

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

A.J.H. Clement

HOLOCENE SEA-LEVEL CHANGE  
IN THE NEW ZEALAND ARCHIPELAGO  
AND THE GEOMORPHIC EVOLUTION OF  
A HOLOCENE COASTAL PLAIN  
INCISED-VALLEY SYSTEM:  
THE LOWER MANAWATU VALLEY,  
NORTH ISLAND, NEW ZEALAND

#### RELATED PUBLICATIONS

Clement, A.J.H., Sloss, C.R., Fuller, I.C., 2010. Late Quaternary geomorphology of the Manawatu coastal plain, North Island, New Zealand. *Quaternary International* 221, 36–45.

HOLOCENE SEA-LEVEL CHANGE  
IN THE NEW ZEALAND ARCHIPELAGO  
AND THE GEOMORPHIC EVOLUTION OF  
A HOLOCENE COASTAL PLAIN  
INCISED-VALLEY SYSTEM:  
THE LOWER MANAWATU VALLEY,  
NORTH ISLAND, NEW ZEALAND

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy in Geography

at Massey University, Palmerston North, New Zealand.



**MASSEY UNIVERSITY**

Alastair John Hopton Clement

2011

Copyright © 2011 Alastair J.H. Clement.

Typeset with L<sup>A</sup>T<sub>E</sub>X

Supervisor:

Dr. Ian C. Fuller

Co-Supervisor:

Dr. Craig R. Sloss

Internal Examiner:

Dr. Alan Palmer

New Zealand Examiner:

Assoc. Prof. Paul S. Kench (University of Auckland)

Overseas Examiner:

Assoc. Prof. Brian G. Jones (University of Wollongong)

# Abstract

The full body of work relating to Holocene sea-level histories in the New Zealand region has been integrated and critically analysed to provide context for the construction of detailed, local-scale Holocene sea-level curves for regions within the New Zealand archipelago. These local-scale sea-level reconstructions in turn provide context for an investigation of the stratigraphic and geomorphic evolution of the Manawatu coastal plain incised-valley system during the Holocene.

The state of knowledge of sea-level fluctuations in the New Zealand region during the Holocene is revealed to be poor. Holocene sea-level histories are fragmented and unreliable, with sea-level reconstructions produced for the whole of the New Zealand masking local-scale trends in Holocene sea-level fluctuations.

Local-scale Holocene sea-level curves produced for regions within the New Zealand archipelago show a north-south trend in sea-level fluctuations. In the Auckland-Northland region present mean sea-level (PMSL) was attained c. 7,700 cal. yr BP. Approximately 7,500 cal. yr BP PMSL was attained in the southwest North Island. PMSL was attained in Pegasus Bay c. 7,100–6,600 cal. yr BP, and in East Otago c. 6,900 cal. yr BP. It is also possible to discern a north-south lag in the timing of sea-level fluctuations following the attainment of PMSL between the southwest coast of the North Island and the East Otago peninsula. The degree to which the north-south lag in the timing of the attainment of PMSL is a manifest response to external driving forces is not yet clear as the local-scale sea-level histories are highly variable, quite contradictory, and appear to be responding inconsistently to different external drivers.

Vibracores and water well logs have been used to reconstruct the sedimentary infill of the lower Manawatu River valley, North Island, New Zealand, in response to Holocene sea-level change and the influx of sediment from the bordering axial ranges. Cross-sections across the incised-valley system have identified: the lowstand incision of the Manawatu River c. 22–18 ka, and associated fluvial terraces buried at depth beneath the Holocene valley fill; the extent of the Holocene estuary which occupied the lower valley at the culmination of the Holocene marine transgression (c. 7,500 cal. yr BP); the sedimentary succession which filled the valley associated with the Holocene sea-level highstand; and late Holocene to recent coastal progradation of 5–6 km. A 3D model of

the sub-surface stratigraphy of the lower valley was constructed from the borehole data and cross sections. Digital elevation models were also constructed for key palaeo-surfaces within the valley's Holocene sedimentary fill. Holocene sea-level fluctuations in the valley were reconstructed from radiocarbon dated estuarine bivalves recovered from vibracores. These radiocarbon dates also record subsidence of the valley due to a combination of sediment compaction, post-glacial water and sediment loading, the evolution of the Wanganui Basin, and neotectonics. Information from all sources was collated and used for the construction of palaeogeographic maps and a series of conceptual models of the evolution of the lower valley.

# Acknowledgements

Many people contributed their expertise and gave support in many varied ways throughout my PhD research.

First and foremost I wish to thank my supervisors, Dr. Ian Fuller and Dr. Craig Sloss: hands-on supervisors who gave freely of their time, knowledge, advice, and keen and critical insight. Both are excellent mentors who provided encouragement, guidance, and support throughout the course of my research.

A great deal of this research hinged on successful fieldwork. In this respect I am extremely grateful to David Feek, whose constant optimism and innovation often meant the difference between success and failure in the field. Thanks also to those who lent a hand, always somewhere wet and often cold: John Appleby; Rob Dykes; Jane Richardson; and Gigi Woods.

Many people freely provided data, both published and unpublished, and information borne of their own expertise, which is gratefully acknowledged: Scott Nichol (GA), unpublished measurements of cores on Great Barrier Island; Christine Prior (GNS), advice about radiocarbon age determinations; Patrick Hesp (LSU), advice on Manawatu geomorphology and dune sequences; Andrew Steffert (Horizons), airborne LiDAR data and orthophotos of the Manawatu; Louise Chick (Waikato), unpublished data on tectonic movements of the Kerepehi Fault; John Ogden (Auckland), unpublished aspects of cores from Whangapaoa Estuary; Martin Hewitt and Mark Peters (Geosystems), advice on NZGeoid05 and grid files for TGO; Will Newell (Geosystems), advice on Trimble R8 use and NMEA message output; John Oldman (NIWA), advice on cores from Mahurangi Estuary; John Dymond (Landcare), subset of the ECOSAT DEM covering the Manawatu; Hisham Zarour (Horizons), bore logs from throughout the Manawatu; John Begg (GNS), data and advice for extrapolating the extent of Manawatu river terraces under the modern floodplain; Alan Hogg (Waikato Radiocarbon Laboratory), advice regarding conventional radiocarbon ages; Fiona Petchley (Waikato Radiocarbon Laboratory), advice on and a keen eye for fossil mollusc species; Dougal Townsend (GNS), preliminary data from unpublished QMAPs; and Clinton Duffy (DoC), unpublished bathymetric data for the Hauraki Gulf.

Thank-you to the many friendly farmers I met through the course of my research who gave valuable local advice and context and allowed access to and across their land: Mark Anderson; Wayne Moxham; Rachel Taylor; Denise Fraser; Des and Lyn Legg; KD Craw; Mark Craw; Bevan Claridge; Salvie;



the Malettas; Adrian Swinbank; Stuart McPhail; Justin and Sally MacLean; Colin Ryder; Ian Barnes; Chris Whittfield; Julian Marshall; Brendan; Chris Preston; Ian Eastern; Malcom Wood; and Kristian Funnell.

I am thankful to have received generous financial support in the form of: a Massey University Vice-Chancellor's Doctoral Scholarship, succeeded by a Top Achievers' Doctoral Scholarship; an IAG Travel Grant to attend the 7th International Conference on Geomorphology (ANZIAG) in Melbourne, 6–11 July 2009; an INQUA 1001 Travel Grant to attend the first joint international conference of IGCP Project 588 and the INQUA Coastal and Marine Processes Commission in Hong Kong, 30 November to 4 December 2010; the Geological Society of New Zealand Wellman Research Award 2008; as well as research grants from the School of People, Environment and Planning's Graduate Research Fund.

Last, but by no means least, I wish to thank my family who have provided constant, immeasurable support throughout the duration of my PhD research.

AJHC.

# Contents

<b>List of Figures</b>	<b>xiii</b>
<b>List of Tables</b>	<b>xix</b>
<b>List of Sheets</b>	<b>xxi</b>
<b>Common abbreviations</b>	<b>xxiii</b>
<b>A note about ages presented in this thesis</b>	<b>xxv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Thesis aims . . . . .	2
1.2 Thesis organisation . . . . .	3
<b>2 Reconstructing Holocene sea-level changes in the New Zealand archipelago: review</b>	<b>5</b>
2.1 Introduction . . . . .	5
2.2 Early investigations of strandlines as evidence of palaeo sea levels	6
2.3 Altimetric correlations with European chronologies . . . . .	7
2.4 Single radiocarbon dates to inform observations of palaeo sea levels in the New Zealand region . . . . .	12
2.5 Radiocarbon dating to establish sea-level chronologies in New Zealand . . . . .	15
2.6 Time-depth curves of palaeo sea-level fluctuations in New Zealand	17
2.7 Modelling and mathematical analyses of Holocene sea-level fluctuations in the New Zealand region . . . . .	20
2.8 Offshore investigations of palaeo sea-level fluctuations in the New Zealand archipelago . . . . .	22
2.9 The de facto standard Holocene sea-level curve for New Zealand	27
2.10 Post-Gibb sea-level histories . . . . .	30
2.11 Conclusions . . . . .	34
<b>3 Local-scale reconstructions of Holocene sea-level change in the New Zealand archipelago</b>	<b>37</b>
3.1 Introduction . . . . .	37
3.2 Local-scale sea-level curve construction methodology . . . . .	38

## Contents

3.2.1	Selection of palaeo sea-level indicators . . . . .	38
3.2.2	Treatment of radiocarbon ages . . . . .	38
3.2.3	Sources of vertical error . . . . .	43
3.2.4	Palaeo sea-level indicators . . . . .	44
3.2.4.1	Formation datums . . . . .	44
3.2.4.2	Maximum and minimum indicators . . . . .	44
3.2.4.3	Ecological ranges of fossil shell species . . . . .	44
3.2.5	Delineation of regions . . . . .	51
3.2.6	Tectonic regimes of the regions . . . . .	51
3.2.6.1	Auckland-Northland . . . . .	51
3.2.6.2	Coromandel Peninsula and the Firth of Thames	55
3.2.6.3	South/southwest North Island . . . . .	55
3.2.6.4	Christchurch and Pegasus Bay . . . . .	57
3.2.6.5	East Otago Peninsula . . . . .	57
3.3	Local-scale Holocene sea-level curves for the New Zealand archipelago: results and discussion . . . . .	58
3.3.1	Auckland-Northland Holocene sea-level interpretation and analysis . . . . .	58
3.3.2	Coromandel-Firth of Thames Holocene sea-level interpretation and analysis . . . . .	61
3.3.3	South/southwest North Island Holocene sea-level interpretation and analysis . . . . .	61
3.3.4	Christchurch and Pegasus Bay Holocene sea-level interpretation and analysis . . . . .	64
3.3.5	East Otago Holocene sea-level curve interpretation and analysis . . . . .	65
3.3.6	Comparison between the local-scale sea-level reconstructions and observations of Holocene sea levels in the New Zealand region . . . . .	68
3.3.7	Sea-level fluctuations in the New Zealand region: South-west Pacific context . . . . .	70
3.4	Synthesis and conclusions . . . . .	71
<b>4</b>	<b>Geology and geomorphology of the lower Manawatu valley</b>	<b>77</b>
4.1	Introduction . . . . .	77
4.2	Geology . . . . .	77
4.2.1	Geological setting . . . . .	77
4.2.2	Torlesse basement . . . . .	79
4.2.3	Axial ranges . . . . .	79
4.2.4	Wanganui Basin . . . . .	81
4.2.5	Fault structures . . . . .	84
4.2.6	Poroutawhao High . . . . .	86
4.3	Geomorphology . . . . .	87
4.3.1	Tokomaru Marine Terrace . . . . .	87
4.3.2	Manawatu River and tributaries . . . . .	91

## Contents

4.3.3	Manawatu River fluvial terraces . . . . .	92
4.3.3.1	Forest Hill Terrace – MIS 4 . . . . .	92
4.3.3.2	Milson Terrace – MIS 3 . . . . .	94
4.3.3.3	Ashhurst Terrace – MIS 2 . . . . .	96
4.3.3.4	Holocene fluvial terraces . . . . .	96
4.3.3.5	Fluvial terrace structure and loess coverbeds . . . . .	96
4.3.4	Manawatu floodplain . . . . .	98
4.3.5	Coastal dune fields . . . . .	99
4.3.5.1	Last Glacial Maximum-age dunes . . . . .	99
4.3.5.2	Holocene-age dunes . . . . .	102
4.3.6	Holocene evolution of the Manawatu River estuary . . . . .	106
4.3.7	Holocene progradation of the Manawatu coastline . . . . .	107
4.4	Regional tectonism . . . . .	107
4.5	Climate . . . . .	108
4.6	Contemporary coastal processes . . . . .	110
4.7	Vegetation: past and present . . . . .	110
4.7.1	Palaeovegetation . . . . .	110
4.7.2	Present vegetation . . . . .	111
4.8	Summary . . . . .	111
<b>5</b>	<b>Models of estuary and incised-valley evolution</b>	<b>113</b>
5.1	Introduction . . . . .	113
5.2	Background to facies and facies models, and their application to estuaries and incised-valleys . . . . .	113
5.3	Background to estuarine facies models . . . . .	115
5.4	Wave- and tide-dominated estuarine facies models . . . . .	119
5.5	Conceptual facies model for wave-dominated estuaries . . . . .	120
5.5.1	Zone 1: Marine-influenced sedimentary facies . . . . .	122
5.5.2	Zone 2: Central basin mud facies . . . . .	122
5.5.3	Zone 3: River-dominated sedimentary facies . . . . .	123
5.6	Criticisms of the conceptual estuarine facies models . . . . .	123
5.7	Wave-dominated Holocene embayments on the southeast coast of Australia: conceptual models . . . . .	124
5.7.1	Wave-dominated barrier estuaries . . . . .	124
5.7.2	Open-ocean embayments . . . . .	124
5.7.3	Drowned-river estuaries . . . . .	125
5.7.4	The position of the Manawatu valley within the context of wave-dominated estuary models from the southeast coast of Australia . . . . .	126
5.8	Background to sequence stratigraphy and incised-valley facies models . . . . .	127
5.9	Model for a simple incised-valley fill . . . . .	129
5.9.1	Straigraphic organisation . . . . .	129
5.9.2	Stratigraphic surfaces . . . . .	131

## Contents

5.10	Estuarine and incised-valley facies models: New Zealand context . . . . .	132
5.11	Summary . . . . .	133
<b>6</b>	<b>Holocene sedimentary infill of the lower Manawatu incised-valley system reconstructed from water well logs</b>	<b>135</b>
6.1	Introduction . . . . .	135
6.2	Previous investigations of the sub-surface geology of the Manawatu Region . . . . .	136
6.3	Cross-section construction methodology . . . . .	140
6.4	Limiting factors and sources of error . . . . .	145
6.4.1	Positions and elevations . . . . .	145
6.4.2	Well log interpretations . . . . .	149
6.4.3	Mismatches between surface geology and DEM topography	149
6.5	Geologic cross-sections in the Manawatu valley: results and discussion . . . . .	150
6.5.1	Introduction . . . . .	150
6.5.2	Upper Manawatu floodplain: Whakarongo through Palmerston North City to Opiki . . . . .	152
6.5.2.1	Sheet 1: Well logs cross-section 1 . . . . .	152
6.5.2.2	Sheet 2: Well logs cross-section 2 . . . . .	155
6.5.2.3	Sheet 3: Well logs cross-section 3 . . . . .	158
6.5.2.4	Sheet 4: Well logs cross-section 4 . . . . .	158
6.5.3	Oroua Floodplain: Feilding and Bunnythorpe to Kairanga and Opiki . . . . .	160
6.5.3.1	Sheet 5: Well logs cross-section 5 . . . . .	160
6.5.3.2	Sheet 6: Well logs cross-section 6 . . . . .	160
6.5.3.3	Sheet 7: Well logs cross-section 7 . . . . .	161
6.5.3.4	Sheet 8: Well logs cross-section 8 . . . . .	161
6.5.4	Manawatu-Oroua floodplain: Linton west to Rangiotu . . . . .	162
6.5.4.1	Sheet 9: Well logs cross-section 9 (eastern half)	162
6.5.5	Central Manawatu floodplain: Opiki to Shannon, Moutoa, and Marotiri . . . . .	162
6.5.5.1	Sheet 10: Well logs cross-section 10 . . . . .	162
6.5.5.2	Sheet 11: Well logs cross-section 11 . . . . .	164
6.5.5.3	Sheet 12: Well logs cross-section 12 . . . . .	164
6.5.5.4	Sheet 13: Well logs cross-section 13 . . . . .	165
6.5.5.5	Sheet 14: Well logs cross-section 14 . . . . .	165
6.5.6	Lower Manawatu floodplain: Moutoa and Marotiri through Foxton and Whirokino to Foxton Beach . . . . .	166
6.5.6.1	Sheet 15: Well logs cross-section 15 . . . . .	166
6.5.6.2	Sheet 16: Well logs cross-section 16 . . . . .	167
6.5.6.3	Sheet 17: Well logs cross-section 17 . . . . .	167
6.5.6.4	Sheet 18: Well logs cross-section 18 . . . . .	168
6.5.6.5	Sheet 19: Well logs cross-section 19 . . . . .	168

## Contents

6.5.7	Lower Manawatu (south): Porotowhao and Koputaroa . . . . .	169
6.5.7.1	Sheet 20: Well logs cross-section 20 . . . . .	169
6.5.8	Coastal Manawatu: Himitangi . . . . .	169
6.5.8.1	Sheet 9: Well logs cross-section 9 (western half) . . . . .	169
6.6	Digital elevation models of key surfaces within the sedimentary fill of the lower Manawatu valley . . . . .	170
6.6.1	Last Glacial Maximum fluvial aggradation surface . . . . .	170
6.6.1.1	Ashhurst/Ohakea LGM aggradation surface DEM construction . . . . .	170
6.6.1.2	Ashhurst/Ohakea LGM aggradation surface DEM results . . . . .	174
6.6.2	Digital elevation model of the estuarine-alluvial interface . . . . .	176
6.6.2.1	Estuarine-alluvial interface DEM construction . . . . .	176
6.6.2.2	Estuarine-alluvial DEM results . . . . .	180
6.6.3	Holocene sedimentary infill volume estimation . . . . .	184
6.6.4	Digital elevation models and volume estimates of incised-valley infilling: discussion . . . . .	184
6.7	Summary . . . . .	186
<b>7</b>	<b>Holocene sedimentary stratigraphy and facies assemblages of the lower Manawatu valley reconstructed from detailed vibracores</b> . . . . .	<b>187</b>
7.1	Introduction . . . . .	187
7.2	Vibracore collection and analysis . . . . .	188
7.2.1	Vibracores . . . . .	188
7.2.2	GPS surveys . . . . .	192
7.2.3	Sediment analysis . . . . .	193
7.2.4	Radiocarbon ages . . . . .	194
7.2.5	Cross-section construction . . . . .	194
7.3	Lithofacies and interpretation . . . . .	198
7.3.1	Marine transgressive sands (MTS) . . . . .	198
7.3.2	Highstand estuarine silts and sands (ESS) . . . . .	201
7.3.3	Fluvial bay-head delta silts and sands (FBD) . . . . .	201
7.3.4	Floodplain alluvium (FA) and fluvial swampy silts (FSS) . . . . .	202
7.4	Vibracores cross-sections in the Manawatu valley: results and discussion . . . . .	203
7.4.1	Sheet 24: Vibracores cross-section 1 . . . . .	203
7.4.2	Sheet 25: Vibracores cross-section 2 . . . . .	222
7.4.3	Sheet 26: Vibracores cross-section 3 . . . . .	222
7.4.4	Sheet 27: Vibracores cross-section 4 . . . . .	222
7.4.5	Sheet 28: Vibracores cross-section 5 . . . . .	223
7.4.6	Sheet 29: Vibracores cross-section 6 . . . . .	223
7.4.7	Sheet 30: Vibracores cross-section 7 . . . . .	224
7.4.8	Sheet 31: Vibracores cross-section 8 . . . . .	224
7.5	Summary . . . . .	225

<b>8</b>	<b>Discussion and synthesis</b>	<b>227</b>
8.1	Introduction . . . . .	227
8.2	Holocene sea-level change on the Manawatu coast . . . . .	227
8.2.1	Holocene sea-level fluctuations in the New Zealand archipelago . . . . .	227
8.2.2	Holocene sea-level changes on the south/southwest coast of the North Island . . . . .	228
8.2.3	Indicators of Holocene sea-level change from the lower Manawatu valley . . . . .	228
8.3	Subsidence in the lower Manawatu valley . . . . .	229
8.3.1	Sediment compaction . . . . .	230
8.3.2	Post-glacial water and sediment loading . . . . .	232
8.3.3	Evolution of the Wanganui Basin . . . . .	233
8.3.4	Influence of the Kairanga Trough . . . . .	233
8.3.5	Influence of neotectonics . . . . .	236
8.3.6	Subsidence in the Manawatu valley: conclusions . . . . .	236
8.4	Comparisons of lower Manawatu valley stratigraphy to tripartite facies models of estuary and incised-valley infilling . . . . .	238
8.4.1	Tripartite facies models of estuary and incised-valley infilling . . . . .	238
8.4.2	Comparisons of lower Manawatu valley stratigraphy with established models of incised-valley evolution . . . . .	239
8.5	Last Glacial Maximum and Holocene palaeogeomorphology of the lower Manawatu valley . . . . .	241
8.5.1	Path of the Manawatu River 18,000–15,000 years BP . . . . .	241
8.5.2	Role of the Poroutawhao High and the Himitungi Anticline at the height of the Holocene marine transgression . . . . .	242
8.5.3	Extent of the Manawatu estuary at the height of the Holocene marine transgression . . . . .	243
8.5.4	Manawatu coastline at the height of the Holocene marine transgression . . . . .	243
8.5.5	Infilling of the Manawatu estuary 8,000 cal. yr BP to present . . . . .	244
8.5.6	Sedimentation rates in the lower Manawatu valley following the culmination of the Holocene marine transgression . . . . .	248
8.6	Palaeogeographic maps and conceptual models of the Holocene evolution of the lower Manawatu incised-valley system . . . . .	248
8.6.1	18,000–9,000 years BP . . . . .	248
8.6.2	9,000–6,800 cal. yr BP . . . . .	250
8.6.3	5,700 cal. yr BP . . . . .	256
8.6.4	4,700 cal. yr BP . . . . .	256
8.6.5	4,700 cal. yr BP to Present . . . . .	256
8.7	LGM to Holocene facies evolution of the Manawatu Valley . . . . .	261
8.7.1	Lowstand incised-valley system . . . . .	261

## Contents

8.7.2	Holocene marine transgression . . . . .	261
8.7.3	Holocene sea-level highstand . . . . .	264
8.7.4	Barrier development and coastal progradation . . . . .	264
<b>9</b>	<b>Conclusions</b>	<b>267</b>
9.1	Findings of this research . . . . .	267
9.1.1	State of knowledge of Holocene sea-level fluctuations in the New Zealand region . . . . .	267
9.1.2	Local-scale reconstructions of Holocene sea-level changes for regions within the New Zealand archipelago . . . . .	268
9.1.3	Water well log reconstructions of the Holocene sedimentary fill of the lower Manawatu valley . . . . .	269
9.1.4	Stratigraphy and facies assemblages reconstructed from detailed vibracores . . . . .	269
9.1.5	Subsidence in the Lower Manawatu valley . . . . .	270
9.1.6	Comparisons of lower Manawatu valley stratigraphy to tripartite facies models of incised-valley infill . . . . .	270
9.1.7	LGM and Holocene palaeogeomorphology of the lower Manawatu valley . . . . .	271
9.2	Future research . . . . .	272
	<b>References</b>	<b>273</b>
<b>A</b>	<b>Contents of the DVD</b>	<b>325</b>
<b>B</b>	<b>Vibracore lithological logs</b>	<b>327</b>
<b>C</b>	<b>Sediment analysis results</b>	<b>433</b>
<b>D</b>	<b>Radiocarbon results</b>	<b>445</b>
<b>E</b>	<b>Other detailed bores from the lower Manawatu valley</b>	<b>459</b>



## Contents

# List of Figures

2.1	Conceptual diagram illustrating the provenance of several recent papers which present and/or make use of palaeo sea-level curves from the New Zealand region . . . . .	6
2.2	Map of the North Island, New Zealand, showing locations utilised by studies of New Zealand palaeo sea-level fluctuations . .	8
2.3	Map of the South Island, New Zealand, showing locations utilised by studies of New Zealand palaeo sea-level fluctuations . .	9
2.4	Quaternary sea-level movements in the New Zealand region (after Brothers, 1954) . . . . .	10
2.5	Summary of Holocene sea-level curves produced for the New Zealand region between 1958–1981, covering the period 20,000 years BP to present . . . . .	16
2.6	Summary of Holocene sea-level curves produced for the New Zealand region between 1958–1981, covering the period 10,000 years BP to present . . . . .	18
2.7	Summary of Holocene sea-level curves produced for the New Zealand region between 1979–2010, covering the period 20,000 years BP to present . . . . .	25
2.8	Summary of Holocene sea-level curves produced for the New Zealand region between 1979–2010, covering the period 10,000 years BP to present . . . . .	26
2.9	Holocene sea-level history for the New Zealand region presented by Clement et al. (2008a,b, 2010) . . . . .	33
3.1	Locations of sites throughout the New Zealand region from which indicators of Holocene palaeo sea levels were recovered .	45
3.2	Locations of sites throughout the northern North Island, New Zealand, from which indicators of Holocene palaeo sea levels were recovered . . . . .	46
3.3	Other locations mentioned in connection with the construction or analysis of the local-scale Holocene sea-level curves for the New Zealand archipelago . . . . .	54
3.4	Local-scale Holocene sea-level curve for the Auckland-Northland region, New Zealand . . . . .	59

List of Figures

3.5	Local-scale Holocene sea-level curve for the Auckland-Northland region, New Zealand, plotted with an expanded vertical axis . . . . .	60
3.6	Local-scale Holocene sea-level history for the Coromandel-Firth of Thames region, New Zealand . . . . .	62
3.7	Local-scale Holocene sea-level curve for the south/southwest North Island, New Zealand . . . . .	63
3.8	Local-scale Holocene sea-level curve for the Christchurch-Pegasus Bay area, New Zealand . . . . .	65
3.9	Local-scale Holocene sea-level curve for the East Otago Peninsula, New Zealand . . . . .	66
3.10	Local-scale Holocene sea-level curve for the East Otago Peninsula, New Zealand, plotted with an expanded vertical axis . . .	67
3.11	Map of the New Zealand region illustrating the north-south lag in the timing of the attainment of PMSL . . . . .	72
3.12	Map of the New Zealand region illustrating the position of sea levels at the 7,700 cal. yr BP time-slice . . . . .	73
3.13	Comparison of Holocene sea-level fluctuations on the south/southwest coast of the North Island, and around the East Otago Peninsula, illustrating the 500–1,000 year north-south lag between the two areas . . . . .	75
4.1	Locality map of the Manawatu region, southwest North Island, New Zealand. . . . .	77
4.2	Tectonic setting of the southern North Island, New Zealand . .	80
4.3	Schematic cross-section across the interface between the Pacific and Australian tectonic plates . . . . .	81
4.4	1:250,000 scale geological map of the Manawatu region . . . . .	82
4.5	Fold axes of the Manawatu anticlines . . . . .	85
4.6	Geologic cross-section across the Horowhenua coastal plain (after Aharoni, 1991) . . . . .	87
4.7	Correlation between climate, oxygen isotope stages, and landform development in the Manawatu region . . . . .	89
4.8	Conceptual model of inferred palaeoenvironmental changes in the Manawatu-Horowhenua region that formed the Tokomaru Marine Terrace (after Sewell, 1991). . . . .	92
4.9	Conceptual model of inferred palaeoenvironmental changes in the Manawatu-Horowhenua region between MIS 6–2 (after Hughes, 2005a,b). . . . .	94
4.10	1:75,000 scale maps of the river terraces between the Manawatu Gorge and Palmerston North City, as presented by Fair (1968), Lieffering (1990), and Lee and Begg (2002). See Figure 4.4 for regional context. . . . .	96

List of Figures

4.11	Generalised stratigraphic columns illustrating the typical arrangement of loess and tephra coverbeds on fluvial terraces in the lower Manawatu valley . . . . .	98
4.12	Late Quaternary sea-level changes in the southwest Pacific region . . . . .	101
4.13	Context map showing the locations of the Whanganui, Whangaeahu, Rangitikei, and Manawatu Rivers . . . . .	104
4.14	Estimates of the extent of the Manawatu River estuary at the culmination of the Holocene marine transgression . . . . .	108
5.1	Classification of estuaries (after Reinson, 1992) . . . . .	116
5.2	Shoreline response (transgression versus regression) to changes in sea-level and sediment supply (after Boyd et al., 1992, 2006) . . . . .	118
5.3	Classification of major clastic coastal depositional environments (after Boyd et al., 1992, 2006) . . . . .	118
5.4	Schematic illustrating the definitions of estuary, the physical processes operating in estuaries, and the resulting tripartite facies zonation (after Dalrymple et al., 1992) . . . . .	119
5.5	Evolutionary classification of coastal environments (after Dalrymple et al., 1992) . . . . .	120
5.6	Distribution of energy types, morphological components, and sedimentary facies within an idealised wave-dominated estuary (after Dalrymple et al., 1992) . . . . .	121
5.7	Classification of wave-dominated estuaries on the southeast coast of Australia (after Roy et al., 1980) . . . . .	125
5.8	Conceptual model of the sedimentary infilling of a drowned-river estuary (after Roy et al, 1980; Chapman et al., 1982; Roy, 1984a,b, 1994) . . . . .	126
5.9	Idealised longitudinal section of a simple incised-valley system (after Zaitlin et al., 1994) . . . . .	130
6.1	Locations of cross-sections and wells used for investigations of the sub-surface geology of the Manawatu region . . . . .	136
6.2	Cross-section through the Holocene marine wedge south of Tangimoana (after Shepherd et al., 1986) . . . . .	140
6.3	Well log correlation across part of the Tokomaru Marine Terrace (after Sewell, 1991) . . . . .	142
6.4	Cross-section running northeast-southwest (line A-A') across the Horowhenua coastal plain (after Hughes 2005a, b) . . . . .	142
6.5	Cross-section running southeast-northwest (line B-B') across the Horowhenua coastal plain (after Hughes 2005a, b) . . . . .	142
6.6	Structural contours for the Ashhurst/Ohakea fluvial aggradation terrace extrapolated beneath the Holocene floodplain (after Begg et al., 2005) . . . . .	145

List of Figures

6.7	Structural contours for the Milson/Rata fluvial aggradation terrace extrapolated beneath the Holocene floodplain (after Begg et al., 2005) . . . . .	145
6.8	Structural contours for the Tokomaru Marine Terrace extrapolated beneath the Holocene floodplain (after Begg et al., 2005)	145
6.9	Locations of geologic cross-sections constructed from well logs in the Manawatu valley . . . . .	150
6.10	Conceptual 3D model of the twenty geologic cross-sections constructed from well logs in the lower Manawatu valley looking southeast across the coastal plain . . . . .	152
6.11	Conceptual 3D model of the twenty geologic cross-sections constructed from well logs in the lower Manawatu valley looking north-northwest across the coastal plain . . . . .	152
6.12	Conceptual 3D model of the geologic cross-sections constructed from well logs looking east across the upper Manawatu floodplain . . . . .	155
6.13	Conceptual 3D model of the geologic cross-sections constructed from well logs looking south across the lower Manawatu floodplain . . . . .	155
6.14	Key to well logs cross-sections symbols and lithological units (Sheets 1–23) . . . . .	159
6.15	Stratigraphic sections from Griffin’s and Barber’s Farms, lower Manawatu valley (after Shepherd and Lees, 1987) . . . . .	163
6.16	Locations of well logs containing gravel units identified as Ashhurst/Ohakea LGM aggradation gravel . . . . .	171
6.17	Digital elevation model of the Ashhurst/Ohakea LGM aggradation surface reconstructed from gravel units identified in water well logs throughout the lower Manawatu valley . . . . .	171
6.18	Example of channel artifacts produced by the Topo to Raster algorithm . . . . .	175
6.19	Digital elevation model of the Ashhurst/Ohakea LGM aggradation surface reconstructed from gravel units identified in water well logs throughout the lower Manawatu valley, adjusted to remove sinks . . . . .	176
6.20	Comparison of the reconstructed digital elevation model of the Ashhurst/Ohakea LGM aggradation surface with the structural contours of the Ashhurst/Ohakea surface extrapolated by Begg et al. (2005) . . . . .	176
6.21	Comparison of the reconstructed digital elevation model of the Ashhurst/Ohakea LGM aggradation surface (adjusted to remove sinks) with the structural contours of the Ashhurst/Ohakea surface extrapolated by Begg et al. (2005) . . . . .	176
6.22	Locations of well logs and vibracores containing sedimentary units identified as the top of the Holocene marine/estuarine fill in the lower Manawatu valley . . . . .	180

List of Figures

6.23	Digital elevation model of the estuarine-alluvial interface reconstructed from sedimentary units identified in water well logs and vibracores throughout the lower Manawatu valley . . . . .	180
7.1	Locations of vibracores recovered from the lower Manawatu valley . . . . .	188
7.2	Vibracoring at site Flood-8 . . . . .	190
7.3	Vibracoring at site LD-5 . . . . .	191
7.4	Logging the side of the drain at site LD-5 . . . . .	191
7.5	Tripod set up to extract vibracore Ran-2 . . . . .	192
7.6	Conceptual diagram illustrating the relationship between ellipsoidal and orthometric heights . . . . .	193
7.7	Locations of vibracore cross-sections in the lower Manawatu valley . . . . .	198
7.8	Representative sections of each of the five major facies identified in vibracores from the lower Manawatu valley . . . . .	202
7.9	Stratigraphic log of drain section and vibracore F . . . . .	203
7.10	Stratigraphic log of drain section and vibracore Kop-1 . . . . .	203
7.11	Stratigraphic log of drain section and vibracore Sh-1 . . . . .	203
7.12	Stratigraphic log of drain section and vibracore Flood-1 . . . . .	203
7.13	Stratigraphic log of drain section and vibracore Sh-2 . . . . .	203
7.14	Stratigraphic log of drain section and vibracore Cut-7 . . . . .	203
7.15	Stratigraphic log of drain section and vibracore Cut-4 . . . . .	203
7.16	Stratigraphic log of drain section and vibracore E-1 . . . . .	203
7.17	Stratigraphic log of drain section and vibracore Cut-2 . . . . .	203
8.1	Conceptual diagram of the structure of the discussion chapter in relation to previous chapters . . . . .	228
8.2	Holocene sea-level curve for the south/southwest coast of the North Island, New Zealand, with index points colour-coded to indicate location . . . . .	229
8.3	Graph illustrating the relationship between the elevations of sea-level index points recovered from the lower Manawatu valley and the distance up valley from the present-day coastline measured against the valley centerline . . . . .	230
8.4	Graph illustrating the relationship for each palaeo sea-level indicator recovered from the lower Manawatu valley between the depth to the LGM Ashhurst/Ohakea aggradation surface (below PMSL) at the location where the indicator was recovered, and the difference between the indicator's inferred palaeo sea-level and the sea-level inferred for the Manawatu region at that time . . . . .	232
8.5	Residual Bouguer anomaly map of the southern Wanganui Basin (after Rich, 1959) . . . . .	234

List of Figures

8.6	Relationship of the Kairanga Trough to the reconstructed Ashhurst/Ohakea DEM, illustrating the depression of the LGM surface coincident with the axis of the trough . . . . .	236
8.7	Positions of radiocarbon dated shell and wood samples recovered from the lower Manawatu valley . . . . .	244
8.8	Locations of palaeo shorelines in the lower Manawatu valley during and following the the Holocene marine transgression . .	244
8.9	Palaeogeographic map of the lower Manawatu valley during the Last Glacial Maximum, c. 18,000–15,000 years BP . . . . .	250
8.10	Conceptual model of the geomorphology of the lower Manawatu valley during the Last Glacial Maximum, c. 18,000–15,000 years BP . . . . .	250
8.11	Palaeogeographic map of the lower Manawatu valley, c. 7,100–6,800 cal. yr BP . . . . .	250
8.12	Conceptual model of the geomorphology of the lower Manawatu valley, c. 7,100 cal. yr BP . . . . .	250
8.13	Conceptual model of the geomorphology of the lower Manawatu valley, c. 6,800 cal. yr BP . . . . .	250
8.14	Palaeogeographic map of the lower Manawatu valley, c. 5,700 cal. yr BP . . . . .	256
8.15	Conceptual model of the geomorphology of the lower Manawatu valley, c. 5,700 cal. yr BP . . . . .	256
8.16	Palaeogeographic map of the lower Manawatu valley, c. 4,700 cal. yr BP . . . . .	256
8.17	Conceptual model of the geomorphology of the lower Manawatu valley, c. 4,700 cal. yr BP . . . . .	256
8.18	Conceptual summary sequence of the facies evolution of the lower Manawatu valley from the Last Glacial Maximum until present . . . . .	262

# List of Tables

2.1	Summary of radiocarbon ages presented by previous investigations of Holocene palaeo sea-level change in the New Zealand region . . . . .	13
3.1	Details of 215 palaeo sea-level indicators from locations throughout the New Zealand region. . . . .	39
3.2	Details of known-age marine samples used to calculate a New Zealand regional marine reservoir correction $\Delta R$ value for the calibration of CRAs from fossil shells and other marine materials in sidereal years (cal yr. BP) . . . . .	47
3.3	Summary of the formation datums and error ranges associated with each of the types of palaeo sea-level indicator used to reconstruct the local-scale sea-level histories in the New Zealand archipelago . . . . .	48
3.4	Tidal ranges for each of the sites throughout the New Zealand region from which palaeo sea-level indicators included in the study were recovered . . . . .	49
3.5	Summary of long-term and event tectonic deformation for localities and regions within the New Zealand archipelago from which indicators of Holocene palaeo sea levels were recovered . . . . .	52
4.1	Summary of radiocarbon ages obtained by previous investigations of geomorphological features of the Manawatu coastal plain . . . . .	100
5.1	Morphological and sedimentological summary of wave-dominated estuaries (after Nichol, 1991; Marra, 1997) . . . . .	122
6.1	Summary of radiocarbon ages obtained in connection with wells and bores drilled across the Manawatu coastal plain . . . . .	139
6.2	Volumes of sedimentary fill estimated using digital elevation models of the LGM aggradation surface and the estuarine alluvial interface in the lower Manawatu valley . . . . .	183
7.1	Vibracore location, elevation, compaction, and length details . . . . .	195
7.2	Vibracore GPS survey details . . . . .	196



List of Tables

7.3	Summary of radiocarbon ages obtained from samples of shell and wood recovered from vibracores and auger holes in the lower Manawatu valley . . . . .	197
7.4	Summary of the defining characteristics of the five facies identified in vibracores recovered from the lower Manawatu valley .	200
8.1	Details of the relationship between the elevations of sea-level index points recovered from the lower Manawatu valley and the distance up valley from the present-day coastline measured against the valley centerline . . . . .	231
8.2	Details of the relationship for each palaeo sea-level indicator recovered from the lower Manawatu valley between the depth to the LGM Ashhurst/Ohakea aggradation surface (below PMSL) at the location where the indicator was recovered, and the difference between the indicator's inferred palaeo sea-level and the sea-level inferred for the Manawatu region at that time . . . . .	234
8.3	Details of estuarine sedimentation rates calculated for vibracores recovered from the lower Manawatu valley . . . . .	249

# List of Sheets

- 1 Well logs cross-section 1
- 2 Well logs cross-section 2
- 3 Well logs cross-section 3
- 4 Well logs cross-section 4
- 5 Well logs cross-section 5
- 6 Well logs cross-section 6
- 7 Well logs cross-section 7
- 8 Well logs cross-section 8
- 9 Well logs cross-section 9
- 10 Well logs cross-section 10
- 11 Well logs cross-section 11
- 12 Well logs cross-section 12
- 13 Well logs cross-section 13
- 14 Well logs cross-section 14
- 15 Well logs cross-section 15
- 16 Well logs cross-section 16
- 17 Well logs cross-section 17
- 18 Well logs cross-section 18
- 19 Well logs cross-section 19
- 20 Well logs cross-section 20
  
- 21 Poroutawhao-Moutoa well logs
- 22 Himitangi-Oroua well logs
- 23 Rangiotu-Foxton well logs
  
- 24 Vibracores cross-section 1
- 25 Vibracores cross-section 2
- 26 Vibracores cross-section 3
- 27 Vibracores cross-section 4
- 28 Vibracores cross-section 5
- 29 Vibracores cross-section 6
- 30 Vibracores cross-section 7
- 31 Vibracores cross-section 8

List of sheets

- 32 Key to well logs cross-sections symbols and lithological units, and  
key to vibracore lithological logs

# Common abbreviations

**GPS** Global Positioning System

**LGM** Last Glacial Maximum

**MIS** Marine isotope stage

**MHT** Mean high tide

**MHWN** Mean high water neaps

**MHWS** Mean high water springs

**MLWN** Mean low water neaps

**MLWS** Mean low water springs

**MSL** Mean sea-level

**NZGD2000** New Zealand Geodetic Datum 2000

**NZMG** New Zealand Map Grid 1949

**NZVD09** New Zealand Vertical Datum 2009

**PMSL** Present mean sea-level

**RTK-dGPS** Real-time Kinematic differential Global Positioning System

**WVD53** Wellington Vertical Datum 1953

## Common abbreviations

# A note about ages presented in this thesis

Many of the radiocarbon ages presented by New Zealand researchers from the mid-1950s until the 1990s were not conventional radiocarbon ages (CRA) as defined by Stuiver and Polach (1977). These ages, determined at Rafter Radiocarbon Laboratory, were not determined with respect to the standards which define a CRA (C. Prior, personal communication). (All ages determined at the Waikato University Radiocarbon Laboratory are CRAs.) These “unconventional” ages are suffixed with “years BP”. Broad statements about the timing of events dated by unconventional ages, such as in the interpretation of sea-level curves constructed using unconventional ages, are similarly expressed in “years BP”. Conventional radiocarbon ages, where available, have been given and are suffixed “ $^{14}\text{C}$  years”. Where conventional radiocarbon ages have been calibrated to sidereal years, these dates are suffixed “cal. yr BP”. Large ages of the order of millions of years are suffixed “Ma”.

A note about ages presented in this thesis