01	855 058	-3									
	F 02	855 058	-5	13.8	50.5	35.7	4.9	6.7	9.7	2.4	1.7	4.4
	F 10	854 058	-6	5	53.2	41.8	5.5	7.3	10.1	2.3	12.8	15
	F 20	853 058	-7	13.1	55.9	31	5.5	6.8	8.7	1.6	13.4	12
	F 30	849 058	-8	5.2	69.1	25.7	5.3	6.4	8.1	1.4	17	7.4
	F 31	849 057	-7	6.2	62.4	31.4	5.3	6.7	9.5	2.1	30.4	4.7
	F 40	837 059	-8	9.9	67	23.1	4.7	5.7	8.9	2.1	25.4	5.2
	F 42	837 057	-8	2.8	64	33.2	5.3	6.7	9	1.85	31.6	4.1
	F 50	830 062	-7	8.8	55.1	36.1	4.8	6.7	9.7	2.45	47.7	5.2
	F 51	830 060	-7	9.7	59.2	31.1	4.7	6	8.7	2	44.3	5.2
	F 52	830 058	-15	5.2	66.9	27.9	4.7	5.7	8.5	1.9	31.7	4.7
Nydia Bay	NY 10	755 037	-4	12.7	41.1	46.2	5.4	7.6	9.8	2.2	19	
	NY 20	759 042	-5	0.4	33.7	65.9	7.4	9.1	10.8	1.7	7.9	7.3
	NY 30	768 051	-5	6.4	39.4	54.2	6.5	8.3	10.9	2.2	2.4	7
	NY 60	789 054	-6	2	53.9	44.1	6.1	7.5	10.3	2.1	12.7	6.3
Kenepuru Sound	K 60	975 020	-7	3.7	38.6	57.7	6.8	8.5	11	2.1	41.9	6.2
	K 81	970 035	-5	0.1	40.7	59.2	6.8	8.7	11.5	2.35	0	6.4
	K 120	948 010	-24	1.1	40.3	58.6	6.8	8.6	11.2	2.2	72.3	6.6
	K 200	885 000	-25	1	15.6	83.4					7.3	6.5
Kaiuma Bay	KA 10	771 959	0	22.5	41.3	36.2	4.3	6.1	9.5	2.6	3.2	6.5
	KA 20	776 952	0	44.1	34.7	21.2	2.3	4.2	7.2	2.45	11.8	7.7
Maori Bay	MA 10	799 036	-1	3.7			5.4	6.4	9.6	2.1	3.8	6.1
	MA 20	802 037	-2	2.4			5.4	6.4	8.2	1.4	31.2	4.7
	MA 30	807 040	-3	2.4			6.2	7.5	9.3	1.55	23.2	4
	MA 40	813 043	-10	8.5			4.6	6	9.2	2.3	19.1	
Mahau	MA 70	807 950	-2	26.8			4.4	6.7	9	2.3	15.9	4.5

Queen Charlotte Sound Offshore Samples

Location	Sample Label	Grid Ref NZMS 260 P/27	Depth m	Content			Summary Grain Size Parameters				Nonlithic content	
				Sand %	Silt %	Clay %	25th % ø	Median ø	75th % ø	QD ø ø	Shell %	Organics %
Grove Arm	GN 50	878 930	-11	22.2	54.1	23.7	4.3	5.9	7.9	1.8	19.1	9.5
	GS 50	878 924	-16	14.3	55.1	30.6	4.9	6.1	8.8	1.95	22.3	6.6
	GN 90	895 938	-22	13.6	49	37.4	5.3	7.2	9.5	2.1	30.1	12.4
	GN 91	897 940	-17	21.3	51.3	27.4	4.2	5.9	7.9	1.85	28.9	
	GN 92	898 941	-18	16.5	44.7	38.8	5.7	9.2	8.5	1.4	21.3	3.2
	GN 93	899 942	-12	48.8	39.1	12.1	3	4.2	6	1.5	7.4	2.5
	GN 94	899 943	-6	32.7	43.5	23.8	3.5	5.2	8	2.25	8.1	3.6
	GN 95	901 945	-4	45.1	45	9.9	3.3	4.2	6	1.35	9.3	
	GS 90	897 930	-22	17.2	48	34.8	5	7	9.5	2.25	24	
	GS 92	897 928	-9	43.9	39.1	17	4.8	7.1	9.5	2.35	18.4	
	GS 93	897 927	-4	57.6	27.7	14.7	0.3	2	6	2.85	8.9	
	GN 110	909 938	-28				5.5	7.2	8.5	1.5	42.8	10
	GS 110	909 934	-28	5.7	61.4	32.9					90.5	
Northern Queen Charlotte bays												
Onahau	ONA 5	915 965	-22				3.6	6	7.5	1.95	20.5	4.8
Ruakaka	R 1	040 993	-33	5.8	58.7	35.5	5.6	7.1	9	1.7	63	
	R 2	030 998	-20	6.7	67.2	26.1	4.5	5.8	8.4	1.95	36.7	3.2
Kumutoto	KAI 2	990 983	-23	52.3	30.6	17.1	0.5	3.8	6.6	3.05	24.7	2.7
	KAI 3	997 990	-33	33.6	38.9	27.5	3.4	5.5	8.4	2.5	26.4	3.9

Tory Channel Offshore Samples

Location	Sample Label	Grid Ref NZMS 260	Depth m	Content Sand %	Content Silt %	Content Clay %	Summary Grain Size Parameters 25th % ø	Median ø	75th % ø	QD ø ø	Nonlithic content Shell %	Organics %
		Q 27										
Deep Bay	DB 10	148 975	-7	3.5	80.1	16.4	5.4	6.4	7.6	1.1	33.5	3.4
	DB 14	149 974	-7	8.1	80.4	11.5	4.6	5.2	6.5	0.95	16.6	2.2
	DB 15	151 972	-5	58	36.7	5.3	3.1	3.8	4.5	0.7	4.2	
	DB 20	154 970	-1	71.9	21.7	6.4	2.5	3	4.2	0.85	6	1.8
	DB 30	157 968	-24	46.9	38.8	14.3	3.4	4.1	6.1	1.35	35.8	
		P 27										
Hitaua Bay	H 20	072 934	-10	9.7	76.8	13.5	4.4	5.2	6.4	1	29	2
	H 30	069 938	-9	8.4	81.6	10	4.4	5.2	6.2	0.9	41.6	
	H 50	075 943	-12	38.6	43	18.4	3.6	4.4	6.5	1.45	7.8	
	H 52	078 943	-20	41.2	42.7	16.1	2.2	5.1	7.2	2.5	12.5	2.4
	H MID	073 940	-11	33.9	54.6	11.5	3.7	4.5	5.9	1.1	8.5	
		P 27										
Maraetai	M 02	054 936	-11	8.7	74.1	17.2	4.8	5.8	7.3	1.25	21.1	
	M 10	053 940	-15	4.5	74.1	21.4	5.2	6.4	7.8	1.3	60	2.8
	M 40	059 948	-17	12	65.2	22.8	4.5	5.6	7.8	1.65	13.2	2.9
	M 41	056 951	-18	22	59.8	18.2	4.1	5	7	1.45	17.3	
	M 42	062 948	-19	11.3	63.4	25.3	4.1	5.7	8	1.95	16.8	
	M 50	061 952	-24	34.4	47.7	17.9	3.8	4.5	6.8	1.5	7.5	2.7
	M 51	064 950	-11	43.9	44.3	11.8	3.6	4.2	5.8	1.1	10.7	
	M 52	060 954	-15	39.2	47.8	13	3.7	4.4	5.9	1.1	10.3	
		P 27 or * Q 27										
Opua Bay	O 10	*113 924	-10	10.1	65.1	24.8	5	6.2	8	1.5	16.7	3.2
	O 20	*106 925	-14	6.6	53.6	39.8	5.8	6.9	9.4	1.8	33.5	4.8
	O 30	*101 926	-18	2.7	56.7	40.6	5.8	7.2	9.1	1.65	34.9	4.6
	O 50	095 932	-17	9.8	65.3	24.9	5	6.2	8	1.5	19.5	3.1
	O 71	092 938	-13	30.8	56.1	13.1	3.8	4.4	5.9	1.05	6.7	2.2

Nearshore Samples

Location	Sample Label	Grid Ref NZMS 260 P/27	Depth m	Slope °	Content Sand %	Content Silt&Clay %	Summary Grain Size Parameters 25th % ø	Median ø	75th % ø	QD ø	Nonlithic content Shell %	Organics %	Sand Fraction (≤4ø) Mean	Sorting	Skewness	Kurtosis
Whenuanui Bay axis	W 3	918 927	-6.2	8.0°	78.2	21.8	2.2	2.8	3.9	0.85	3.5	2.92	2.51	0.83	-0.04	1.22
	W 4		-9.2	8.0°	80.5	19.5	2.1	2.8	3.5	0.7	6.2	2.36	2.52	0.73	-0.09	0.97
	W 5		-9.2	2.5°	88.7	11.3	2.1	2.5	3.2	0.55	4.2	2.15	2.44	0.77	-0.01	1.28
Prodelta Slope	WD 1	918 927	-7.7	8.0°	78.1	21.9	2.2	2.8	3.8	0.8	2.9	2.41	2.52	0.7	-0.05	0.99
	WD 2		-9.2	2.0°	78.9	21.1	2.3	2.8	3.8	0.75	4.5	2.87	2.59	0.68	-0.02	1.08
	WD 3		-12.3	2.0°	64.9	35.1	2	3.2	5.8	1.9	8.2	3.4	2.02			
East Point	WE 1	917 929	-4.6	20.5°	97.1	2.9	-0.2	0.4	2	1.1	12.7	1.37	0.85	1.28	0.51	0.84
	WE 3		-6.2	5.0°	74.2	25.8	0.6	2.3	5.1	2.25	24.3	1.64	1.27	1.23	0.34	0.79
	WE 4		-12.3	2.0°	49.8	50.2	2.6	4.4	9.2	3.3	3.6	2.74	2.16	1.28	-0.39	0.71
Kenepuru	K 1	943 995	-1.5	4.0°	71.8	28.2	1.2	1.8	4.8	1.8	0.7	2.75	1.56	0.72	0.31	1.11
	K 2		-2.2	4.0°	79.4	20.6	1.8	2.2	3.5	0.85	1.3	2.8	2.23	0.64	0.24	0.94
	K 3		-3.1	10.0°	49.2	50.8	2.4	4.2	7.6	2.6	3.7	5.41	2.51	0.71	0.26	0.85
	K 4		-5.5	7.0°	37.3	62.7	3	5.2	9.2	3.1	2	5.13	2.25	0.77	0.11	0.88
	K 5		-6.2	0.0°	42.8	57.2	2.5	5.2	9.1	3.3	8.1	4.35	2.3	0.81	0.14	1.19
Momorangi	M 1	889 927	-10.8	0.0°	46.6	53.4	5.3	4.6	11	2.85	1.9	3.72	3.01	0.66	-0.15	1.2
	M 2		-11.4	0.0°	7.6	92.4	6.5	8.8	10.6	2.05	1.7	8.87				
	M 3		-7.7	4.0°	28.3	71.7					1.9	6.28				
	M 4		-4.6	12.0°	44.8	55.2	3.1	10.2	12.3	4.6	1	4.29	2.98	0.71	-0.24	1.27
Onahau (Fence Bay)	ON 1	921 971	-9.2	6.0°	30.7	69.3					2.2	5.82				
	ON 2		-7.7	5.0°	29.9	70.1	-0.2	0.4	2	1.1	2.6	5.95	2.57	1.06	-0.32	1.07
	ON 3		-5.8	9.5°	35.6	64.4	3	5.8	10	3.5	5.4	4.66	1.93	1.34	-0.16	0.76
	ON 4		-3.1	11.0°	83.7	16.3	0.8	1.8	3.2	1.2	5.7	1.74	1.55	1.18	0.01	0.88
	ON 5		-1.2	6.0°	97	3	3.7	5.7	9.9	3.1	8.3	0.75	-0.07	0.76	0.23	1.73
Umungata	U 1	888 942	-9.2	5.0°	7.2	92.8	4.8	5.8	9	2.1	1.1	8.54				
	U 2		-6.5	5.0°	29.7	70.3	3.7	5.7	9.9	3.1	1.9	4.69				
	U 3		-4.6	9.0°	93.2	6.8	-0.6	0.7	2.4	1.5	11.8	2.98				
Okiwa	OK 2	867 921	-1.8	2.0°	31.7	68.3					1.7	3.97				
	OK 3		-5.5	15.0°	15.8	84.2	4.8	6.6	10.5	2.85	1.7	6.02				
	OK 4		-3.1	11.0°	33.4	66.6	4.4	8.6	10.6	3.1	16.2	6.37				
	OK 5		-6.2	10.0°	12.8	87.2	4.8	6.6	10.5	2.85	1.3	6.43				
	OK 6		-6.8	5.0°	19.7	80.3					1.7	6.22				

1

UNIVERSITY OF CANTERBURY LIBRARY
AU03757528B

UNIVERSITY OF CANTERBURY LIBRARY
AU03757536B

UNIVERSITY OF CANTERBURY LIBRARY
AU03757544B

UNIVERSITY OF CANTERBURY LIBRARY
AU03757552B