http://researchspace.auckland.ac.nz

ResearchSpace@Auckland

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author's right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

To request permissions please use the Feedback form on our webpage. http://researchspace.auckland.ac.nz/feedback

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form and Deposit Licence.

Note: Masters Theses

The digital copy of a masters thesis is as submitted for examination and contains no corrections. The print copy, usually available in the University Library, may contain alterations requested by the supervisor.
ALTERNATING CONVERGENT AND NON-CONVERGENT TECTONICS,

100 MILLION YEARS TO PRESENT, PUKETORO AREA,

NORTHEASTERN NEW ZEALAND.

Jill A. Kenny

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Geology, University of Auckland, 1986.
Frontispiece: A view of the study area from Pirauau Trig, looking north to Mts Hikurangi (left) and Aorangi (right).
ABSTRACT

The area mapped comprises 180 km\(^2\) of rolling hill country between Waitahaia and Ihungia, 70 km north of Gisborne, in the extreme northeast of the North Island of New Zealand. The region is within Cretaceous and Tertiary rocks of the northern part of the northeast-trending East Coast Deformed Belt.

Six formations and one group (containing seven lithofacies) have been recognised. Mokoiwi Formation, Taitai Sandstone Member, Karekare, Whangai and Ihungia Formations have been retained. Waitahaia, Owhena and Tikihore Formations, and Mangatu siltstone, Wheturau siltstone and Te Waka greensand lithofacies are names introduced from the upper Waipaoa, Mangatu and Waitahaia Catchments. Smectite mudstone ("bentonite") is given lithofacies status here. The term Mangatu Group has been reinstated (Kenny 1984a) and the following lithofacies have been erected - Whakoau limestone, Opossum Creek sandstone and Hauturu greensand. New Rakauroa and Upper Calcareous Members and two other lithofacies are described for the Whangai Formation. Two conglomerate lithofacies, a breccia and two limestone lithofacies (Kouetumarae and Bexhaven) are recognised in the Ihungia Formation.

Two autochthonous domains and three stacked allochthonous sheets are established. The autochthonous "basement" domain consists of highly deformed, sandstone-dominated submarine fan sediments of Ngaterian (Late Albian to Early Cenomanian) age (Waitahaia Formation), accreted to an eastward-younging series of subduction-related imbricated packets. The relatively undeformed mudstone-dominated, fining upwards "cover" domain has accumulated in slope basins upon the accretionary prism (older
Karekare Formation - Arowhanan and Mangaotanean; Late Cenomanian to Turonian) eventually burying the "basement" inter-basin structural highs (younger Karekare Formation, Owhena and Whangai Formations - Teratan to Teurian; Senonian to Paleocene).

An allochthonous domain was emplaced possibly from the northwest at approximately 25 Ma (Oligocene-Miocene boundary), scraping off uppermost autochthonous sediments in its path, and incorporating some as lubricants. The domain contains Mokoïwi and Waitahaia Formations, both of which are comparable to the autochthonous "basement"; but in addition they have been rotated during emplacement. Many smaller sheets of sandstone, siltstone, mudstone, greensand and limestone are included in the overlying Mangatu Group domain, also emplaced from the northwest, probably in Tongaporutuan (latest Miocene) times. In this domain mixed lithologies within mélange and "bentonite" represent a fining upwards, passive margin sequence, poor in terrigenous detritus, of Late Cretaceous to Oligocene age.

The uppermost domain is thought to have been emplaced "piggy-back" upon the Mangatu Group domain. In the study area it is composed entirely of gently folded, mudstone-dominated Miocene Ihungia Formation strata. It is proposed that the formation was deposited in basins formed in accreted Karekare and Whangai Formations during early development of the Miocene to Recent Hikurangi subduction system.

Post-emplacement megascopic faulting and folding affect the region.
ACKNOWLEDGEMENTS

I would like to thank my family and friends, especially my parents, Martin Little and the Williams family (Ruangarehu Station), for their encouragement and support throughout this project.

I would also like to express my thanks to the following people:-
- Dr Peter Ballance and Associate Professor Bernhard Spörli (supervisors, University of Auckland);
- Mr Martin Little, Mr Barry Curham, Mr Keith Johnston, Ms Elva Leaming and Professor Phillippa Black (University of Auckland);
- Dr Fred Brook (New Zealand Geological Survey, Otara);
- Dr Ian Speden and Mr Phil Moore (New Zealand Geological Survey, Lower Hutt);
- Mr Colin Mazengarb and Mr Dave Francis (New Zealand Geological Survey, Gisborne);
- Mr Chris Phillips (formerly of New Zealand Forest Service, Gisborne);
- Mr Williams (Ruangarehu Station), Mr Hansen (Ihungia Station), Mr Creswell (Te Pora Station), Mr Moulder (Pouturu Station), Mr Lougher (Puketoro Station), Mr Rhodes (Mangatarata Station), Mr Chaffey (Bexhaven Station), Mr Carlson (Bremner Station), Mr Millar (Huiaru Station), Mr Kirby (Owetea Station) and Mr Poi (Waitahaia Station);
- Mr Andy Stevenson (topdressing plane/aerial photography).

This project has been financed in part by a Post Graduate Scholarship (1981-1983) and a McKee Trust Grant (1981), both awarded by the University Grants Committee.
CONTENTS

Frontispiece i
Abstract ii
Acknowledgements iv
Contents v
List of figures xii
List of tables xxiv

PART I - INTRODUCTION 1
Chapter 1 - Introduction 1
1.1 Thesis Setting 1
1.2 Location 2
1.3 Field Mapping 3
1.4 Previous Work 5
1.5 Aims 6
1.6 Samples 7

PART II - STRATIGRAPHY, SEDIMENTOLOGY, PETROGRAPHY, PALEONTOLOGY 8
Chapter 2 - Introduction to Part II 8

Chapter 3 - Stratigraphy, Sedimentology and Petrography of Clarence and Raukumara Series Rocks 12
3.1 Mokoiwi Formation 12
3.1 a Definition and Distribution 12
3.1 b Stratigraphy and Sedimentology 14
   i Mokoiwi siltstone 14
   ii Taitai Sandstone Member 18
   iii Conglomerates and Breccias of the Taitai Sandstone Member 18
3.1 c Petrography 19
   i Mokoiwi siltstone 19
   ii Taitai Sandstone Member 23
   iii Conglomerate Clasts in Taitai Sandstone Member 25
3.1 d Thickness 27
3.1 e Paleontology and Age 27
3.1 f Provenance 28
3.1 g Environment and Processes of Deposition 31
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>Waitahaia Formation</td>
<td>37</td>
</tr>
<tr>
<td>3.2 a</td>
<td>Definition and Distribution</td>
<td>37</td>
</tr>
<tr>
<td>3.2 b</td>
<td>Stratigraphy and Sedimentology</td>
<td>39</td>
</tr>
<tr>
<td>3.2 c</td>
<td>Petrography</td>
<td>48</td>
</tr>
<tr>
<td>3.2 d</td>
<td>Thickness</td>
<td>51</td>
</tr>
<tr>
<td>3.2 e</td>
<td>Paleontology and Age</td>
<td>51</td>
</tr>
<tr>
<td>3.2 f</td>
<td>Provenance</td>
<td>52</td>
</tr>
<tr>
<td>3.2 g</td>
<td>Environment and Processes of Deposition</td>
<td>55</td>
</tr>
<tr>
<td>3.3</td>
<td>Karekare Formation</td>
<td>58</td>
</tr>
<tr>
<td>3.3 a</td>
<td>Definition and Distribution</td>
<td>58</td>
</tr>
<tr>
<td>3.3 b</td>
<td>Stratigraphy and Sedimentology</td>
<td>60</td>
</tr>
<tr>
<td>3.3 c</td>
<td>Petrography</td>
<td>66</td>
</tr>
<tr>
<td>3.3 d</td>
<td>Age and Paleontology</td>
<td>69</td>
</tr>
<tr>
<td>3.3 e</td>
<td>Thickness</td>
<td>73</td>
</tr>
<tr>
<td>3.3 f</td>
<td>Provenance</td>
<td>73</td>
</tr>
<tr>
<td>3.3 g</td>
<td>Environment and Processes of Deposition</td>
<td>76</td>
</tr>
<tr>
<td>3.4</td>
<td>Discussion</td>
<td>80</td>
</tr>
<tr>
<td>3.4 a</td>
<td>Environment of Deposition</td>
<td>80</td>
</tr>
<tr>
<td>3.4 b</td>
<td>Petrographical Comparisons</td>
<td>81</td>
</tr>
<tr>
<td>3.4 c</td>
<td>Regional Comparisons</td>
<td>84</td>
</tr>
</tbody>
</table>

| Chapter 4 - Stratigraphy, Sedimentology and Petrography of Mata Series and Paleogene Rocks |
|-----------------------------------------------|-----------------------------------------------|
| 4.1 Whangai Formation                        | 87                                           |
| 4.1 a Definition and Distribution             | 87                                           |
| 4.1 b Stratigraphy and Sedimentology         | 89                                           |
| 4.1 c Petrography                            | 95                                           |
| 4.1 d Thickness                              | 98                                           |
| 4.1 e Age and Paleontology                   | 99                                           |
| 4.1 f Provenance                             | 100                                          |
| 4.1 g Environment and Processes of Deposition | 100                                          |
| 4.2 Tikihore Formation                       | 103                                          |
| 4.2 a Definition and Distribution             | 103                                          |
| 4.2 b Stratigraphy and Sedimentology         | 103                                          |
| 4.2 c Petrography                            | 106                                          |
| 4.2 d Thickness                              | 108                                          |
PART III - STRUCTURE

Chapter 7 - Introduction of Part III

Chapter 8 - Structures in Autochthonous Lithologies

8.1 Soft Sediment Deformation
8.1 a Soft Sediment Folds
8.1 b Clastic Intrusions
8.1 c Boudinage and Broken Formation
8.1 d Discussion

8.2 Early Structures
8.3 Major N - S-Trending Faults and Folds
8.3 a Folding
8.3 b Faulting
8.3 c Discussion
8.3 d Analysis

8.4 Later Structures
8.4 a Descriptions of Each Event
8.4 b Analysis of the Events

8.5 100 m-Wide "Zone of Disruption"
8.5 a Broken Formation
8.5 b Faulting
8.5 c Folding
8.5 d Discussion

8.6 Preliminary Discussion and Analysis of Autochthonous "Basement" Domain

Autochthonous "Cover" Domain
8.7 Structures within the Karekare Formation
8.8 Structures within the Whangai Formation
8.9 Summary of Structures in the Autochthonous "Cover" Domain
Chapter 9 - Structures in Allochthonous Lithologies

Structures of the Allochthonous Equivalents of the Basement

9.1 Autochthon/Allochthon Boundary

273

9.2 Structure of the Mokoiwi Formation

9.2 a Early Folding within Mokoiwi Formation

9.2 b Early Faulting within Mokoiwi Formation

9.2 c Other Early Structural Features

9.2 d Later Folding in Mokoiwi Formation

9.2 e Later Shearing in Mokoiwi Formation

9.2 f Structures in Taitai Sandstone

9.2 g Analysis of Structures within Mokoiwi Formation

280

280

284

285

286

287

289

9.3 Structure of the Allochthonous Waitahaia Formation

9.3 a Early Folding

9.3 b Early Faulting

9.3 c Boudinage

9.3 d Later Folding

9.3 e Later Faulting

9.3 f Analysis of Allochthonous Waitahaia Formation

294

294

296

297

297

298

299

9.4 Discussion of Allochthonous Mokoiwi and Waitahaia Formations

302

306

306

308

310

311

318

318

322

326

326
9.7 b Veins and Shears
   i Tensional veins 332
   ii Sheared veins 332
   iii Tension gashes 338
9.7 c Model for Timing of Developments of Cleavage and Veins 340
9.7 d Brown Sandstone Sliver 342
9.7 e Discussion 344

9.8 Structures in the Hauturu Greensand Lithofacies 348

9.9 Structures in Mélange 352
9.9 a Description 352
9.9 b Analysis 356
   i Striations 356
   ii Lozenge geometries 357
   iii Kink folds 357
9.10 Discussion 359

Ihungia Formation Domain 365
9.11 Internal Structures 365
9.11 a Folding 365
9.11 b Faulting 369
9.11 c Whangai Breccia 370

9.12 Lower Contact 371
9.13 Upper Contact 373
9.14 Analysis 373
9.15 Discussion 375

Chapter 10 - Post-Emplacement Structures 381
10.1 Folding 381
10.2 Faulting 384
10.3 Discussion of Post-Emplacement Faulting and Folding 396
# PART IV - CONCLUSIONS

## Chapter 11 - Discussion of the Middle Cretaceous

### 11.1 Summary of the Middle Cretaceous Geology in the Study Area

- Models for Development of N - S-Trending Structures
- Extension Model for Basin Development and Infilling
- Compression Model for Basin Development and Infilling
- Regional Comparisons
- Diachronism of Deformed Cover/Contact
- Provenance of Middle Cretaceous Sediments
- Neogene Subduction

### Chapter 12 - Discussion of Allochthonous Domains

- Application of Geometrical Models of Thrusts
- Low-Angle Extensional Tectonics
- Discussion of the Allochthon
  - Timing of Events
  - Speeds of Emplacement
  - Duration and Distance of Allochthonous Movements

### Chapter 13 - Summary

## Appendix 1 - Descriptions of sample lithologies referenced

## Appendix 2a - Cretaceous Macrofauna

## Appendix 2b - Miocene Macrofauna

## Appendix 2c - Foraminifera present in Ihungia Formation

## Appendix 3 - Detailed stereonets

## References

## Contents of back pocket:-

- Locality Map; Lithostratigraphic Map (scale 1:25000); Geology of the Autochthonous Basement (scale 1:10000); Geology of the Whakoau Area (scale 1:10000); Geology of the Middle Mata River Area (scale 1:10000); Biostratigraphic Map of the Ihungia Formation (scale 1:25000); Geological Symbols and Legend for all maps; Cross-Sections.
LIST OF FIGURES

Figure 1.1 Major structural elements of the eastern North Island, showing the spatial relationships of the East Coast Deformed Belt with the Hikurangi Trough, axial ranges and Taupo Volcanic Zone (modified after Kingma 1965; Spörli 1980; van der Lingen and Pettinga 1980).

Figure 1.2 Location of the study area. Locality names within the area appear in the locality map in the back pocket.

Figure 2.1 Areal extent of the six formations and one group, mapped in the study area and in the Ihungia Catchment.

Figure 3.1 Distribution of Mokoiwi Formation (including Taitai Sandstone Member) in the study area and in the western Ihungia Catchment.

Figure 3.2 Disrupted alternating sandstone and siltstone beds of the Mokoiwi Formation (Mokoiwi siltstone sensu stricto) at Locality 9 (Figure 3.2).

Figure 3.3 Knoll of Taitai Sandstone Member surrounded by Mokoiwi siltstone (subdued relief) at Locality 7 (Figure 3.2).

Figure 3.4 Current directions from measurements of sole markings on sandstones from the Mokoiwi Formation. Lines around the outer circle represent measurements from which exact current directions could be determined. Lines in the inner circle show trends only. Flute casts are shown by thick lines; thin lines represent load casts. Probable original orientations have been achieved by rotating bedding to horizontal about the local strike.

Figure 3.5 Distribution of Waitahaia Formation in the study area and mid-Ihungia Catchment.

Figure 3.6 Stratigraphic column from Locality 4 (Figure 3.5) which is representative of the assemblage of regularly-spaced, thick sandstones alternating with thin-bedded alternating sandstones and mudstones.
Figure 3.7 Seven examples of Bouma sequences in thick sandstone units. Each sketch represents a thickness of 1 m.

Figure 3.8 Parallel and convoluted laminations in thin-bedded sandstone at Locality 5 (Figure 3.5). Younging direction is towards the right (west).

Figure 3.9 Flute casts on the underside of a sandstone bed at Y15/558431 (50 m west of Locality 15, Figure 3.5). After rotation of these near-vertical beds about the strike, flute casts in this vicinity indicate current flow towards the north (towards the right in this photograph).

Figure 3.10 Current directions from measurements of sole markings on sandstones from the Waitahaia Formation. Lines around the outer circles indicate current directions; lines in the inner circles are trends only.

Figure 3.11 Disc-shaped concretions lying in mudstone, parallel to bedding. Note the thin calcite vein passing through the centre of the discs, also parallel to bedding.

Figure 3.12 Spherical sandstone concretions enclosed by similar sandstone.

Figure 3.13 Current directions in lithologies of Ngaterian age in middle Raukumara Peninsula.

Figure 3.14 Model of submarine fan deposition, relating facies, fan morphology, and depositional environment (after Walker 1978: 946). Mid-fan deposits of the Waitahaia Formation are represented in the centre of the model.

Figure 3.15 Distribution of Karekare Formation in the study area.

Figure 3.16 Typical alternating sequence in lower Karekare Formation, 50 m upstream from Locality 1 (Figure 3.15) in lower Puketoro Stream (Y15/55154090).

Figure 3.17 Karekare Formation current flow directions for lower and upper sequences.

Figure 3.18 Distribution of Teratan, Mangaotanean and Arowhanan Stages of the Karekare Formation. Note the diachronicity of stages abutting against the contact with the Waitahaia Formation.
Figure 3.19 Just exposed undulating shell of *Inoceramus rangatira* at Y15/55154070 in Puketoro Stream, in mudstone of the lower Karekare Formation.

Figure 3.20 Simplified stratigraphic columns of the Karekare Formation. Note that only the highest and lowest occurrences of *Inoceramus* are indicated within a stage, or the only occurrence within that stage.

Figure 3.21 Simplified QFL diagram of positions of Karekare (K), Waitahaia (W) and Mokoitiwi (M) Formations, including Taitai Sandstone (T).

Figure 4.1 Distribution of Whangai Formation in the study area.

Figure 4.2 Typical calcareous Upper Calcareous Member of the Whangai Formation at Y16/55104005 in Puketoro Stream.

Figure 4.3 Slightly disrupted sedimentary contact between "Waingata Limestone" (left) and siliceous upper Whangai Formation near Locality 15, Waitahaia River (Y16/50553845).

Figure 4.4 Distribution of Tikihore Formation in the study area.

Figure 4.5 Distribution of Paleocene and Eocene lithofacies in the study area. Smectite clay ("bentonite") is not illustrated because it is only exposed along fault zones.

Figure 4.6 Smectite mudstone, with red discolouration, from a wide shear zone at Locality 4 (Figure 4.5).

Figure 4.7 Wet, puggy smectite mudstone at Locality 5 (Figure 4.5) with large spherical concretions on the left of the photograph.

Figure 4.8 Distribution of Oligocene lithofacies in the study area.

Figure 4.9 *Zoophycos* trace fossil on a fallen block of Whakoau limestone. Hammer handle for scale.

Figure 4.10 Diagram showing proportions of quartz, glauconite and total calcite in thin-sections and X-ray diffraction samples of Te Waka and Hauturu greensand lithofacies. Note that the calcareous nature of the Te Waka lithofacies was only apparent in the X-ray diffraction analysis, but not in thin-section analysis hence the very low calcite reading for the latter in this diagram.
Figure 4.11 Simplified representation of pre-allochthonous stratigraphic relationships of Upper Cretaceous and Paleogene lithofacies. Relative areal extent of each lithology is not intended to be represented by the spaces assigned in the diagram.

Figure 4.12 Simplified QFL diagram of lithologies in the Whangai and Tikihore Formations and Mangatu Group which contain lithic fragments.

Figure 4.13 Triangular diagram showing proportions of total quartz (monocrystalline quartz and siliceous matrix), detrital accessories (feldspar, biotite, muscovite, epidote and apatite) and the remainder of minerals (mostly lithic and fossil fragments and authigenic minerals).

Figure 5.1 Distribution of Ihungia Formation in the study area, and in western Ihungia Catchment.

Figure 5.2 Mudstone-dominated Ihungia Formation at Locality 2 (Figure 5.1).

Figure 5.3 Dark sandstone exposed in a tributary of upper Puketoro Stream, Locality 9 (Figure 5.1).

Figure 5.4 Float boulders illustrating grain sizes of shell material observed in sandstone at Locality 11 (Figure 5.1).

Figure 5.5 Dark sandstone supporting sparsely distributed conglomerate pebbles of the lower conglomerate. Note the larger, black igneous boulder on the far right of the photograph. Locality 18 (Figure 5.1).

Figure 5.6 Clast-supported pebbles and cobbles in fallen blocks of the upper conglomerate at Locality 26 (Figure 5.1).

Figure 5.6 Siliceous upper Whangai clast in a matrix of rusty coloured fine sandstone. The clast is more than 1 m wide and is parallel to bedding. Note also the dark chert nodules.

Figure 5.8 Gradational contact (partly obscured by vegetation) between limestone (above) and shell-rich Ihungia mudstone (below), at Locality 36 (Figure 5.1).

Figure 5.9 Leptastrea bottae (Milne, Edwards and Haime) in sample Y16/f389 from Locality 14 (Figure 5.1).
Figure 5.10 Simplified stratigraphic columns for the study area and Ihungia Catchment to show thickness variations and positions of lithofacies other than the dominant mudstone-dominated flysch, in the Ihungia Formation. Note that thicknesses of each stage and substage are based on biostratigraphy tentatively determined using foraminiferal studies. Stream names in this figure have been added to the Locality map (Figure 5.1).

Figure 6.1 Typical spectra of minerals identified by electron probe microanalyser.

Figure 6.2 Compilation of QFL data from Chapters 3, 4 and 5.

Figure 7.1 Approximate position of the autochthon/allochthon boundary in Raukumara Peninsula.

Figure 7.2 Areal extent of the five structural domains recognised in the Waitahaia area.

Figure 7.3 Strain ellipse

Figure 8.1 Extent of the autochthonous "basement" and its relationship with the geology of the rest of the study area and western Ihungia Catchment.

Figure 8.2 Diagramatic representation of the Separation Arc Method and the Mean Axis Method as they apply to a slide in the Waitahaia Formation.

Figure 8.3 Field sketch of a possible soft sediment fold, Waingata Stream.

Figure 8.4 Field sketch of clastic dikes at Locality 3.

Figure 8.5 Field sketch of a clastic dike at Locality 3 showing sandy material injected along bedding, and a break-out of sand perpendicular to bedding.

Figure 8.6 Orientation of boudin stress axes with respect to bedding.

Figure 8.7 Relationship of boudins and clastic intrusions with bedding.

Figure 8.8 Simplified equal area stereonets of group 1 and rotated group 3 faults.

Figure 8.9 Examples of small folds within the fold system.

Figure 8.10 Equal area stereonet depicting a summary of poles to megascopic reverse faults, chlorite gouge zones and mesoscopic conjugate faults.
Figure 8.11 Method of obtaining principal stresses from known slip direction.

Figure 8.12 Equal area stereonet showing striations of shear planes, together with estimated principal stress directions.

Figure 8.13 Equal area stereonet summarising tight to isoclinal folds in the Waitahaia Formation.

Figure 8.14 Minor folding showing reverse slip a) on limbs of a regional anticline and b) on the upper plate in an area of a reverse slip simple shear regime.

Figure 8.15 Equal area stereonet summarising the vertical undulating beds at Localities 5 to 8.

Figure 8.16 Parallelism between axial planes of folds and fault planes.

Figure 8.17 Summaries of principal stress directions for each of the five events in the post-N-S-trending phase.

Figure 8.18 Small multiple conjugate fractures at Y15/573433 on the Mata River.

Figure 8.19a Outcrop log of the western bank of the Mata River.

Figure 8.19b Outcrop log of the eastern bank of the Mata River.

Figure 8.20 Summaries of principal stress directions for each of the five events in the "Zone of Disruption".

Figure 8.21 Summaries of equal area stereonets displayed in Appendix 3.8a and b, for folds of the younger phase in the "Zone of Disruption".

Figure 8.22 Summary of orientations of the older folding phase after the effects of later folding have been removed.

Figure 8.23 Location of Waingakia and Ruatahunga Streams in relation to the main rivers in the region, and the present study area.

Figure 8.24 Poorly exposed unconformity separating tightly folded Waitahaia Formation from Karekare Formation, Waingata Stream.

Figure 8.25 The unconformity between steeply dipping Waitahaia Formation and moderately south-dipping Karekare Formation, Puketoro Stream.

Figure 8.26 Summary of stereonet analysis of undulations within the Karekare Formation.

Figure 8.27 Extent of the autochthonous cover (Karekare Formation), and its relationship with the geology of the rest of the study area and western Ihungia.
Figure 8.28 Recumbent fold in Karekare Formation on the western slopes of Puketoro Stream.

Figure 8.29 Simplified equal area stereonet of faults and striations in the Karekare Formation.

Figure 8.30 Extent of the autochthonous "cover" (Whangai Formation) and its relationship with the geology of the rest of the study area and western Ihungia.

Figure 8.31 Summary of undulations in the Whangai Formation.

Figure 8.32 Equal area stereonet representing some of the faulting in the Whangai Formation along the Waitahaia River.

Figure 8.33 Equal area stereonet summary of folding in the Whangai Formation along the Waitahaia River.

Figure 8.34 Equal area stereonet representing other fault movements in the Whangai Formation along the Waitahaia River.

Figure 8.35 Typical pattern of undulations in upper Whangai Formation at Y15/56473980 on the Mata River.

Figure 8.36 Equal area stereonet summary of folding in the Whangai Formation along the Mata River.

Figure 8.37 Summary of shearing in the Whangai Formation along the Mata River.

Figure 8.38 Summary of stylolite cleavages ($S_1$ and $S_2$) and veins along the Waitahaia and Mata Rivers.

Figure 9.1 Autochthon/allochthon boundary passing through the study area and western Ihungia Catchment.

Figure 9.2 Simplified equal area stereonet of Appendix 3.25, showing slip directions analysed from lozenges and striations on shear planes in the Waitahaia River area.

Figure 9.3 Summary of trends seen in striation measurements collected from Kaikomako Stream.

Figure 9.4 Average $S_1$ and $S_2$ cleavages and associated veins after 80° anticlockwise rotation back to an assumed original position, comparable to the autochthonous material.

Figure 9.5 Extent of the allochthonous Mokoiwi Formation, and its relationship with the geology of the rest of the study area and western Ihungia Catchment.
Figure 9.6  Typical folding in the Mokoiwi Formation, at Locality 1.  
Figure 9.7  Simplified equal area stereonets of folds in the Mokoiwi Formation at Localities 1 and 2.  
Figure 9.8  Simplified equal area stereonets of faults in the Mokoiwi Formation at Localities 1 and 2.  
Figure 9.9  Summary of Appendix 3.19a depicting quartz veins and boudins in Mokoiwi Formation.  
Figure 9.10 Disharmonic folds in Mokoiwi Formation at or near Locality 1.  
Figure 9.11 Summary of later shearing in Mokoiwi Formation.  
Figure 9.12 Sheared disharmonic folds within the dominant recumbent folding of the Mokoiwi Formation, Locality 1.  
Figure 9.13 Equal area stereonet of a shear in Taitai Sandstone at Locality 6.  
Figure 9.14 Extent of the allochthonous Waitahaia Formation, and its relationship with the geology of the rest of the study area and western Ihungia Catchment.  
Figure 9.15 Equal area stereonet summary of folds in allochthonous Waitahaia Formation.  
Figure 9.16 Pre-emplacement reverse shears in allochthonous Waitahaia Formation.  
Figure 9.17 Summary of later folds in allochthonous Waitahaia Formation.  
Figure 9.18 Summary of conjugate faults, striations and single faults associated with emplacement of the Waitahaia Formation.  
Figure 9.19 Diagrammatic representation of folding of Mokoiwi and Waitahaia Formations, followed by simple rotation to juxtapose the formations horizontally.  
Figure 9.20 Two possible mechanisms for emplacement of the Mokoiwi and Waitahaia Formations.  
Figure 9.21 Extent of the allochthonous Whangai and Tikihore Formations and Mangatu Group, and their relationships with the geology of the rest of the study area and western Ihungia Catchment.  
Figure 9.22 Summary of cecumbent folds in allochthonous material of Upper Cretaceous to Paleocene age.
Figure 9.23 Summary of conjugate faults in Tikihore Formation and striations in various lithologies.

Figure 9.24 Summary of two phases of faulting observed in upper Whangai Formation at Locality 6.

Figure 9.25 Model illustrating deformation of upper layers of the autochthon by emplacement of an allochthonous mass above it.

Figure 9.26 Model showing detachment of deformed upper autochthon strata to form an allochthonous sheet above the Mokoiwi and Waitahaia allochthonous material.

Figure 9.27 Extent of the allochthonous Opossum Creek sandstone lithofacies, and its relationship with the geology of the rest of the study area.

Figure 9.28 Summary of gentle folding in the Opossum Creek sandstone.

Figure 9.29 Summary of faults mapped in Opossum Creek, in Opossum Creek sandstone.

Figure 9.30 Summary of each of the seven phases of faulting observed along the Mata River.

Figure 9.31 Three dimensional model of part of the outcrop of Opossum Creek sandstone at Locality 2.

Figure 9.32 Summary of slickensided veins in Kaikomako Catchment within Opossum Creek sandstone.

Figure 9.33 Equal area stereonets illustrating position of cleavage planes in Opossum Creek sandstone along the Mata River.

Figure 9.34 Principal stress directions from conjugate faults in Opossum Creek sandstone.

Figure 9.35 Extent of the allochthonous Whakoau limestone lithofacies, and its relationship with the geology of the rest of the study area. Simple equal area stereonets are superimposed for comparison of bedding in ten locations.

Figure 9.36a Interrelationships of $S_1$, $S_2$ and $S_3$ cleavages at Locality 6.

Figure 9.36b $S_1$ and $S_2$ cleavages in a slab of Whakoau limestone.

Figure 9.37 Summaries of gentle folding of $S_1$ ($S_0$) and $S_2$ cleavages.

Figure 9.38 Summary of $S_3$ cleavages.
Figure 9.39 Development of slickensides on the underside of a folded $S_1$ plane. Steps indicate movement of illustrated block towards $120^\circ$.

Figure 9.40 Emplacement-related shearing (possibly flexural slip) along $S_1$ cleavage which has folded $S_2$ cleavage.

Figure 9.41 Emplacement-related low angle shear with associated synthetic and antithetic normal and reverse shears.

Figure 9.42 Percentages of directions of all slickensided veins, dipping less than $45^\circ$, in Whakoau limestone.

Figure 9.43 Post-emplacement sheared veins around Locality 9.

Figure 9.44a Illustration of curvature of veins into bedding and subsequent folding of veins, bedding and $S_2$ cleavage.

Figure 9.44b At least two stages of vein development represented; also lobe with splay, vuggy calcite in vein thickening, pervasive $S_3$ cleavage.

Figure 9.44c Drag folds in bedding caused by reverse shear. Cut by normal shear almost parallel to bedding. Both shears accompanied by slickensides.

Figure 9.44d Slickensides on a folded plane; indicate a phase of dextral shearing.

Figure 9.45 Orientations of tension gashes in simple shear zones with positive dilatation and negative dilatation.

Figure 9.46a Negative dilatation en-echelon tension gashes associated with a normal fault.

Figure 9.46b Negative dilatation tension gashes between two normal sheared veins. Also shown here is $S_3$ cleavage apparently unaffected by deformation which warped bedding; vuggy calcite growth in void caused by sigmoidal distortion of another tension gash; partial use of bedding planes by vein.

Figure 9.46c Positive dilatation tension gashes associated with normal shearing veins. Veins, bedding and tension gashes all involved in gentle fold.

Figure 9.46d Positive dilatation vein arrays developing from main shear veins along bedding. Main veins curved into bedding before everything affected by gentle fold.

Figure 9.47 Extension directions of tension gashes, plotted on equal area stereonet.
Figure 9.48a Disruption of bedded sequence in brown sandstone sliver at Locality 1.

Figure 9.48b Stereonet analysis of faults in the brown sandstone.

Figure 9.49 Extent of the Hauturu greensand lithofacies, and its relationship with the geology of the rest of the study area and western Ihungia Catchment.

Figure 9.50 Summary of structures in the Hauturu greensand lithofacies.

Figure 9.51 Extent of mélange enclosing sheets of Mangatu Group domain, and its relationship with the geology of the rest of the study area and western Ihungia Catchment.

Figure 9.52 Summary of shear fabrics in the mélange.

Figure 9.53 Appraisal of lozenge formation, derived from Pettinga (1982).

Figure 9.54 Summary of equal area stereonet analyses of striations in mélange material.

Figure 9.55 Percentages of directions of all striations in mélange material on planes dipping less than 45°.

Figure 9.56 Summary of stereonet analysis of separation directions obtained from lozenge fabrics.

Figure 9.57 Hypothetical scenario for positions of material of Middle Cretaceous to Oligocene ages, in the source area of the décollements, in the autochthon.

Figure 9.58 Extent of the allochthonous Ihungia Formation, and its relationship with the geology of the rest of the study area and western Ihungia Catchment.

Figure 9.59 Megascopic folds in the Ihungia Formation domain.

Figure 9.60 Summary of equal area stereonet analysis of striations and conjugate faults in Ihungia Formation.

Figure 9.61 Deposition of sediments in a piggy-back basin formed between two thrust sheets in a gravitational spreading situation.

Figure 9.62 Section of the southern Po basin complex.

Figure 9.63 Section through the Glaus basin and marginal area of the Ebro basin, northern Spain.

Figure 10.1 Post-emplacement fold trends in the study area and western Ihungia Catchment.

Figure 10.2 Location of measured and extrapolated offsets on faults.
Figure 10.3 Comparative ages of megascopic faults in the study area and Ihungia Catchment.

Figure 10.4 Model of a simplified form of reverse listric fault joining the basal Ihungia Formation thrust plane asymptotically.

Figure 10.5 Principal faults of the eastern North Island active during the Kaikoura Orogeny.

Figure 11.1a Diagram showing reverse faulting and minor folding on the limbs of regional anticlines and synclines, with respect to the Waitahaia Formation.

Figure 11.1b Diagram illustrating faulting and folding in an accretionary wedge of a subduction zone as it may have occurred in the Waitahaia Formation.

Figure 11.2 Extension (rifting) model.

Figure 11.3 Relationship between Waitahaia Formation and Karekare Formation using a modified version of Surlyk's model.

Figure 11.4 Tracings of seismic profiles from the present continental shelf and slope off eastern North Island.

Figure 11.5 Profile 72-124, with Waitahaia and Karekare Formations superimposed in their postulated positions.

Figure 11.6 Relative positions of lithostratigraphic units, from East Cape to Marlborough, in the vicinity of one of a number of supra-accretionary prism basins.

Figure 11.7 Simplified stratigraphic columns comparing the age of the unconformity separating "basement" and oldest "cover" sediments in Raukumara Peninsula.

Figure 11.8 Cartoon of the proposed Cretaceous geological history of the Raukumara Peninsula region, showing response of sediment to subduction from the east.

Figure 11.9 Addition of provenance information to the cartoon of Cretaceous geological history.

Figure 12.1 Simplified cross-section through Whakoau and Pirauaau Trigs, showing a folded possible imbricate system of allochthonous sheets.

Figure 12.2 Diagramatic interpretation of gravity gliding.

Figure 12.3 Diagramatic interpretation of gravitational spreading.

Figure 12.4 A form of extensional faulting - fallen pile of books.

Figure 12.5 Forms of extensional faulting.

Figure 12.6 Simplified diagrams of possible emplacement mechanisms 428/429.
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Stratigraphic relationships within the study area, with brief lithologic descriptions.</td>
<td>10</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Percentages of point counts of five samples of Mokoiwi siltstone. 300 points were counted for each thin-section.</td>
<td>20</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Percentages of minerals identified from mudstone belonging to Mokoiwi siltstone, using X-ray diffraction methods.</td>
<td>22</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>Percentages of point counts of two samples of Taitai Sandstone Member. 300 points were counted for each.</td>
<td>23</td>
</tr>
<tr>
<td>Table 3.4</td>
<td>Percentages of minerals identified from mudstone belonging to Taitai Sandstone sample AU 38809, using X-ray diffraction methods.</td>
<td>25</td>
</tr>
<tr>
<td>Table 3.5</td>
<td>Percentaged point count of sample AU 38799 of a sandstone constituent of conglomerate within Taitai Sandstone Member (300 points counted).</td>
<td>26</td>
</tr>
<tr>
<td>Table 3.6</td>
<td>Percentages of minerals in four samples of Waitahaia Formation sandstone. 300 point counts were made for samples AU 38812, 38820 and 38822; 150 counts were made for sample AU 38821 because of the poor quality of the slide.</td>
<td>49</td>
</tr>
<tr>
<td>Table 3.7</td>
<td>Percentages of minerals identified from mudstone belonging to the Waitahaia Formation, using X-ray diffraction methods.</td>
<td>50</td>
</tr>
<tr>
<td>Table 3.8</td>
<td>Percentages of minerals in five samples of Karekare Formation. 300 points were counted for each thin-section except AU 38838 where poor condition of the thin-section allowed for only 100 counts.</td>
<td>67</td>
</tr>
<tr>
<td>Table 3.9</td>
<td>Percentages of minerals identified from muds belonging to Karekare Formation, using X-ray diffraction.</td>
<td>68</td>
</tr>
<tr>
<td>Table 3.10</td>
<td>Average percentages of minerals from Mokoiiwi, Waitahaia and Karekare Formations. Please note that percentages are only approximate, with the decimal point a result of division.</td>
<td>82</td>
</tr>
<tr>
<td>Table 3.11</td>
<td>Average compositions of mudstones in Karekare, Waitahaia and Mokoiiwi Formations, analysed using X-ray diffraction methods.</td>
<td>82</td>
</tr>
</tbody>
</table>
Table 4.1 Percentage of minerals in eight samples of Whangai Formation. 300 points were counted for AU 38875 and 38856, 100 points were counted for the remainder.

Table 4.2 Percentages of minerals analysed from Whangai Formation mudstones by X-ray diffraction methods.

Table 4.3 Percentages of minerals in Tikihore Formation sandstone samples AU 38893, 38898 and 38899, and siltstone AU 38894.

Table 4.4 Percentages of minerals identified from a calcareous sample (AU 38899) and a carbon-rich sample (AU 38900) of the Tikihore Formation, using X-ray diffraction.

Table 4.5 Percentages of minerals identified from the Mangatu siltstone lithofacies, using X-ray diffraction.

Table 4.6 Percentages of minerals identified from Wheturau siltstone, using X-ray diffraction methods.

Table 4.7 Percentage of minerals in sample AU 38908 of Te Waka greensand lithofacies.

Table 4.8 Percentage of minerals identified from Te Waka greensand, using X-ray diffraction methods.

Table 4.9 Percentages of minerals identified from smectite mudstone (AU 38911), sheared smectite (AU 38913) and red mudstone (AU 38912), using X-ray diffraction methods.

Table 4.10 Percentages of minerals point counted from a sandy phase (AU 38915) of the Whakoau limestone lithofacies. 100 points were counted.

Table 4.11 Percentages of minerals identified from Whakoau limestone using X-ray diffraction methods. Sample AU 38916 is from the upper sheet; AU 38921 is from the lower sheet.

Table 4.12 Percentage of minerals in four sandstone samples of Opossum Creek lithofacies. 300 points were counted from samples 38924 and 38922, and 100 points for 38925 and 38926.

Table 4.13 Percentages of minerals identified from Opossum Creek sandstone lithofacies, using X-ray diffraction. Samples AU 38927 and 38928 are from massive sandstones between Localities 5 and 6 (Figure 4.8) AU 38923 is a noncalcareous siltstone from Locality 9 and AU
38938 is brown sandstone from western Whakoau (Locality 12).

Table 4.14 Percentages of sand grains and lithic fragments in two breccia samples. 50 and 100 point counts were made of AU 38934 and 38935 respectively. Subrounded, cloudy plagioclase varies from An$_{20}$ to An$_{35}$. Biotite and interstitial matrix is partly chloritised.

Table 4.15 Percentages of minerals counted in sample AU 38937 of brown sandstone assigned to the Opossum Creek lithofacies. 300 points were counted.

Table 4.16 Percentages of minerals in AU 38939 and 38941 of Hauturu greensand lithofacies. AU 38940 is an "iron nodule" within the greensand. 300 points were counted for the first two examples, and 100 points for AU 38940.

Table 4.17 Percentages of minerals identified from the Hauturu lithofacies using X-ray diffraction.

Table 4.18 Average percentages of minerals from Whangai and Tikihore Formations and the Mangatu Group.

Table 4.19 Average percentages of muds in Whangai and Tikihore Formations and the Mangatu Group, analysed using X-ray diffraction methods.

Table 5.1 Age ranges of foraminifera used to determine biostratigraphy of the Ihungia Formation (after Walters 1965 for the Gisborne district, with additional data from Hayward 1976; Hornibrook 1978; Hoskins 1982; Brook 1983).

Table 5.2 Percentages of minerals in Ihungia Formation mudstone using X-ray diffraction techniques.

Table 5.3 Percentages of minerals in a dolomite concretion (AU 38956) and immediately surrounding Ihungia mudstone (38957), using X-ray diffraction.

Table 5.4 Percentages of minerals in two samples of Ihungia Formation very fine grained sandstones. 100 counts were made of each sample.

Table 5.5 Percentages of minerals in Waiauan/Lillburnian (AU 38964), Clifdenian (AU 38965) and Lower Altonian/Upper Otaian (AU 38966) sandstones of
the Ihungia Formation, using X-ray diffraction.

Table 5.6 Percentages of minerals in 100 counts of dark sandstone in Ihungia Formation.

Table 5.7 Recent depth distribution of some benthic foraminiferal genera as an indication of possible distributions in the Ihungia Formation (modified after Boltovskoy and Wright 1976; Brook 1983). Those genera with wide depth ranges are marked by dots, while those with more limited ranges are emphasised by crosses.

Table 6.1 Composite of all percentages from point count analyses.

Table 6.2 Values (in ⁰) of peaks representing each mineral recorded from powdered rocks by X-ray diffraction, based largely on Pei-Yuan Chen (1977). Values underlined by a dashed line should be moderately important peaks; those underlined by a solid line should be dominant peaks.

Table 6.3 Alteration of peak shape, size or position (in ⁰) in clay minerals when oriented or treated with glycerol or heat (500⁰C).

Table 6.4 Composite of all percentages from X-ray diffraction analysis.

Table 8.1 Summary of stress and strain axes and sequence of events of structures in the Waitahaia Formation.

Table 10.1 Slip directions of sections of faults which were measured according to the method described by Ragan (1973), with local topography also included in the analyses.

Table 10.2 Apparent senses of movement of faults where either one or no marker horizons are offset.

Table 12.1 Possible timing of emplacements of allochthonous sheets.

Table 12.2 Ages postulated for emplacement events in the East Cape region and Northland.