PROTECTION OF AUTHOR'S COPYRIGHT

This copy has been supplied by the Library of the University of Otago on the understanding that the following conditions will be observed:

1. To comply with s56 of the Copyright Act 1994 [NZ], this thesis copy must only be used for the purposes of research or private study.

2. The author's permission must be obtained before any material in the thesis is reproduced, unless such reproduction falls within the fair dealing guidelines of the Copyright Act 1994. Due acknowledgement must be made to the author in any citation.

3. No further copies may be made without the permission of the Librarian of the University of Otago.
Uplifted Marine Terraces and some other aspects of Late Quaternary Geology in Northern Taranaki

Robert Oliver Duff

A thesis submitted as partial requirement for the degree of Master of Science at the University of Otago, Dunedin, New Zealand

(1993)
"You look at where you're going and where you are and it never makes sense, but then you look back at where you've been and a pattern seems to emerge. And if you project forward then sometimes you can come up with something."

- Robert M. Pirsig.

"Everyone knows the use of the useful but no-one knows the use of the useless."

- Chang Tzu.
Abstract

At least four Pleistocene uplifted marine terraces occur in the north Taranaki area. These are the NT1, NT2, NT3, and an older terrace formation (informally named 'Urenui upland terrace surface'). The NT1 Terrace, correlated with δ18O Substage 5a (c. 80ka B.P.), is restricted to the Turangi Road-Motunui coastal area. An average uplift rate of 0.29m.ka⁻¹ is inferred from the NT1 strandline altitude at Turangi Road. The NT2 Terrace, correlated with δ18O Substage 5e (c. 120ka B.P.), is the dominant terrace in north Taranaki occurring along the entire length of the field area (Motunui-Awakino River mouth). The NT2 Terrace is the sole terrace formation north of White Cliffs and is clearly delineated by a linearly concordant abandoned sea cliff. The average uplift rate for the last 120ka was inferred from the NT2 strandline altitude at several localities: At Tongaporutu river mouth 0.27m.ka⁻¹, 10km further north at Mohakatino an uplift rate of 0.20m.ka⁻¹ was found. About 3km north at Mokau River mouth uplift rates of c. 0.15m.ka⁻¹ and 0.17m.ka⁻¹ were respectively calculated for the north and south sides. A clear trend of constant tectonic uplift rates between Motunui and Tongaporutu and linearly decreasing uplift rates north of Tongaporutu toward the Awakino River was thus found. The NT3 Terrace, correlated with δ18O Substage 7a (c. 210ka B.P.), wedges out just north of Urenui (near Okoki Pa). The 'Urenui upland terrace surface' occurs above the NT3 Terrace in the Urenui-Onaero area and probably encompasses more than one terrace formation, but these were not differentiated. The completely dissected North Taranaki Surface (NTS) occurs inland of the marine terraces. The altitude of the envelope of ridge-crest concordance (c. 250m above MSL) is not representative of total tectonic uplift as it has been erosionally degraded by an unpredictable amount.

Non-marine terraces, sometimes looking remarkably like marine terraces are common throughout the north Taranaki landscape. Four criteria were used to distinguish them from non-marine terraces. (1) Absence of marine coverbeds. (2) Excessive shore-parallel and shore-normal tilt. (3) Lack of terrace-surface dissection compared with that expected of a marine terrace of similar altitude. (4) Parallelism of the coverbed/sedimentary rock contact with bedding in the North Taranaki Basin rocks. The non-marine terraces and related landforms result from the structural and lithological configuration of gently southwest dipping sandstones-mudstones of North Taranaki Basin sedimentary rocks. Two models providing a mechanism of topographic exploitation are presented. One involves groundwater sapping, the other, earthquake induced planar sliding. The latter is favoured.

A 2-4 m rhyolitic deposit occurs in the Mokau area above the NT2 Terrace. The informally named Mokau rhyolitic deposit consists of highly weathered, devitrified matrix crystal-rich in sodic-andesine plagioclase (high temperature form) and B-quartz. A common highly weathered vermicular-form phyllosilicate was identified as original biotite. Thickness and bedding characteristics infer a distal ignimbrite style emplacement. Age is estimated to be at least 0.5Ma. The Mokau rhyolitic deposit is tentatively correlated with either early Whakamaru Group ignimbrite/s or the Rocky Hill Ignimbrite.

A Holocene notch feature associated with holes much like those seen formed in the modern intertidal zone by an isopod crustacean S. quoyanum was studied at Aria Beach, Mokau. It was concluded that the notch was a 'structural notch' and hence not directly related to paleo-sealevel. The holes are not considered to be of intertidal origin, but their genesis remains ambiguous.

A multifractal analysis of topography based on the model of Chase (1992) was proposed but not applied to real data.
Acknowledgements

I would sincerely like to thank the following 'participants' who have contributed in varying ways during the course of this thesis.

Associate Professor C. A. Landis, my supervisor. Thankyou Chuck.

Associate Professor J. D. Campbell, who even though he is officially retired was more than happy to offer his comments on my work and to show general interest in my progress. Thankyou Doug.

Another member of the academic staff who I also would like to personally thank is Dr Peter Koons.

Dr Brad Pillans for the initial inspiration to study marine terraces, and Dr Brent Alloway for helpful information regarding his work in the north Taranaki area.

Surveyors who trustfully lent me their valuable survey equipment are gratefully acknowledged. Thanks go to Alan Blaikie and Neil Sutherland of the Surveying Dept for the amazing 'total station', and also to Bland & Howarth Ltd. of New Plymouth for freely lending me a theodolite.

All the staff of the Geology department, and also to Mark Gould of the Medical School for his cheerful help on the SEM.

Andrew Winter of New Plymouth for flying me up the north Taranaki coast in a Cessna and providing fine perspectives on the landscape which proved invaluable to the thesis.

To all the other post-grad students for putting up with "Big Bad Bob", cheers and good luck!

The landowners who gave me permission to walk over their land, especially the Warrens of "Lazy Acres" (Mokau), and the unnamed farmer who gave me a memorable landrover ride into the Urenui heartland.

Thankyou to my field assistants who included my Mother, my brother Alastair, and my friends Tim Farrier and Dave Pentecost.

Finally thanks to all my friends in and out of Dunedin for being an essential part of my 'other life'. I would especially like to acknowledge Peter Clayworth and Andy Holdaway for their friendship throughout the period of my thesis.

This thesis is dedicated to my parents, Gowan and Jean, with love, for allowing me the Freedom to find out for myself.
# Table of Contents

Abstract ........................................................................................................ iii
Acknowledgement ....................................................................................... iv
Table of contents ....................................................................................... v
List of tables ............................................................................................. ix
List of figures .......................................................................................... x
List of photographs ................................................................................ xi

Chapter One
Introduction ............................................................................................ 1

1.1. Introduction ....................................................................................... 2
  1.1.1. Aims ........................................................................................ 2
  1.1.2. Field area description ............................................................. 3
  1.1.3. Climate .................................................................................... 5
  1.1.4. Vegetation .............................................................................. 5
1.2. Miocene geology of coastal north Taranaki .............................................. 6
1.3. Relevant workers ........................................................................... 9
1.4. Comparison between the terrace settings of northern and southern Taranaki ................................................................. 13
1.5. Quaternary timescale ................................................................... 15
1.6. Quaternary climato-eustatic fluctuations ................................................. 16
1.7. Recommended marine terrace terminology ........................................... 18
1.8. Tectonic uplift rates and strandline altitudes ........................................ 18
1.9. The problem of height above sea level .............................................. 20
1.10. Surveying ..................................................................................... 20

Chapter Two
NT1 Terrace, Turangi Road ........................................................................ 22

2.1. Introduction ..................................................................................... 22
2.2. Description ..................................................................................... 22
2.3. Coverbeds ...................................................................................... 23
2.4. NT1 strandline height above modern analogue at Turangi Road .......... 24
2.5. Summary ....................................................................................... 26
Chapter Seven
Holocene and older features at Aria Beach, Mokau

7.1. Introduction ................................................................. 101
7.2. Possible fossil wave-cut notch and associated borings ........................... 103
7.3. Origin of the holes ................................................................ 103
7.4. Origin of the coastal notch at Aria Beach ....................................... 106
7.5. Other Holocene features ..................................................... 113
7.6. NT2 Terrace ..................................................................... 115

Chapter Eight
Mokau rhyolitic deposits ......................................................... 118

8.1. Introduction ................................................................... 118
8.2. Mokau rhyolitic localities .................................................... 118
8.3. Pahaoa Hill Outcrops .......................................................... 120
8.4. Other rhyolitic volcaniclastic deposits in North Taranaki .................. 132
8.5. Characterisation of the Mokau rhyolitic deposit ............................... 136
8.6. Mangakino Volcanic Centre Ignimbrites .................................... 138
8.7. Discussion ...................................................................... 141
8.8. Summary/conclusion ........................................................ 141

Chapter Nine
Alteration of minerals within the Mokau rhyolitic deposit .......................... 142

9.1. Chemical weathering of feldspars ........................................... 142
9.2. Chemically weathered minerals from the Mokau rhyolitic deposit ........ 143
9.3. Etched plagioclase feldspars from the Mokau rhyolitic deposit ............ 144
9.4. Altered phyllosilicates from the Mokau rhyolitic deposit ................... 144
9.5. Zeolite (?) on mineral surfaces within the Mokau rhyolitic deposit ...... 145
9.6. Clay transformation rates in tephras ...................................... 146
Chapter Ten
Landscape: a theoretical and quantitative approach.............. 158

10.1. Fractals and landscape evolution .................................................. 158
10.2. Landscape evolution on the South Taranaki/Wanganui marine terraces ................................................................................... 161
10.3. A theoretical approach to landscape evolution in northern Taranaki...... 163
10.4. Summary/Synthesis ....................................................................... 165

Chapter Eleven
Late Quaternary tectonics.......................................................... 169

11.1 Rates of tectonic uplift ............................................................. 169

References cited ............................................................................... 171

Appendix I ..................................................................................... 176
List of table

1-1 South Taranaki/Wanganui marine terrace sequence (Pillans, 1990a) .................. 13
1-2 Strandline altitude vs. tectonic uplift spreadsheet ........................................ 19
3-1 Altitude of features of interest at Onaero ..................................................... 41
3-2 NT2 Terrace coverbeds near Waiau Stream .................................................... 42
4-1 Urenui terrace altitudes (Chappell, 1964) ....................................................... 47
8-1 Electron microprobe analysis of Mokau rhyolitic deposit matrix ..................... 123
8-2 Feldspar composition recalculated from electron microprobe analysis .......... 123
8-3 Electron microprobe analysis of weathered phyllosilicate ............................. 124
9-1 Age vs. percentage clay for rhyolitic tephras (Lowe, 1986) ......................... 146
List of figure

1-1 North Taranaki coast. ................................................................. 4
1-2 Miocene geology. ........................................................................ 8
1-3 Quaternary sea level fluctuations (Pillans, 1990a). ..................... 11 (reverse)
1-4 Quaternary timescale. .............................................................. 15
1-5 Scales of Quaternary global climate change (Boulton, 1992). ....... 16
1-6 Marine terrace components and terminology (Pillans, 1990a). .... 18
2-1 NT1 Terrace coverbeds. ............................................................. 28
2-2 Turangi Road site. ................................................................. 29
2-3 Apparent age of the wave-cut platform vs. uplift rate (Pillans, 1990a). 25
3-1 Stratigraphic column: NT2 Terrace coverbeds and older units. .... 34
3-2 'Loess'-Paleosol' sequence, Onaero (Alloway et. al, 1992) ........... 39
3-3 NT2 Terrace coverbeds near Waiau Stream. ............................... 43
3-4 NT2 Terrace coverbeds near Onaero Beach. .............................. 44
3-5 Waiau Stream benches. ............................................................ 45 (reverse)
4-1 Onaero-Urenui drainage patterns. ............................................. 59
4-2 Onaero-Urenui interfluve patterns. ........................................... 60
5-1 NT2 Terrace coverbeds, Wai-iti slip. ........................................ 67
5-2 Pukearuhe location map. .......................................................... 68
5-3 Pukearuhe stratigraphy. ........................................................... 71
5-4 Coverbeds section north of Mohakatino. ................................... 78
5-5 Coverbeds south of Mohakatino. .............................................. 79
6-1 Non-marine terrace profile, Waikiekie, Tongaporutu. ................. 86
6-2 Non-marine terrace mechanism (hypothesis I) ......................... 92
6-3 Planar sliding model (hypothesis II). ........................................ 95
7-1 Schematic diagram of notch formation, Aria Beach, Mokau. ....... 109
7-2 Small scale map, Aria Beach. ................................................... 113
7-3 NT2 Terrace coverbed stratigraphy, Aria Beach. ....................... 117
8-1 Location maps for the Mokau rhyolitic deposit at Pahaoa. ........... 119
8-2 Phyllosilicate XRD. ................................................................. 125
8-3 Grainsize analysis for the Mokau rhyolitic deposit. .................... 127
8-4 Location maps for the Mokau rhyolitic deposit at Tainui/Tuhingakakapo. ................................. 132
8-5 Tuhingakakapo outcrop of Mokau rhyolitic deposit. ................. 135
9-1 Clay-rich matrix XRD Mokau rhyolitic deposit. ....................... 147
10-1 Analogy between Laplacian growth and dendritic drainage pattern. 160
10-2 Terrace dissection vs. age in south Taranaki (Pillans, 1988) ....... 161
List of photographs

2-1 Turangi Road - oblique aerial. ............................................................. 22
2-2 Motunui area - oblique aerial. ........................................................... 26
2-3 Modern wave-cut platform cut in andesitic lahar, Turangi Road. ............ 26
3-1 Cross-bedded sands overlying NT3 WCP. ............................................. 32
3-2 Mud/lahar contact on modern WCP, Turangi Road. ............................... 33
3-3 NT2 Terrace coverbeds (Q19/240 457) ............................................... 34 (reverse)
3-4 Onaero/Urenui - oblique aerial. ......................................................... 40
4-1 Urenui/Onaero - oblique aerial. .......................................................... 49
4-2 NT2 Terrace riser, Ngatimaru Road. .................................................. 50
4-3 NT3 abandoned sea cliff/ terrace riser south of Urenui. ......................... 51
4-4 Carved landscape Urenui. ............................................................... 58
5-1 Wai-iti - oblique aerial. ................................................................. 63
5-2 Bore holes and cemented cobbles, Tongaporutu. .................................. 75
5-3 NT2 Terrace coverbeds, Mohakatino coast. ......................................... 76
5-4 Variegated sands, Mohakatino. ......................................................... 77
5-5 Holocene river terrace (with cultural sediments), Mohakatino. ............... 82
5-6 Close-up of river terrace. ............................................................... 85
6-1 Tongaporutu - oblique aerial. .......................................................... 85
6-2 Panorama of Tongaporutu coast from White Cliffs walkway ................. 86 (reverse)
6-3 Mokau - oblique aerial. ................................................................. 88
6-4 NMT, inland from Awakino .............................................................. 97
6-5 View south from Waikiekie NMT ..................................................... 98
6-6 Panorama of inland Awakino area from Pahaoa trig. ........................... 99
6-7 Tuahu "back-basin". ........................................................................ 100
6-8 Waipinga Stream - oblique aerial. ................................................... 100
6-9 Modern coastal platform, Mohakatino. .............................................. 90
6-10 Pukearuhe - oblique aerial. ............................................................ 93
6-11 Tongaporutu 'cirque' - oblique aerial. .............................................. 94
7-1 Holocene coastal notch 'A', Aria Beach. ............................................. 102
7-2 Holocene coastal notch 'C', Aria Beach. ............................................ 107
7-3 Holocene coastal notch 'D', Aria Beach. ............................................ 108
7-4 Holocene coastal notch, Tongaporutu. ............................................... 110
8-1 Conical hillocks at Pahaoa. ............................................................. 121
8-2 Ignimbrite blocks, outcrop 'A', Mokau rhyolitic deposit. ....................... 121
8-3 Ignimbrite block close-up. ................................................................ 122
8-4 Ignimbrite block close-up. ................................................................ 122
8-5 Outcrop 'B', Mokau rhyolitic deposit ............................................. 128
8-6 Outcrop 'C' ................................................................................ 130
8-7 Tainui outcrop of Mokau rhyolitic deposit ('jaffas'). ....................... 133
8-8 Tainui outcrop (planar bedding). .................................................. 134

SEM photographs (9-1 to 9-16)
9-1 Doughnut shaped feldspar ........................................................... 149
9-2 Doughnut shaped feldspar with etch pits ....................................... 149
9-3 Almond shaped etch pits .............................................................. 150
9-4 Almond shaped etch pits .............................................................. 150
9-5 Fresh feldspar cleavage surface, unetched. .................................... 151
9-6 Grooved striations following crystallographic orientation. ............... 151
9-7 Large prismatic etch pits ............................................................. 152
9-8 Large prismatic etch pits ............................................................. 152
9-9 Prismatically etched feldspar in matrix. ....................................... 153
9-10 Zeolite coated phyllosilicate. ....................................................... 154
9-11 - Zoom 1. ........................................................................... 154
9-12 - Zoom 2. ........................................................................... 155
9-13 - Zoom 3. ........................................................................... 155
9-14 Expanded phyllosilicate in matrix. .............................................. 156
9-15 Close-up of zeolite "matt" coating quartz. .................................... 157
9-16 Close-up of zeolite "forest" coating phyllosilicate of 9-10. ............... 157
10-1 Degraded LIGM seacliff between Tongaporutu and Mohakatino rivers. 166
10-2 High altitude (7800m) aerial photo of the Tongaporutu area. ........... 168
Chapter One
Introduction...........................................................................................................1

1.1. Introduction....................................................................................................2
  1.1.1. Aims .................................................................................................2
  1.1.2. Field area description ......................................................................3
  1.1.3. Climate .........................................................................................5
  1.1.4. Vegetation ....................................................................................5
1.2. Miocene geology of coastal North Taranaki .................................................6
  1.2.1. Mohakatino Formation ....................................................................6
         Purupuru Tuff ..................................................................................6
         Ferry Sandstone ............................................................................7
         Tawariki Mudstone ....................................................................7
  1.2.2. Mt Messenger Sandstone Formation ...............................................7
  1.2.3. Urenui Formation .........................................................................7
1.3. Relevant workers .......................................................................................9
  1.3.1. Chappell, 1964 .............................................................................9
         Main findings in North Taranaki ..................................................10
         Discussion ....................................................................................10
  1.3.2. Chappell, 1975: Warping and uplift rates .....................................11
  1.3.3. Pillans: South Taranaki/Wanganui uplifted marine terraces ........11
1.4. Comparison between the terrace settings of northern and southern Taranaki ....................................................................................................13
1.5. Quaternary timescale ...............................................................................15
1.6. Quaternary climato-eustatic fluctuations ................................................16
1.7. Recommended marine terrace terminology ............................................18
1.8. Tectonic uplift rates and strandline altitudes ..........................................18
1.9. The problem of height above sea level ..................................................20
1.10. Surveying .............................................................................................20
Chapter One

Introduction

1.0. Preamble

The idea of a project on uplifted marine terraces arose in my third year (1990) out of an essay I wrote on Quaternary sea level fluctuations and the intimately associated phenomena of the oxygen isotope record and climatic variation. I had also read of the Milankovitch theory of orbital forcing, which furnishes an astronomical explanation for climate change. Coincidentally the Hochstetter lecture that year (1990) was by Dr Brad Pillans on the fascinating topic of periodicity within the climatic record and its agreement with the predictions of the Milankovitch theory. Soon after this when I was beginning to contemplate a topic for my honours (later to become a Masters), a visiting DSIR (now CRI) geologist, John Begg, mentioned a well developed set of uplifted marine terraces that he had seen when flying into New Plymouth from further north. With encouragement from C. A. Landis and J. D. Campbell I then decided to embark on a study of uplifted marine terraces in northern Taranaki.

This thesis is concerned with Late Quaternary geology. It is therefore intimately connected with the landscape and its historical geomorphology. The Late Quaternary record has potentially greater resolution than the older records. This is because more recent structures are often geologically transient and in the long term record will not generally be preserved. For example, uplifted marine terraces are progressively dissected and stripped of coverbeds, ultimately to become rugged hill country with virtually no 'memory' of the previous state.

As the geological record gains greater resolution, so the various disciplines of geology become more sharply demarcated into distinct yet intimately related disciplines. This thesis touches to various degrees on neotectonics, Quaternary sea level and climatic fluctuation, regional to meso-scale geomorphology, soil science, and tephrochronology (especially as it relates to North Island rhyolitic volcanism). The modern 'mainstay' tools of geology were employed (including the SEM, electron microprobe, and the XRD), as well as the main tool of land surveying, the 'total station' (electronic theodolite).
1.1. Introduction

1.1.1. Aims

In the beginning this project (initially an Honours project) was planned to be a study of Quaternary uplifted marine terraces north of Urenui, with an emphasis on surveying of terrace strandline altitudes and the determination of Quaternary uplift rates. When it was discovered that coastal North Taranaki is dominated by the Last Interglacial Maximum (LIGM) terrace north of Urenui and that higher landforms were of non-marine origin, these initial intentions were somewhat modified. The emphasis thus shifted to a more general geological and geomorphological study. As a Masters, the field area was extended to include areas south of Urenui as far as Motunui. Several topics emerged during the course of this study. The individual topics were:

(1) Marine terraces - This was mainly limited to a discussion of the NT1 and NT2 terraces formed 80 and 120 thousand years ago during δ18O sub-stages 5a and 5e respectively. Average rates of tectonic uplift were calculated at several localities.

(2) Holocene coastal features - These included river terraces, the coastal plain, coastal notches, and enigmatic intertidal-like "holes". The latter two were evaluated as to their origin and hence as to their applicability in determining rates of uplift/eustacy.

(3) Non-marine terraces - These were seen to be an important geomorphic feature of the North Taranaki landscape, and the need to clearly distinguish them from marine terraces was recognised. Mechanisms were proposed by which non-marine terraces might form.

(4) Geomorphology and theoretical landscape evolution - The work of several recent authors was reviewed and an attempt to apply their work to certain large scale features of the North Taranaki landscape was made.

(5) Mokau rhyolitic deposit - The unexpected discovery of a thick weathered rhyolitic deposit near Mokau prompted a comprehensive description of this unit.

---

1 LIGM = Last Interglacial Maximum: Occurred during δ18O Stage 5c, with a +5 metre paleo-sealevel at c. 120ka B.P. (Pillans, 1990a). Last Interglacial Cycle: Encompasses δ18O stages 5c, 5c, 5a. Relative high stands of sea level were at 120ka, 100ka, and 80ka, with paleo-sealevels of +5m, -11m, and -20m respectively.
1.1.2. Field area description
The field area covers some 50km along the coast from Turangi Road near Motunui, to Awakino, and extends a variable distance inland, generally not more than several kilometres (figure 1-1). The total study area however is somewhat larger and more arbitrarily defined, with geomorphological information being derived from aerial photographs and topographic maps. The greater study area thus encompasses the highly dissected hill country lying inland beyond the relatively narrow coastal belt of uplifted marine and non-marine terraces.

The wave-cut platform of each uplifted marine terrace is cut into gently south-westerly dipping mudstones, siltstones and sandstones of the Mt. Messenger, Mohakatino, and Urenui formations (mid- to upper Miocene). See section 1.2.

Very rugged hill country with a strikingly uniform ridge-crest height, referred to by Chappell as the "North Taranaki Surface", lies immediately inland behind the uplifted terrace/s. The steep hill country has a high drainage density testifying to high rainfall, and moreover high runoff rates from the dominant mudstone-sandstone lithology. Topographic relief of the steep hill country shows short wavelength dissection (fine texture or feral relief of Cotton, 1948) and is characterised by rectilinear hillslope geometry and sharp serrated ridges. The serrated ridges are formed by first order streams which cut parallel groove-like channels that descend in a vertical plane from the ridge into the valley floor below. Consequently the landscape has a rough angular, appearance that is in sharp contrast to the rolling farmlands of the uplifted marine terraces on the coast.

Four Pleistocene uplifted marine terraces are recognised in North Taranaki, with Urenui being the only area where all four terraces are consecutively exposed. The LIGM terrace is the most prominent terrace. It is continuous along the entire coastal study area apart from one major break for some 4.5km between Pukearuhe and Katikatiaka Pa where eroding coastal cliffs (the White Cliffs) tower over 200m above the black sand beach, truncating the rugged hill country of the "North Taranaki Surface". North of Pukearuhe only the LIGM terrace is present, and it is bounded on the inland side by high abandoned fossil sea cliffs which rise up to 200m above the uplifted terrace. The fossil sea cliff is dissected in places by rivers and streams flowing to the coast from the inland dissected hill country. Apart from this interruption the LIGM terrace surface forms a raised coastal plain at an approximate elevation of 40m, and is bounded on its inland side by an abandoned fossil sea cliff. The LIGM terrace dominates the entire coast until just north of Awakino, where it then narrows dramatically. The LIGM terrace is referred to as the "NT2 Terrace" throughout the rest of the text after Chappell (1975) and subsequently Alloway (1986).

Older and higher uplifted marine terraces are more fragmentary and are only well developed at Urenui, but may be traced into the Taranaki Ring Plain (the circular volcaniclastic apron centred on Mt. Taranaki). Well developed high terraces occur above the LIGM terrace at the Tongaporutu end of the White Cliffs walkway, as well as north of Mokau, but these are shown to be non-marine in origin.

Uplifted Holocene deposits are recognised at the Mohakatino and Urenui river mouths where uplifted river/estuary deposits occur above the modern analogue.
FIGURE 1-1: North Taranaki coast from Waitara to Awakino River (from 1:250,000 geological map of Taranaki (Sheet 7, Hay, 1967)). The field area extends from Turangi Road to Awakino.
1.1.3. Climate

"The climate of Taranaki is determined largely by its position in relation to the large scale weather patterns affecting New Zealand. Situated on the western side of the North Island, Taranaki is exposed to all weather systems migrating over the Tasman Sea. Taranaki is therefore generally a sunny, windy region with a good supply of evenly distributed rainfall and moderate temperatures" (Thompson, 1981). Taranaki's rainfall patterns are closely related to elevation and exposure to the main rain-bearing northerly to westerly winds. "As winds approach from the west, winds come from a northerly quarter, temperatures are mild and the heaviest rainfalls occur at this time" (ibid.).

For northern-most Taranaki mean annual rainfall is between 1600 and 2000 mm on the coast and increases inland to over 2000mm (eg. 2150mm at Uruti). The wettest months are May, June and July with over 30% of the annual total. The driest months are January, February and March with only about 20% of the annual total.

The warmest months are January and February with mean daily temperature (MDT) normals of 17.5 and 18.0°C respectively for Mohakatino station. The coldest month is July with a MDT normal of 9.5°C. Frosts are not common on the coast. The MDT range for the year is only about 7°C with little month to month variation. Note that mean air temperature reduces with height by about 0.6 °C/100m.

1.1.4. Vegetation

Coastal Taranaki has been classified into two bio-climatic zones by C.M. Lees (1987): A coastal zone extending from the shore to about 4km inland with the first 1km subject to salt-laden winds. And a semi-coastal zone extending from the seaward limit of *Kohekohe* from as close as 150m from the shore, up to about 10 km inland.

An accurate picture of native vegetation prior to major European settlement (about 1840 A.D.) has been built up from the notes of visiting 19th century scientists by C.M. Lees: Around 1840 A.D. the coastal plain was characterised by a dense tangle of fern, flax, and cabbage tree with occasional areas of scrub containing stunted trees and shrubs with *nikau* palms, ferns and white *clematis*. Occasional remnants of heavy bush were also present. Inland of this was a type of semi-coastal forest dominated by kohekohe along with prominent *pukatea*, *tawa* and rikau palm. Further inland were warm temperate forest-covered lowlands dominated by *rimu*. From the authors casual observations, *nikau* palm is very prominent in more sheltered areas. While in more exposed areas are wind-swept trees and shrubs with lopsided crowns directed away from the coast probably resulting from salt-burn and constant winds.
Nearly all flat coastal and terrace areas are now in pasture with native vegetation existing only as isolated pockets within stream valleys and native reserves. In northernmost Taranaki only a narrow coastal strip is present, with rugged hill country often densely covered in native forest in behind.

† Kohekohe = *Dysoxylum spectabile*
Nikau = *Rhopalostylis sapida*
Pukatea = *Laurelia novae-zelandiae*
Tawa = *Beilschmiedia tawa*
Rimu = *Dacrydium cupressinum*

1.2. Miocene geology of coastal North Taranaki
The North Taranaki coast has recently undergone scrutiny by petroleum geologists because of the 'window' it provides into the geology of the North Taranaki Basin. Sedimentary rocks of the North Taranaki Basin are exposed in the cliffed coastline from just west of Waiau Stream in the southwest, to Awakino River mouth in the north. The rocks are entirely mid- to late Miocene with the greater thickness of the sequence being Tongaporutan in age. The sedimentary sequence unconformably overlies Triassic basement exposed at the western end of the Awakino Gorge and youngs in a southward direction. The sequence dips gently to the southwest and the sedimentary record is fairly continuous in coastal exposures. In places the coastline parallels strike.

The coast between Waiau Stream and Awakino River encompasses three formations within the Mohakatino Group. Formation boundaries are shown in figure 1-2, which summarises the stratigraphic sequence for the North Taranaki coast.

Mohakatino Formation (Grange, 1922). Age: late Sw

Mt Messenger Sandstone formation (Hay, 1967). Age: early - mid TT.

Urenui Formation (Morgan & Gibbs, 1927). Age: mid - late TT.

1.2.1. Mohakatino Formation
The Mohakatino Formation (c. 300m thick) is composed of three members; volcaniclastic Purupuru Tuff, Ferry Sandstone and Tawariki Mudstone (all Hay, 1967).

**Purupuru Tuff**
Purupuru Tuff is a well-stratified volcaniclastic fine to coarse sandstone with siltstone and mudstone interbeds, and contains much andesitic detritus derived from submarine
volcanism. A 30m thick, massive, non-volcanic fine sandstone forms a prominent bluff in the abandoned LIGM seacliff above SH3 beneath Pahaoa hill.

**Ferry Sandstone**

Ferry Sandstone is well exposed in the LIGM cliffs above SH3 for c. 5km south of the Mokau River. Some 60m of sandstone and siltstone form prominent yellow-brown weathered bluffs which are laterally traceable in the hills and coastal cliffs. Much of the coastal section of Ferry Sandstone is almost along strike.

**Tawariki Mudstone**

Tawariki Mudstone outcrops from c. 1km north of Kawau Pa to Tongaporutu River where it contacts with the overlying formation. The Tawariki Mudstone also contains subsidiary sandstone and tuffaceous siltstone.

### 1.2.2. Mt Messenger Sandstone Formation

Mt Messenger Sandstone (c. 650m thick) is composed of three "units" and occurs in coastal sections from the Tongaporutu River (south head) to Pukearuhe. The regional tilt of the Mt Messenger Formation is greater than that of the underlying Mohakatino Formation, which is the surface expression of structural dips increasing across the western edge of the underlying basement thrust. The upper and lower units are dominantly sandy. The middle unit is mainly siltstone with interbeds of sandstone and mudstone, some up to 30m thick.

### 1.2.3. Urenui Formation

The very gradual transition from Mt Messenger Formation to the overlying Urenui Formation occurs between Pukerauhe Road beach and Pariokariwa Point. This coincides with a prominent outjutting of the coast as the main coastal marine terrace (NT2 Terrace) suddenly appears again after the break that forms the White Cliffs.

The Urenui Formation is c. 900m thick in coastal section, and is composed mainly of siltstones and silty-mudstones which are commonly massive to weakly bedded (note frequent concretionary layers). The Urenui Siltstones are punctuated at three stratigraphic levels by channelised fine sandstone sequences 30 to 60 m thick.

The above was summarised from *Field Guide for the North Taranaki Coastal Region* (prepared for the NZAPG field excursion) by King (1991).
FIGURE 1-2: Stratigraphic column for coastal exposures of North Taranaki Basin sedimentary rocks. Synthesized from figure 4 (parts 1 to 4) of King (1991).
1.3. Relevant workers

The most recent and intensive field work on the Quaternary geology of northern Taranaki was by Chappell in 1964. The Taranaki area contributed roughly half of the material towards his unpublished M.Sc thesis; *The Quaternary Geology of the Southwest Auckland-North Taranaki Coastal Region*.

In North Taranaki Chappell covered the coastal area (up to several kilometres inland), from Urenui in the south, to just beyond Awakino in the north. Chappell considered the cover-bed stratigraphy and general geomorphology of the region. The very extensive but highly dissected "North Taranaki Surface" (*NTS*), rises with very low gradient far into the North Taranaki hinterland and beyond toward the base of Ruapehu. Chappell considered the *NTS* to be the dissected remnants of an "old-from-birth peneplain" which began to form in the upper Miocene.

At lower levels descending from the coastal edge of the *NTS* several marine terraces in varying stages of preservation were recognised. Chappell placed these landforms in a conceptual framework involving oscillating glacio-eustatic controlled sea level, the peaks of which reached progressively lower levels. Chappell evidently envisaged an extraordinarily high late Miocene sea-level at the height of the present *NTS*, some 260m above present sea level, which was then progressively lowered as the Pleistocene Ice Age intensified.

Chappell hypothesized the *NTS* and the terrace landforms to result from two separate stages of geomorphic evolution, each controlled by a different eustatic regime.

The first stage involved the slow emergence and planation of the "North Taranaki Depression" ie. the North Taranaki Basin starting in the upper Miocene (Tt) during a long, stable climatic period. The second stage involved a "fall in base-level", which Chappell believed accounted for the "steep dissection of the North Taranaki Surface and deep entrenchment of the main streams". From successively lower terrace remnants on the coast Chappell drew evidence of lowering sea levels.

Chappell identified five marine terraces (four Pleistocene and one Holocene) and concentrated mainly on the extensive second terrace which he believed to be a "composite terrace" (Terrace 2 and 2A); formed from the deposits of two separate transgression peaks.
Main findings in North Taranaki

Chappell (1964) investigated the area being studied by the present author rather thoroughly and covered sections in the vicinity of Urenui, Mount Messenger, and the mouths of the Tongaporutu River, Rapanui Stream, Mohakatino, Mokau and Awakino rivers. His main conclusions were:

That a post-glacial (Holocene) transgression maximum deposited water-laid (estuarine) sediments at a height up to, but not greater than 1.8 m (+0.3/-0 m) above present high tide. The character of the sediments Chappell observed forming these deposits was very similar to those found forming modern tidal flats.

That the terrace north of White Cliffs is a composite terrace ("Terraces 2 and 2A"), which contains the records of two separate oscillations of sea level. The oldest sea level "stillstand" is marked by a well defined "nick-point" in the Miocene rocks at the base of the abandoned sea cliff. Chappell identified the "younger" sea level by the maximum height of "water-laid" sediments found in the terrace coverbeds. For "Terrace 2A", Chappell presented a table and accompanying outline map with locations and heights a.p.s.l. (in feet) for the maximum elevation of marine sediments at various localities. There does not appear to be any particularly well defined trend in the heights that Chappell gave for Terrace 2A. Highs of 29 and 30 metres on the south and north banks of the Tongaporutu River and highs of 30 and 26 metres on the south and north banks of the Mokau River with lower values in between of (from south to north); 21m, 27m, 24m, 18m, 21+m and 15+m.

That at Urenui (south of White Cliffs) the two oscillations of sea level which form a composite terrace to the north, are differentiated into two separate surfaces and are separated by a terrace riser. He also mapped several higher terraces at Urenui and briefly discussed their underlying deposits.

Discussion

Some of the concepts and terminology used by Chappell in 1964 to interpret his fieldwork are now in need of revision, making it appropriate for a re-evaluation of some of his work within the present day framework of:
Well constrained global paleo-sea levels (heights and dates) for the Late Quaternary.

The approximate rate of regional tectonic uplift in North Taranaki of 0.2-0.3 mm.a\(^{-1}\) (Pillans, 1990a; and Chappell, 1975)

Standardized marine terrace terminology (Pillans, 1990b).

There are also areas and aspects which Chappell did not investigate, notably the existence of non-marine terraces, which warrant further study.

### 1.3.2. Upper Quaternary warping and uplift rates (Chappell, 1975).

In this paper Chappell dealt with uplifted marine terraces in the Bay of Plenty and the west coast of the North Island from which he inferred uplift rates for the upper Quaternary. For the west coast from Taranaki to Auckland he inferred an essentially spatially uniform time-averaged uplift rate of around 0.3 mm.a\(^{-1}\).

For the west coast Chappell perceived gentle warping of the c. 500ka terrace of southwest Auckland and its correlatives in Taranaki and Wanganui (Kaiatea Group terraces). For all terraces younger than c. 500ka to the north of the Wanganui terraces, uplift is spatially uniform over a distance of greater than 350km. Using this observation Chappell implied an absence of post-120ka deformation.*

Chappell notes that steady emergence of the west coast north of Wanganui, after the c. 500ka transgression is "synchronous with final diminution and emergence of the Wanganui marine basin". However he excludes a causal link (ie. flexural coupling) between the two because it would imply an "abnormally high flexural rigidity of the lithosphere". Rather he links the Wanganui basin emergence and west coast uplift to a "common deep tectonic cause".

### 1.3.3. South Taranaki/Wanganui uplifted marine terraces

Synopsis

The definitive work of Pillans (1983, 1990a) on the well developed South Taranaki/Wanganui marine terraces provides a reliable standard sequence of uplifted marine terraces in New Zealand (Table 1-1), allowing correlation with the fluctuating upper Quaternary sea-level and climatic record from the around the world (see figure 1-3 from Pillans, 1990a). The strandline altitude of each terrace was measured using surveying barometers to a reported accuracy of ±5m at inland sites, and ±2m on coastal

* See figure 8 in Chappell (1975) for differential movement for this stretch of coast.
sections. The strandline altitude was found to vary along its length in a simple anticlinal doming fashion, indicating differential uplift rates.

Age constraints on the Ararata and Rapanui strandlines were achieved by fission track (F/T) dating of the Rangitawa Tephra, and amino acid racemization (AAR) dates on wood in the respective lowermost coverbeds of these terraces. The Rapanui is the Last Interglacial terrace *sensu stricto* ie. Oxygen Isotope ($\delta^{18}O$) Stage 5e which is standardly recognised as the 120ka highstand of +5 metres above present mean sea-level. The Ararata terrace age of 400ka is based on F/T dating on zircon and glass from the Rangitawa (Pumice) Tephra; a rhyolitic tephra marker found above the wave-cut surface in the coverbeds of terraces Ararata and older. Other terrace strandline ages were constrained by various aspects of the coverbed stratigraphy, particularly the number of "tephric loesses", as well as radiocarbon and AAR dating of wood. The interstadial sea-level events recorded in the South Taranaki/Wanganui marine terraces are tied into the general pattern of global Quaternary sea-level change (tuned to orbital variations predicted by the revised Milankovitch Theory). Thus each of the twelve dated terraces is tentatively assigned to an oxygen isotope climatic stage or substage. Twelve high-sea-level strandlines are recognised ranging in age from 60ka to 680ka. By plotting the heights (Y) against uplift rate (X) and fitting a straight line to the points for each terrace, the slope of the line (A) gives the age of the terrace.* Pillans assumed paleo-sealevels (C) for terraces Rapanui and older but allowed the intercept C to vary for the younger Last Interglacial terraces, the derived paleo-sealevels showed good agreement with the 'standards' defined from Huon Peninsula and Barbados.

Age and altitude data, plus paleo-sealevel data/assumptions result in a simple hinging uplift model with mean uplift rates increasing inland with increasing strandline age (constant uplift is assumed inland of the Ararata Terrace). The shore-normal slope of the wave-cut platform gradually increases up the terrace flight from about 0.3° on the 80ka terrace, to about 1.1° on the 680ka terrace. This implies shore-normal tilting along an an offshore hinge line (or zero uplift isobase) at an angular rate of $2.8 \times 10^{-5}$ rad.ka$^{-1}$.

A further summary of Pillans work is given in section 10.2.

* See figure 4 in Pillans, 1983.
TABLE 1-1: South Taranaki/Wanganui marine terraces: Age and possible Oxygen Isotope Stage (from Pillans, 1990b).

<table>
<thead>
<tr>
<th>Marine Terrace</th>
<th>Estimated Strandline Age (ka)</th>
<th>Oxygen Isotope Stage ((\delta^{18}O)) Stage (Possible)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rakaupiko</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>Hauriri</td>
<td>80</td>
<td>5c</td>
</tr>
<tr>
<td>Inaha</td>
<td>100</td>
<td>5c</td>
</tr>
<tr>
<td>Rapanui</td>
<td>120</td>
<td>5e</td>
</tr>
<tr>
<td>Ngarino</td>
<td>210</td>
<td>7a</td>
</tr>
<tr>
<td>Brunswick</td>
<td>310</td>
<td>9</td>
</tr>
<tr>
<td>Braemore</td>
<td>340</td>
<td>9</td>
</tr>
<tr>
<td>Ararata</td>
<td>400</td>
<td>11</td>
</tr>
<tr>
<td>Rangitatau</td>
<td>450</td>
<td>11</td>
</tr>
<tr>
<td>Ball</td>
<td>520</td>
<td>13</td>
</tr>
<tr>
<td>Piri</td>
<td>600</td>
<td>15</td>
</tr>
<tr>
<td>Marorau</td>
<td>680</td>
<td>17</td>
</tr>
<tr>
<td>(undifferentiated older terraces)</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

1.4. Comparison between the terrace settings of northern and southern Taranaki

Similarities

The South Taranaki sequence resembles that in North Taranaki as follows:

1. Basement lithologies: Mainly mudstone and siltstone in South Taranaki (Pliocene-Pleistocene shallow marine sediments). Mudstones, siltstones and sandstones in North Taranaki (middle-late Miocene, slope to shelf sediments).

2. North Taranaki and South Taranaki/Wanganui are approximately equal distances north and south of the andesitic volcanoes of Taranaki (Taranaki/Egmont, Pouakai, and Kaitake) which has been the main provenance of andesitic material for the last half million years for the Taranaki area.

3. Similar overall modern climate:

- Moderate to high rainfalls without greatly significant seasonality, however differences do exist (see below).
- Very similar temperatures: Mean daily temperature normals for year in North Taranaki are typically 13.8°C (Mohakatino station). Compared with 13.3°C in South Taranaki (Patea) and mean daily range of 6.6°C and 6.8°C respectively (Thompson, 1981).

- Exposure of both areas to the prevailing westerly moving depressions. However local topography and strike of the coast modify the prevailing wind direction.

(4) Similar native vegetation and bioclimatic zones: A narrow coastal zone up to 4km inland (section 1.1.3.), with a broader semi-coastal zone up to 10km inland (Lees, 1987).

Differences

Of the differences between the two areas, the most obvious is the presence of a better preserved flight of terraces in the South Taranaki/Wanganui area (12 compared with 4 recognised at Urenui in North Taranaki).

Patterns and rates of tectonism differ: South Taranaki has generally higher uplift rates (0.3-0.7 mm.a\(^{-1}\)) and obvious tectonic warping. It is interesting to consider that the present North Taranaki tectonic regime (roughly constant uplift of c. 0.3mm.a\(^{-1}\)) may be an analogue for the future tectonic regime of the South Taranaki/Wanganui terraces, at a time when warping ceases and uplift rates slow.

Modern annual rainfall: Coastal North Taranaki has 1600 to 2000 mm.a\(^{-1}\) compared with 1100 to 1400 mm.a\(^{-1}\) in coastal South Taranaki. This may have a significant effect on the effective erosional diffusivity (Koons, 1989), and therefore on rates of transport-limited erosion, and hence differing rates of landscape evolution (ie. more rapid in North Taranaki).

In South Taranaki the terrace marine coverbeds commonly contain fossil shells, however in North Taranaki fossil shells never occur. This may imply differences in the pH of terrace coverbed groundwater between the two areas. The shallow groundwater of the North Taranaki area is generally slightly acidic, while that of South Taranaki has a wider range from acidic to alkali (Taranaki Catchment Commision, 1984).

Overall, although there are significant differences, the North Taranaki and South Taranaki/Wanganui terraces are expected to have evolved through the operation of similar depositional and erosional processes. However, there is likely to be some detectable differences in process rates sensitive to climate and lithology.
1.5. Quaternary timescale

FIGURE 1-4: Timescale for the late Pliocene and Quaternary showing some of the important events such as rhyolitic chronohorizons and climatically related phenomena.
1.6. Quaternary climato-eustatic fluctuations

Changes in global climate (and hence eustatic sea level) occur on a wide range of timescales from $10^7$ to $10^1$ years* (see figure 1-5 from Boulton, 1992). Changes with a frequency of less than $10^6$ years are mostly attributed to changes in solar insolation (net incident radiation) due to predictable variations in the earth's orbital parameters (Boulton, 1992).

Spectral analysis of the deep sea $\delta^{18}O$ record for the Late Quaternary (part of the CLIMAP project) revealed three periodicities of c. 100ka, 40ka, and 20ka (Imbrie & Imbrie, 1979). These periodicities had been suspected on the basis of Inter-Glacial high stands of sea level recorded in uplifted marine terraces, and corresponding with remarkable precision to variations in the earth's orbital behaviour, namely the eccentricity ($T=100$ka), the axial tilt ($T=41$ka), and the precession of the equinoxes (dual periodicity

* The fractal dimension ($D$) of a time series, $f(t)$, provides a convenient measure of the (self-affine) scale invariance of climate change. Analysis of the deep sea $\delta^{18}O$ record for the Late Quaternary yields $D=1.22$ (time scales of $c.10^6$ to $10^9$), while variation in the precipitation record for the last 140 years in the USA has a $D$ value of 1.26 (Fluegman & Scott Snow, 1989).
of 23 and 19 ka). The 100ka glacial cycles have dominated the last 800ka, since the late Cenozoic ice age dramatically intensified (figure 1-5: left hand inset clearly shows an increase in the magnitude of cold period spikes).

"However although the frequency of climate change on earth is determined by the inherent frequencies of orbital change, there is not a good match between the magnitude of insolation change and the magnitude of climate response" (Boulton, 1992). This is because the climate system is composed of three major coupled elements; the atmosphere, ocean, and ice-sheets; each with its own response time (atmosphere << oceans < ice-sheets). The solar input is amplified by feedbacks within the climate system eg. the growth of ice sheets in response to a decreasing insolation, in turn leading to an increase in reflectivity and larger degree of cooling. In addition to a non-linear relationship between the magnitude of insolation change and the magnitude of climate response, there is a complex time lag between cause and effect eg. the 41ka climatic cycle lags behind variation in the earths axial tilt by c. 5ka (Imbrie & Imbrie, 1979). This time/phase lag is due to differing equilibration times within the climate system, ice sheets for example, may have equilibration times in excess of 10ka (Boulton, 1992).
1.7. Recommended marine terrace terminology

To avoid ambiguity and confusion, and to follow discussion within this thesis, it is essential to refer to features using an accepted and standardized terminology. This is well set out in figure 1-6 (from Pillans, 1990b), and will be adhered to throughout this thesis. The main area of lay confusion seems to be between "terrace surface" or often simply "terrace" which refers to the presently exposed topographic surface, and "wave-cut platform" which refers to the buried planated surface within the terrace. It is this wave-cut platform (WCP) which has a direct relationship to pre-sealevel. The age of a terrace refers to the time of formation of the strandline. Uplift rates are simply based on the present altitude of the strandline divided by its age (section 1.8.).

![Recommended marine terrace terminology](image)

**FIGURE 1-6:** Recommended marine terrace terminology from Pillans (1990b).

1.8. Tectonic uplift rates and strandline altitudes

The tabulated sheet below (Table 1-2) allows strandline altitude to be calculated for various aged terraces using different hypothetical average uplift rates. The calculated strandline altitude is simply \((\text{age} \times \text{uplift rate}) + \text{paleo-sealevel}\). For terraces older than the LIGM ie. older than the Rapanui Terrace, it is assumed that paleo-sealevel is equal to that of the present day.
TABLE 1-2: Tabulated calculation sheet allowing strandline altitude to be found for various terraces using different hypothetical average uplift rates. Terrace names, their strandline ages and paleo-sealevels are from Pillans (1990a) and refer to the South Taranaki/Wanganui terraces- in bold. Holocene sea levels and ages are from Gibb (1986) - in italics.

<table>
<thead>
<tr>
<th>Terrace</th>
<th>Age (ka)</th>
<th>Paleo-s1</th>
<th>Average uplift rates (m.ka⁻¹ or mm.a⁻¹)</th>
<th>Columns contain calculated altitude (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>Marorau</td>
<td>680</td>
<td>0?</td>
<td>136</td>
<td>170</td>
</tr>
<tr>
<td>Piri</td>
<td>600</td>
<td>0?</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>Ball</td>
<td>520</td>
<td>0?</td>
<td>104</td>
<td>130</td>
</tr>
<tr>
<td>Rangitatau</td>
<td>450</td>
<td>0?</td>
<td>90</td>
<td>113</td>
</tr>
<tr>
<td>Ararata</td>
<td>400</td>
<td>0?</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Braemore</td>
<td>340</td>
<td>0?</td>
<td>68</td>
<td>85</td>
</tr>
<tr>
<td>Brunswick</td>
<td>310</td>
<td>0?</td>
<td>62</td>
<td>78</td>
</tr>
<tr>
<td>Ngarino</td>
<td>210</td>
<td>0?</td>
<td>42</td>
<td>53</td>
</tr>
<tr>
<td>Rapanui</td>
<td>120</td>
<td>+5</td>
<td>29</td>
<td>35</td>
</tr>
<tr>
<td>Inaha</td>
<td>100</td>
<td>-11</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>Hauriri</td>
<td>80</td>
<td>-20</td>
<td>-4</td>
<td>0</td>
</tr>
<tr>
<td>Rakaupiko</td>
<td>60</td>
<td>-28</td>
<td>-16</td>
<td>-13</td>
</tr>
<tr>
<td>Last Glacial Max.</td>
<td>20</td>
<td>-120</td>
<td>-116</td>
<td>-115</td>
</tr>
<tr>
<td>6.5ka (Gibb)</td>
<td>7</td>
<td>0</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>3.5ka (Gibb)</td>
<td>3.5</td>
<td>0.5</td>
<td>1.2</td>
<td>1.4</td>
</tr>
</tbody>
</table>
1.9. The problem of height above sea level

On the north Taranaki coast, and exposed coasts in general, tying geological features of interest, especially Holocene features, to modern sea level presents several difficulties, both theoretical and practical:

Firstly, the concept of 'Mean Sea Level' is an abstraction, it "...being a calculated value based on measurements made at regular intervals in the course of no longer than approximately the last 150 years, [it] is a level of which there is no long term record in sedimentary deposits or landforms..." (Jardine, 1986).

Secondly, on a high energy exposed coast there are generally no enduring features to provide a record of sea level averaged over any significant duration ie. a beach may record the last high tide mark, but this level is as much dependent on weather and local surf conditions as on potentially predictable changing tidal effects. On the north Taranaki coast, beaches are often not present at all, the coast being marked by inaccessible, rapidly retreating cliffs. Only around river mouths and estuaries are sea level indicators common; for example, intertidal borings and other biological horizons.

For features older than Holocene, which are of sufficient height, an uncertainty of one or two metres will not result in an unacceptably large error for tectonic purposes. In these cases the complexities of sea level definition and determination may be ignored and the value of 'Mean Sea level' simply accepted (ie. 'altitude' used in standard surveying practices). The problem of "height above sea level" then largely becomes a technical one.

1.10. Surveying

The main practical problem in establishing the altitude of a feature is prohibitive distance from an established surveying bench mark or trig station, or some suitable coastal reference datum (eg. exposed modern wave-cut platform). Geodetic bench marks are spaced every few kilometres along S.H.3, hilltop trig stations are similarly of relatively low density. Excessive (horizontal) distance, or obstructed sight lines, are either out of range of the theodolite or require multiple set ups to link up with a tie point. This is potentially overcome by the very careful use of surveying barometers (as used by Pillans in South Taranaki/Wanganui), or perhaps in the near future, portable Global Positioning Systems (GPS) with accurate determination of the vertical co-ordinate.

The instruments used in this project were theodolites, both the traditional mechanical-optical design and the much more powerful 'Sokkisha' electronic "total station".
The total station gives digital read out of horizontal and vertical angles to a precision of ±0.1 second of arc, and contains an inbuilt electronic distance measurement device which uses an infra-red light beam bounced off a prism placed at the point of interest. A digital read out of the horizontal and vertical components of slope distance from theodolite to prism is given to a precision of ±0.001m. The range of this instrument is around 500m. If there is a high enough density of precise surveying datums (eg. geodetic bench marks and first or second order trig stations), with unrestricted lines of sight, then the total station is the ideal instrument for absolute heighting in relation to 'Mean Sea Level' (the datum to which all geodetic benchmarks are related).

The standard mechanical-optical theodolite eg. 'Wild-Tla', is generally less precise in the measurement of angles (this may however be improved through multiple observations). Horizontal and vertical distance measurement may be achieved with the use of a surveying staff/rod set up at the point of interest. Small marks on the theodolite cross-hairs called "stadia wires" are then used to read off numbers from the staff, which are then used in conjunction with vertical angles to calculate horizontal and vertical distance. The range of this instrument/method is not more than 100m and errors are proportionately large. The main use of this type of vertical and horizontal distance measurement is in the creation of small scale local maps of an area.

**Important note:** The height of the uplifted wave-cut platform as measured at some coastal locality is not to be confused with the strandline height (the height of importance in tectonic evaluations). The elevation of the strandline is the desired information but the feature itself is very rarely exposed. By projecting the sloping wave-cut platform back to the position of the strandline (as estimated from aerial photos or maps) it is possible to derive an estimate of strandline elevation. It is not until this value has been derived that a valid discussion of uplift rates can be attempted.

See Appendix I for further information on basic surveying technique.
Chapter Two
NT1 Terrace, Turangi Road

2.1. Introduction

2.2. Description

2.3. Coverbeds

2.3.1. Age of the NT1 Terrace strandline

2.4. NT1 strandline height above modern analogue at Turangi Road

2.4.1. Surveying

2.4.2. Other measurements

2.4.3. Inferred uplift rate for the NT1 strandline at Turangi Road

2.5. Summary
Chapter Two

NT1 Terrace, Turangi Road

2.1. Introduction

The NT1 Terrace strandline is the youngest uplifted Pleistocene strandline known in north Taranaki. It was first identified by Alloway (1989), who briefly described the uplifted NT1 Terrace at Turangi Road (Q19/238 460), and in the section at Airedale Reef near Waitara (Q19/185 458).

PHOTO 2-1: Oblique aerial photo taken from an altitude of c. 550m showing the Turangi Road coastal section (Q19/238 460). The change in orientation of the coast exposes the NT1 fossil seacliff, and NT1 Terrace coverbeds, as well as the NT2 Terrace coverbeds. See overlay.

2.2. Description

The NT1 Terrace is very narrow (not more than 200m wide) and is presumed to have been totally removed in most areas along the north Taranaki coast by erosion during the last c. 7ka†. However, where present it is clearly defined by a prominent terrace-riser (see photographs 2-1 & 2-2).

† From the work of Gibb (1986) it is known that the culmination of the post-glacial marine transgression at present sea-level occurred at an average date of 6700±110 years B.P. (radiocarbon), or 7300±100 years B.P. (calibrated calendar years). Taking the average of these two dates gives 7000 years B.P.
The uplifted wave-cut platform (WCP) and coverbeds of the NT1 Terrace are exposed in coastal cliffs c. 100m east of the Turangi Road end. The NT1 WCP is separated from the higher NT2 WCP by a buried fossil seacliff. The NT1 fossil seacliff truncates the outer edge of the NT2 WCP as is clearly visible in the above photographs. The NT1 fossil seacliff and terrace coverbeds are exposed by a major change in orientation of the present coastline (see figure 2-1).

2.3. Coverbeds

Previous work: Alloway (1989) described the coverbeds at the Turangi Road site as;
"...two 1.0 - 1.5m thick gravel units comprising sub-rounded to rounded cobbles and boulders in a sandy pebble matrix separated by up to 0.2m of andesitic planar to weakly cross-bedded sands...further westwards the gravel units upwardly grade to well cemented iron stained sands unconformably overlain by Holocene grey andesitic beach sands...".

This Author: Refer to figure 2-1. The NT1 WCP is overlain by rounded andesite beach-cobbles and boulders, which are identical in lithology, rounding, and sorting to the modern boulder-bank. Both modern*, NT1, and NT2 wave-cut platforms are cut into "unnamed laharic unit" (Alloway, 1989), hence the similar composition etc; of reworked boulders and cobbles.

The NT1 WCP is overlain by c. 2.0m of andesitic beach cobbles and pebbles. Pebbles are dominant at the base. Interstitial pebbles between cobbles become larger upward. At ~1m an intervening layer c. 0.3m thick separates the lower beach cobbles unit from a higher beach cobbles unit. The intervening bed consists of a lower cross-bedded medium andesitic sand layer, and is overlain by a weathered clay-rich andesitic tephra-like material containing feldspar and euhedral hornblende crystals. The tephric-like material appears to consist of poorly defined clasts and contains root casts.

The higher beach cobbles unit differs from the lower unit in that the interstitial matrix between cobbles consists of dark well-sorted medium andesitic sands. The top 0- 40 cm of this unit is sand, but closer to the NT1 strandline a paleosol containing wood fragments appeared to be formed in the sand.

Overlying the beach cobbles and sands is a 1.8- 2.0 m thick poorly sorted unit containing sub-angular to rounded andesitic clasts in a weathered, iron-oxide streaked, clay-rich

* The modern WCP and its coverbeds (boulders and sand) could be thought of as the "NT0 terrace"
andesitic tephric matrix. This unit is thought to be laharc though whether it is primary or was derived via slumping from the Motunui lahar within the NT2 Terrace coverbeds is uncertain.

2.3.1. Age of the NT1 Terrace strandline
At Airedale Reef Alloway ascribed an age of less than 100 ka B.P. to the NT1 strandline based on the absence of Okawa Formation within the NT1 Terrace coverbeds. He also considered that the NT1 strandline must be older than the post-glacial period (> c. 10ka) based on the presence of iron-cemented sands within the coverbeds. On the basis of a strandline altitude of "approximately 2.5 metres above HWL", and assuming an uplift rate of 0.3mm.a⁻¹, Alloway correlated the NT1 strandline with the Hauriri strandline (Pillans, 1983) in South Taranaki. The Hauriri strandline has a 'best-fit' age of 81ka B.P., and was formed at a paleo-sealevel of -20 metres (Pillans, 1983).

2.4. NT1 strandline height above modern analogue at Turangi Road
The NT1 Terrace strandline and surrounding area (figure 2-2) were surveyed with a 'TopCon' electronic theodolite, or "total station", trustingly lent by the University of Otago Surveying Department. A high degree of precision was therefore available. The NT1 strandline was found to be at a height of 3.5 ± 0.5 m above the modern analogue (ie. modern WCP in photo 2-3). See figure 2-2.

2.4.1. Surveying
Relative to the point of measurement on the modern WCP (ie. the theodolite setup, or "datum"), the strandline is at an altitude of 4.2m. Relative to the overall modern WCP, which is not of a precisely uniform height, it is harder to define an absolute value for its elevation. A cliff-parallel variation from datum on the modern WCP of 0.8m was measured (the maximum of three measurements). The strandline height relative to this point is therefore 3.4m. Given that only one value was obtained for the strandline elevation, and only three cliff-parallel spot heights on the modern WCP were taken, the most reliable elevation of the NT1 strandline (at the shoreline angle) is 4.0±0.5 m above the modern WCP. The modern WCP has a slope of 1.2° perpendicular to the immediate coastal cliffs. Projecting this to the cliff base, the modern WCP rises some +0.50m, thus the NT1 strandline has an altitude of 3.5±0.5 m relative to its modern analogue.

2.4.2. Other measurements
(1) The outermost edge of the NT2 WCP is 6±0.5 m (tape-measure) above the NT1 strandline ie.10 ± 0.5 m above the modern-analogue.

(2) The modern WCP formed on bouldery "unnamed" lahar had a measured dip
(perpendicular to the coastline) of $1.2 \pm 0.1^\circ$ (based on two measured lines).

(3) At an oblique angle to the strandline of about $40^\circ$ formed by the cliff, the NT1 WCP had an apparent dip of $2.5^\circ \pm 0.3^\circ$. This equates to true dip of about $1.8^\circ \pm 0.2^\circ$. This relative steepness is thought to be due to the proximity of the WCP to its strandline.

(4) The sandy beach-face between exposed modern WCP and cliff had a measured dip of $4-5^\circ$ (free-face). (Note the transient nature of beach sand on this exposed part of the coast-line).

2.4.3. Inferred uplift rate for the NT1 strandline at Turangi Road

Assuming the NT1 Terrace (Hauriri equivalent) strandline formed 81ka years ago ($A = 81$ka), at a paleo-sealevel altitude of $-20m$ ($C = -20m$) relative to present sea-level (Pillans, 1983 - see section 1.12). The uplift rate ($x$) can be calculated from the measured height of the strandline at Turangi Road ($Y = 3.5 \pm 0.5$ m).

\[ Y = Ax + C \]
\[ \Rightarrow x = (Y - C)/A \]
\[ \Rightarrow x = (3.5+ 20)/81 \pm 0.5/81 \text{ m.ka}^{-1} \]
\[ = 0.290 \pm 0.006 \text{ m.ka}^{-1} \]
\[ = 0.29 \pm 0.01 \text{ mm.a}^{-1} \]

Using the sealevel record established from Huon Peninsula, Papua New Guinea ($A = 83$ka, $C = -13$m; Chappell et al., 1974), a different rate of uplift is obtained (emphasising how sensitive the equation is to inaccuracies/anomalies): \( x = 0.199 \pm 0.006 \text{ mm.a}^{-1} \).

The sea-level record from the closest locality is the most desirable, because of geoidal 'bumps' and other variations, so $0.29 \pm 0.01 \text{ mm.a}^{-1}$ is the best estimate of average uplift rate during the last c. 80ka in north Taranaki at Turangi Road.

Nb: The slight age difference between the highstands at PNG and south Taranaki, is an artifact of the higher uplift rates at PNG (see figure 2-3 below from Pillans; 1990a).

**FIGURE 2-3** Shows how higher uplift rates (line A) makes the recorded age of the sea level high stand appear older ($T_A$). From Pillans (1990a).
2.5. Summary

The NT1 Terrace at Turangi Road identified and tentatively dated by Alloway (1989) as the 80ka terrace, was examined in further detail. The NT1 Terrace coverbeds were described and the altitude of the NT1 strandline and WCP relative to the modern WCP were determined. Assuming the 81ka strandline ($\delta^{18}O$ substage 5a) formed at a paleo-sea level highstand of -20m (Pillans, 1983), an average uplift rate for this time interval of 0.29 m.ka$^{-1}$ was inferred. The NT1 coverbeds did not show a particularly well defined sequence of units which could facilitate linkage to climatic episodes of the Last Glacial Cycle, except that at the top of the beach cobble unit a paleosol was tentatively identified beneath an c. 2m thick unit of probable laharc origin.
PHOTO 2-2: Oblique aerial photo taken from an altitude of c. 550m, just north of Waitara near Airedale Reef (Q19/185 458). The very well defined NT1 terrace-riser (topographic expression of a buried fossil sea cliff) is clearly visible.

PHOTO 2-3: Q19/238 460: View from the NT1 Terrace surface at Turangi Road. Shows the modern WCP ("NT0" terrace) at low tide, formed mainly in unnamed laharc unit (from Pouakai Volcano). Note the lineation running diagonally across the WCP with a strike of N77°E. It is not thought to be a fault, since it stops abruptly at the seaward end and cannot be confidently traced to the coastal cliffs at the other end. It also has no demonstrable displacement so it considered to be a joint.
FIGURE 2-1: Coverbeds of the NT1 Terrace exposed by a change of strike in the coast c. 100m east of the end of Turangi Road.
FIGURE 2-2: Schematic scale map of the Turangi Road NT1 Terrace and its strandline (altitude 3.5±0.5 m relative to its modern analogue), and surrounding area. The NT1 fossil sea cliff truncates the outer edge of the NT2 Terrace. Note location map inset.
Chapter Three
The NT2 Terrace coverbeds, and older units, east of Turangi Road

3.1. Introduction ..........................................................................
3.2. Description and interpretation .............................................
  3.2.1. Sediments pre-dating the LIGM ....................................
  3.2.2. Sediments of the Last Glacial Cycle ..............................
3.3. Stratigraphic units used by Alloway ....................................
  3.3.1. Unnamed laharic unit (Alloway, 1989) ..............................
  3.3.2. Ninia tephra (informal formation, Alloway- 1989) ............
  3.3.3. Motunui Lahar Deposit (Informal formation, Alloway 1989)..........................................................................
  3.3.4. Epiha Tephra (Formation, Alloway 1989) .........................
3.4. The NT2 Terrace Soil Accession ...........................................
3.5. Onaero Surveying ............................................................
  3.5.1. Introduction .................................................................
  3.5.2. Surveying ..................................................................
  3.5.3. Findings ......................................................................
  3.5.4. Other observations ....................................................
3.6. NT2 Terrace coverbeds, near Waiau Stream .........................
  3.6.1. NT2 Terrace coverbeds, Onaero Beach..........................
3.7. Waiau Stream benches .......................................................  
  3.7.1. Description ..............................................................
  3.7.2. Tentative interpretation ..............................................
3.8. Summary ............................................................................

...
Chapter Three

The NT2 Terrace coverbeds, and older units, east of Turangi Road

3.1. Introduction
On the coast about 400m east of the NT1 Terrace (Q19/238 460) at Turangi Road, a recent cliff collapse allowed access to the coverbeds of the NT2 Terrace (Q19/240 457). The stratigraphic section (figure 3-1) at this site is nearly continuous, and also exposes units which underlie the NT2 wave-cut platform (WCP), including an older buried WCP (NT3?). Section 28 of Alloway (1989) is close to this described section, but this was not discovered until after fieldwork had been done. The following discussion provides another perspective on Alloway's "Section 28" rather than a reinterpretation. It was also hoped that such a study would facilitate the linkage of coverbed stratigraphy further north with the more well constrained stratigraphy of the Taranaki Peninsula.

Alloway's stratigraphic nomenclature is used except in the case of "unnamed laharic unit" which I have referred to as "lahar-1" (a summary of each of Alloway's units is given at the end of this section).

3.2. Description and interpretation

3.2.1. Sediments pre-dating the LIGM
At the cliff collapse site (Q19/240 457), Quaternary sediments unconformably overlie the late Miocene Urenui Formation. Although the contact between Urenui Formation and overlying Quaternary sediments was not exposed, prominent gently sloping exposures of Urenui Formation (very hard, concretionary fine sandstone) in the tidal zone show that the contact must be angularly unconformable.

The lowermost Quaternary unit inferred to unconformably overlie Urenui Formation and underlying lahar-1 (see notes below), appears regressive:

The lowermost unit is tentatively inferred to be shallow-marine and consists of cross-bedded andesitic pebbly sand (photo 3-1), with the cross-bedding sharply defined by concentrations of blue-black "iron-sand" (titanomagnetite-rich). The cross-bedded sands quickly give way to sandy, tephric, carbonaceous muds which are inferred to be non-marine. The lowermost unit is directly overlain by lahar-1.

To the west, in the vicinity of the NT1 strandline (Q19/238 460), the contact between
lahar-1 and the underlying unit described above (at Q19/240 457), is again exposed on some parts of the modern WCP.

Here the unit is a pale-brown, slightly carbonaceous, sandy clay/mud, and contains scattered rounded quartz and andesite pebbles. A thin (c. 1mm) matt of black fibrous plant material occurs at the upper contact of this unit with lahar-1, showing that the carbonaceous clay/mud was subaerially exposed before being inundated by lahar-1 (photo 3-2).

The andesitic sediments underlying lahar-1 (see photo 3.-1), attest to active volcanism from the now extinct Pouakai Volcano. According to Alloway, Mt Taranaki/Egmont volcanism began at about 130ka B.P. The sediments beneath lahar-1, as well as lahar-1 itself, most likely were deposited prior to this date since the NT2 WCP was cut at c. 120ka and sea level was still very high at 130ka (±5m: Pillans, 1990). It would seem, from the inferred regressive sequence underlying lahar-1, that the sediments and the lahar were deposited during a phase of falling sea level. The proximity of the inferred WCP (unconformable upper contact of the Urenui Formation) suggests deposition of overlying units shortly after a highstand of sea level. The sea level highstand which cut the WCP (beneath lahar-1) is older than the LIGM, it is therefore reasonable to assume that it was cut during δ¹⁸O Stage 7a, the Penultimate Interglacial Maximum at c. 210 ka B.P. The WCP is therefore the NT3 WCP, which is equivalent to the Ngarino Terrace WCP in South Taranaki/Wanganui. It then follows that the overlying units were deposited shortly afterwards during the ensuing period of regression.
PHOTO 3-1: (Q19/ 240 457) Cross-bedded andesitic sands and pebbles beneath sandy tephric muds. Cross-bedding is sharply defined by concentrations of black iron sands. This unit probably represents Pouakai-derived material, prograding in a shallow-marine environment across an abraded platform of Urenui Formation. This lowermost Quaternary unit is overlain by lahar-1.
PHOTO 3-2: Q19/238 460: The contact between lahar-1 above, and pale-brown carbonaceous clay/mud below, is exposed on the modern WCP close to the NT1 Terrace at Turangi Road. Right at the contact (tip of pen) a thin matt of fibrous plant material occurs. This further supports the emergence of an older (probably NT3) WCP which underlies a similar clay/mud unit further east at Q19/240 457.
Reddish-brown andisol (Holocene climatic regime) (Sr1)
Yellowish LLA (Sy1)
Reddish andisolic paleosol (Sr2)
Ephra Tephras (80 to 100 Ka. B.P.) & Te Arei Tephra (77 Ka. B.P. ?)
Upper woody-lignite
Fine-grained, slightly carbonaceous muds

Basal leafy-lignite/tephra sequence detail.

65 cm.

Ponga-root mat.
Fine-grained, tephric lignite
-blocky structure.

'Dirty' tephra.

Andesitic tephras (coarse-ash & lapilli)

Tephric lignite: beiled, & leafy.

Moist, fine-grained, leafy lignite.

Shallow marine coverbeds:
-rounded andesitic cobbles fining up to medium/coarse sand.
-W.C.P. of NT2 Terrace - Cut during LIGM:
(Oxygen Isotope Stage 5e, max. at c. 120 Ka. B.P.)
W.C.P. at 3 to 3.5 km from NT2 strand-line.

Lahar 1: rounded-angular andesitic boulders & cobbles in clay-rich matrix.
- Precedes LIGM
- Unnamed laharian unit (Alloway, 1989)

More friable.
- Tephric, clay-rich, sandy, slightly carbonaceous sedis.
- non-marine

Euhedral hnh.

Cross-bedded sand, grit, & small pebbles.
- Probably shallow-marine.

Angular unconformity - NT3 W.C.P. (Alloway, 1989) at c. 7 km from its strand-line
Urewere Formation: Miocene, gently dipping, hard fine silt.
- exposed on inland-crest at lower titles.

FIGURE 3-1: Stratigraphic column for Q19/240 457, 400 m cast of the NT1 Terrace at Turangi Road.
Column exposes NT2 Terrace coverbeds, as well as older Quaternary units unconformably overlying late Miocene Urewere Formation.
PHOTO 3-3: NT2 Terrace coverbeds at Q19/240 457 overlying Lahar-1. Note thick lignite beds including intercalated andesitic tephas overlying Motu nui lahar. See stratigraphic column (fig.3-1) for details.
3.2.2. Sediments of the Last Glacial Cycle

Marine coverbeds overlying the NT2 WCP consist of rounded andesitic cobbles, gravel and sand (mid-lower right of photo 3-3), and represent, at least in part, andesitic clasts reworked from lahar-1. These sediments are shallow marine and were deposited on a gently sloping shelf, not more than 3-3.5 km from the coast (which is the distance from the NT2 strandline representing maximum LIG transgression).

A thin, dark-brown andisolic paleosol is formed at the top of the marine sands and gravels. Judging from its thickness, and the extent of paleosol development in the marine sands, the surface was probably not long emergent before it became inundated by the "Motunui laharic deposit" (see notes below).

The Motunui laharic deposit is overlain by fine-grained lignite with intercalated beds of andesitic tephra, showing that vegetation became quickly established on the fresh lahar surface during a period of very active volcanism (photo 3-3). It was observed along the coast south of Onaero, that the thickest lignite beds occur within hollows in the upper laharic surface. Shallow depressions in the lahar surface must have facilitated the formation of swamps or even small lakes which would have provided for the accumulation of plant material along with andesitic tephra beds.

The eight tephras (A to H in figure 3-1), calated within leafy lignite beds, are believed to represent the "Ninia" tephras described at, or near this section by Alloway (see notes below).

The texture of the lignite coarsens upwards. At the base the lignite is fine grained and contains fine grass-like leaves. At a level 65cm from the base a matt of roots remarkably like those surrounding a ponga tree-fern was found (see detail in figure 3-1). Immediately above this the lignite becomes thick and woody (photo 3-3). This transition from grass to tree-fern to hardwood can be simply interpreted as the improvement of drainage as the depression became infilled with organic and tephric material.

The woody lignite is overlain by a pale, fine-grained, massive, slightly carbonaceous unit, which Alloway described at Section 28 as "olive-grey carbonaceous muds". The muds are overlain by a second woody lignite containing in situ tree-stumps. A set of several thick andesitic tephra layers immediately follows. These are interpreted as the "Epiha" tephras (see notes below), and may also contain the Te Arei Tephra whose age is estimated at 77 ka B.P. by Alloway (1989).
The uppermost 4m consists of loess-like andisols and andisolic paleosols (see section 3.5 for terminology) which are difficult to differentiate without detailed knowledge of pedology, but which appear to consist of only one LLA (Sy1) sandwiched between Holocene andisol (Sr1) above, and andisolic paleosol below (Sr2). The LLA is recognised principally by its yellowish colour and relative lack of soil structure (in fresh exposures). The paleosol is recognised by its reddish colour and more prominent soil structure.

The complete andisol succession for the Last Glacial cycle consists of five paleosols alternating with five LLA's. The thickness of andisol beds above the tephra is only about 4m, which is much less than the typical thickness of andisolic beds seen along the coast further east (eg. figures 3-3 & 3-4). Also, the top of the Epiha Tephras has a sharply contrasting colour and structure with the overlying paleosol, which suggests a disconformity. The andisol sequence at this site may therefore be incomplete.

3.3. Stratigraphic units used by Alloway

3.3.1. Unnamed laharic unit (Alloway, 1989).
Here referred to as "lahar-1". One of several unnamed lahars originating from the extinct Pouakai volcanic centre, closely following emergence of the NT3 terrace.

Age (this author): 210- 120 ka B.P. Younger than the cutting of the NT3 WCP, and older than the cutting of the NT2 WCP. Probably closer in age to the NT3 (say 200ka).

3.3.2. Ninia tephra (informal formation, Alloway- 1989)
Description: "Well preserved tephra layers within lignite, in coastal cliffs...east of Waitara (eg. Section 28...)". Section 28 is an informal reference locality for the Ninia tephra. The tephra "comprises a closely spaced set of at least four pumiceous coarse ash beds". The tephra overlies Motunui lahar and underlies Epiha Tephra. At a "poorly accessible" inland site described by Alloway, and ascribed informal type-section status; at least thirty-four bedded, fine-ash to fine-lapilli layers which overlie Motunui lahar and underlie Okawa Formation (a lahar which did not quite reach the coast in the field area) are exposed.

Age: Ninia tephra is the lowermost tephra formation overlying sands above the NT2 WCP, and inland occurs beneath the palesol unit, Sr5. On this basis an age of c. 100- 115 ka. B.P. was estimated.
3.3.3. Motunui Lahar Deposit (Informal formation, Alloway 1989)

Description and contacts: "A single c. 4.25m thick, dominantly unstratified heterolithologic mudflow unit", occurs within the NT2 coverbeds exposed within coastal cliffs from just east of Waitara to the Onaero River. The lahar overlies "planar to low angle cross-stratified, well sorted andesitic sands and gravels". Alloway describes a thin carbonaceous paleosol "directly developed in these gravels, but this was not noticed by the author at this particular site. The Motunui lahar is closely overlain by Ninia Tephra (bed "Ni.a") and lignite.

Origin: This lahar was believed by Alloway to have been channelised down the Waitara River Valley. Alloway was unsure whether the "Motunui laharic deposit originated from a youthful ancestral Egmont volcano or an actively degrading Pouakai Volcano".

Age: Alloway assigns an age of c. 115ka B.P. to the Motunui lahar based on its spatial relationship to the underlying NT2 WCP.

3.3.4. Epiha Tephra (Formation, Alloway 1989)

Description: The tephra is "particularly well exposed along the north Taranaki coast where it comprises a closely spaced set of at least seven coarse-ash and lapilli beds". At section 28, Epiha Tephra is separated from Ninia tephra by a thick woody lignite, then "olive yellow carbonaceous muds". The uppermost Epiha tephra bed, is separated from Te Arei Tephra above by several centimetres of "light-grey clay loam".

Age: Based on its stratigraphic relationship to other formations the Epiha Tephra has an estimated age-range of 80-100 ka B.P.

3.4. The NT2 Terrace Soil Accession

The following is a basic summary of the findings of Alloway et al. (1992). Two coastal sections observed between Turangi Road and the Onaero River mouth, are then discussed within this framework.

For about 10m below the NT2 Terrace surface, an alternating sequence of horizontal yellowish and reddish-brown units can be found. Parent material is mainly derived from the andesitic Taranaki/Egmont Volcano whose eruptive history has been documented for the last c. 130ka by Alloway (1989). Parent material thus accumulates during, and shortly after eruptive events, and undergoes subsequent weathering with resultant soil formation. Alloway (1989) initially classified the reddish-brown units as "paleosols",
and the yellowish units as "tephric loesses"; respectively corresponding to warm-humid periods of soil formation, with intervening cool-dry periods of reworked tephric loess accretion. Later on he realised that, more correctly, "the whole stratigraphic column for the last 130,000 years was essentially one big weathered soil accession and not simply loess with intervening periods of soil formation" (pers. comm. Alloway; August 1992). Contrastings degrees of weathering and soil formation are controlled by alternating climatic phases during the Last Glacial cycle.

Alloway et al. (1992) have recently re-classified the yellowish beds; which exhibit a "poorly developed to massive soil structure", as "loess-like andisol" beds. In contrast, the reddish-brown beds have "moderate to well developed soil structure", and are classified as paleosols.

Previous palynological investigations (reported in Alloway, 1989) have shown the yellowish loess-like andisols to have formed during cool or cold climatic episodes (stadials) following the Last Interglacial (which climaxed around 120 ka. B.P.), and the reddish paleosols to have formed during relatively warm climatic episodes (interstadials).

Alloway's findings are partly based on an intensive investigation of a NT2 coverbed sequence (fig.3-2), exposed in a road-cutting just north of Onaero (Q19/284 442). This site provides a rare, complete exposure of the full succession of the loess-like andisols and intervening paleosols. Alloway et al. (1992) refers to the yellowish "loess-like andisol" beds as Sy beds; #1 -5, and the reddish-brown paleosol beds as Sr beds; #1 -5. The alternating Sy-/Sr- sequence was carefully analysed to yield the total quartz content of the residual sediment, after the clay (allophanic) and organic material has been dissolved. Variation in the fine-grained quartz fraction (<9% of the total) was taken to indicate rates of aerosolic quartz addition from non-andesitic provenances.

Alloway was then able to correlate this with the deep-sea (DSDP Site 594), and ice-core (Vostok) record of atmospherically transported sediment, verifying earlier more proxy correlations of the Taranaki soil accession with the global climatic record since the Last Interglacial Maximum (δ18O Stage 5e).

The quartz accumulation rate (QAR) results indicate that the Sy1 and Sy3 units are correlated with δ18O Stages 2 and 4 respectively; the only episodes of full-glacial climate in the western North Island during the Last Glacial cycle. Moreover, the climate during δ18O Stage 2 was the most severe, and this is supported by prominent eolian
sand dunes in this portion of the stratigraphic record, and which are absent from that portion corresponding to δ¹⁸O Stage 4 (loess-like andisol bed Sy3). Less severe, cool climatic conditions occurred during mid-δ¹⁸O Stage 3, which correspond to loess-like andisol bed Sy2; and δ¹⁸O Stage 5d and 5b, which correspond to loess-like andisol beds Sy5 and Sy4 respectively (fig. 3-2, below).

![Figure 3-2: Stratigraphic column for the road cutting just north of Onaero, containing alternating paleosols (Sr) and loess-like andisols (Sy). Total quartz content (TQC) and quartz accumulation rate (QAC) are shown alongside. QAR is highest during Sy1, corresponding to δ¹⁸O Stage 2 (the Last Glacial Maximum). Modified from Alloway et al. (1992).](image-url)
3.5. Onaero Surveying

3.5.1. Introduction

The NT2 wave-cut platform (WCP) and its coverbeds are exposed in a S.H.3 road cutting c. 1.5km west of the NT2 Terrace riser/strandline position (photo 3-4). The section is found c. 300m north of the Onaero River bridge at Q19/123 456. This is the locality from which Alloway (1989, et al. 1992) documented the 'loess-like andisol' (LLA) and andisolic paleosol succession. Using the aerosolic quartz content of each andisol unit Alloway was able to correlate them with δ18O stages of the Last Glacial cycle (see section 3.4).

3.5.2. Surveying

Using a 'Sokkisha' total station (see Appendix I and section 1.9), the height of the NT2 WCP in the road-cutting was measured relative to a nearby geodetic benchmark ('EC16'). Very precise altitude control relative to MSL was thus achieved. Other features of interest were also 'tied-in' to the geodetic benchmark (see photo 3-4 for location of surveyed features and Table 3-1 for altitudes): These were the inner and outer bends of the Holocene river terrace surface immediately downstream of the old Onaero River bridge (c. 500m from the Onaero River mouth), and the HWM from the most recent high-tide at that location.

PHOTO 3-4: Oblique aerial view of Onaero-Urenui area from an altitude of about 550m. Surveyed Holocene area near Onaero River bridge at lower right. See overlay.
TABLE 3-1: Altitudes above MSL of features of interest at Onaero.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Notes</th>
<th>Altitude1 (m above MSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT2 wave-cut platform</td>
<td>WCP/coverbed contact 1*</td>
<td>27.62</td>
</tr>
<tr>
<td></td>
<td>WCP/coverbed contact 2*</td>
<td>27.44</td>
</tr>
<tr>
<td></td>
<td>rnd. cobbled/sand contact</td>
<td>30.43</td>
</tr>
<tr>
<td>Geodetic benchmark</td>
<td>'EC16' (datum)</td>
<td>11.34</td>
</tr>
<tr>
<td>Holocene River terrace</td>
<td>Inner bend of terrace</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>Outer bend of terrace</td>
<td>6.52</td>
</tr>
<tr>
<td>HWM on riverbank below bridge</td>
<td>High tide on 20/8/91 was</td>
<td>1.26</td>
</tr>
</tbody>
</table>

3.5.3. Findings

The main finding is that the altitude of the NT2 WCP, at an important climo-stratigraphic 'type' locality, is at altitude of 27.5 ± 0.1 m above MSL. The WCP is overlain by c. 2.9m of rounded andesitic pebbles-cobbles in a sandy matrix, which alternate with laminated to weakly cross-bedded coarse andesitic sands. These are in turn overlain by well-sorted pale-grey sands, then the andisol succession described by Alloway et al. (1992).

3.5.4. Other observations

(1) The slope between the two points, contact #1 and #2 is essentially flat if measurement error is considered, or 0.3° if it is ignored.

(2) Siltstone of the NT2 WCP, exposed by running water at the side of the road-cutting, contained distinctive small holes, probably marine-borings.

---

1 Height above "Mean Sea-Level" measured relative to Geodetic Datum 1949.

* Contact #1 is the outermost exposure of the WCP. Contact #2 is 40m up the road.
3.6. NT2 Terrace coverbeds, near Waiau Stream

About 100m north of Waiau Stream (Q19/260 448) coverbeds of the NT2 Terrace are exposed in coastal cliffs. The NT2 wave-cut platform (WCP) is cut into late Miocene (Tt) siltstone of the Urenui Formation. Approximately 15m of coverbeds overlie the WCP which is at a height of about 9m above HWM at a distance of c. 2.0km from the NT2 strandline. Immediately overlying the WCP is the Motunui laharic deposit (at the north head of Waiau stream, shallow marine sands are preserved between the WCP and the lahar). The incised channel (fig. 3-3) and lack of marine sands (with paleosol) indicates subaerial exposure of the NT2 WCP after the LIGM highstand and incision of stream channels prior to inundation by the lahar.

The general coverbed sequence (figure 3-3) is similar to that described in section 3.2 in that Motunui lahar is directly overlain by a thin lignite, followed by andesitic tephras and an andisolic soil accession. Note that shallow marine coverbeds (with paleosol) are often totally absent in this area of coast, with Motunui lahar directly overlying the WCP.

The sequence overlying Motunui lahar is described in Table 3-2 below. Overlying the tephras, 'A' and 'B', with a sharp colour change, is a thick, weathered soil accession of andesitic derivation. The alternating yellowish and reddish-brown beds would be expected to have a high degree of correlation with Alloways Sy-/Sr-sequence at the nearby Onaero road cutting (Q19/284 442). It seems likely that a complete record of each climatic episode in the Last Glacial Cycle is present.

TABLE 3-2: Coverbed sequence overlying Motunui lahar with oldest unit at top, youngest at bottom.

<table>
<thead>
<tr>
<th>Unit label</th>
<th>Description</th>
<th>Climatic affinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>Thin, dark carbonaceous band overlying Motunui lahar.</td>
<td>δ¹⁸O Stage5d</td>
</tr>
<tr>
<td>A</td>
<td>Pale-brown andesitic tephra, gently undulating beds. Probably Ninia Tephra (est. age c. 100-115 ka.)</td>
<td>δ¹⁸O Stage5d-c</td>
</tr>
<tr>
<td>B</td>
<td>Pale-grey, reworked andesitic tephra. Massive with short vertical joints which terminate abruptly at the top. Reworked Ninia Tephra?</td>
<td>δ¹⁸O Stage5d?</td>
</tr>
<tr>
<td>C</td>
<td>Orange-brown unit. Faint, discontinuous, paler and darker bands can be seen within the unit, probably tephras (Epih?). Short vertical joints, generally not confined to any particular horizon occur throughout, though not at the base. However, at far-right, a distinct set of joints occupies the middle portions, and is clearly bounded at the top by a darker layer.</td>
<td>δ¹⁸O Stage5</td>
</tr>
<tr>
<td>D</td>
<td>A thin, but distinct dusky red-brown horizon. Could be a more oxidised zone at the top of unit-C, rather than a paleosol (?).</td>
<td>δ¹⁸O Stage5c?</td>
</tr>
<tr>
<td>E</td>
<td>A thin, well defined, pale-yellowish bed i.e. a loess-like andisol (Sy/24).</td>
<td>δ¹⁸O Stage5b?</td>
</tr>
<tr>
<td>F</td>
<td>Reddish-brown paleosol (Sr/4).</td>
<td>δ¹⁸O Stage5a?</td>
</tr>
</tbody>
</table>
A thicker loess-like andisol (Sy?3), becomes darker toward top merging into H ie. subsequent soil formation in the loess-like andisol.

**H** A thin, but prominent dark-brown paleosol (Sr?3).

**I** Prominent loess-like andisol (Sy?2).

**J** A thin, but prominent dark-brown paleosol (Sr?2).

**K** A thin, more subtle yellowish loess-like andisol (Sy?1).

**L** Dark-brown soil of the most recent warm climatic episode (Sr1).

By counting back from the most recent soil (Sr1), each yellowish and reddish-brown bed is tentatively assigned to Alloway's scheme, except the first paleosol/loess-like andisol pair, Sr5-Sy5-, which cannot be identified, but should stratigraphically overlie Motunui lahar assuming Alloway's ages of c. 115ka B.P. for the Motunui lahar, and slightly younger for Sy5 and Sr5 (see figure 3-2).

FIGURE 3-3: NT2 Terrace coverbeds just north of Waiau Stream with emphasis on the soil accession overlying Motunui laharic unit (c. 115 ka B.P.). Note incised channel.
3.6.1. NT2 Terrace coverbeds, Onaero Beach

In coastal cliffs (Q19/275 449) just north of the beach houses at Onaero Beach Road, is exposed a coverbed sequence of the NT2 Terrace. The NT2 wave-cut platform (WCP) is formed in late Miocene siltstone of the Urenui Formation. Approximately 15m of coverbeds (fig. 3-4) overlie the WCP which is at a height of about 9m above the HWM at a distance of c. 1.5km from the NT2 strandline. Immediately overlying the WCP is the Motunui laharic deposit, which thins noticeably in the last several hundred metres before reaching the southern banks of the Onaero River (the abruptly defined northern limit of Motunui lahar coastal exposures). The coverbed sequence is typical of that found in coastal exposures between Onaero River and Turangi Road end.

A thin lignite bed overlies the lahar as at the previous section (Q19/260 448). However, the unit immediately overlying the lignite is, unlike the obviously tephric unit at the previous sections to the south, more similar in overall appearance to the other loess-like andisols higher up the cliff-section. This unit is tentatively correlated with Alloway's Sy5. Overlying this unit is a prominent andisolic paleosol (Sr5), followed by the loess-like andisol (LLA); Sy4. A more subtle paleosol (Sr4) then occurs and is overlain by a LLA (Sy3). Further up a prominent paleosol (Sr3) is overlain by a LLA (Sy2). A thin paleosol (Sr2) then occurs, and another LLA (Sy1). Finally, a dark soil of the most recent warm climatic episode occurs (Sr1). The number of alternating beds seem to match perfectly with Alloways Onaero Sy-/Sr- sequence (only 1.2km distant), suggesting that a complete record of each climatic episode in the Last Glacial cycle is present at this coastal site (figure 3-4).

FIGURE 3-4: Field sketch showing the number of alternating beds in the soil accession overlying Motunui lahar and lignite in the NT2 Terrace coverbeds, Onaero beach.
3.7. Waiau Stream benches

3.7.1. Description

Cliff exposures west of Waiau Stream mouth reveal a sequence of progressively more elevated benches formed in Urenui Formation siltstone (figure 3-5).

The two main benches are labelled A and B. The coverbed stratigraphy of each bench was investigated but was difficult to resolve, especially bench-A, as access was impossible, forcing remote inspection by binoculars. Obviously bench-A is older than bench-B (higher elevation and more coverbed divisions).

**Bench-A** occurs at c. 8m above the modern boulder bank, and is about the same height as the NT2 WCP which occurs just west (right) of figure. The basal unit overlying bench-A contains rounded (andesite) cobbles and is either a marine conglomerate or a thin weathered laharic layer (ie. Motunui lahar). The yellowish unit which overlies it consists of very poorly sorted cobbles and pebbles (probably andesite) in a yellowish-brown matrix (not a LLA). The next unit up is a brown layer interpreted to be an andisolic paleosol. This is overlain by a yellowish unit (probably a LLA) which 'lenses out' at either end, and is overlain by a very subtle, thin brown bed, which is interpreted to be a paleosol. The paleosol/LLA association is repeated up-section. The highest unit is a reddish-brown soil of the Holocene climatic phase.

**Bench-B** occurs at c. 4m above the modern boulder bank (representing storm HWL). Bench-B is overlain by a veneer of andesitic cobbles then andesitic sands with bands of andesitic and quartzose pebbles. The andesitic sands are laminated to cross-bedded grey sands, and are sorted into iron-sand layers which alternate with hornblende and feldspar-rich layers, cross-bedding implies a current flowing inland. The sands are overlain by a thick yellowish tephric clay which grades upwards into a soil/loam with recent erosion and deposition of a sandy soil at the very top (probably a result of landdestabilisation from farming). No tephra markers were found.

### 3.7.2. Tentative interpretation

It is suggested that the andesitic cobbles and sorted sands overlying bench-B are very shallow marine. The altitude is comparable to that of the NT1 strandline at Turangi Road and hence bench-B may also be associated with this high sea level event.

The affinities of bench-A are also difficult to define, but owing to its altitude close to that of the NT2 WCP, the absence of marine sands (with paleosol), but possible presence of Motunui lahar, it is most probably a surface that was stripped and eroded during the
FIGURE 3-5: Cliff exposures from just east of Waiau Stream (left) to the west (right). A sequence of benches descend from the level of the NT2 WCP (just right of figure) at c. 9 m above HWM, towards the Waiau Stream mouth where the lowest bench is c. 2m above HWM.
period of formation of the lowermost paleosol which occurs in the marine sands exposed in coastal cliffs.

3.8. Summary
Sections 3.1 to 3.3 reached similar conclusions to Alloway (1989), finding that an abraded platform cut in Urenui Formation and overlain by lahar-1, exposed in coastal cliffs at ~MTL, is probably wave-cut, and that the sediments overlying it are regressive, recording the transition from shallow marine to sub-aerial conditions, before inundation by a lahar sourced from the now extinct Pouakai Volcano. The WCP is thought to have formed during the $\delta^{18}$O Stage 7 highstand, which is correlated with the NT3 Terrace for North Taranaki, and the Ngarino Terrace of South Taranaki/Wanganui.

A lignite overlying Motunui lahar records a transition from grass to tree-fern to hardwood. Ninia Tephras occur at the base of the first lignite, while Epiha Tephras (and Te Arei) overlie the second lignite. The andisolic succession at the studied site consisted of the sequence Srl-Sy1-Sr2-?Sy2 with the remaining beds not able to be identified.

In sections 3.4 to 3.7 a range of topics were considered. Aside from the surveying, the main theme was the NT2 Terrace soil accession in the framework of Alloway (1992), and whether this could be simply applied 'in the field' ie. visually and at a distance (in the predominant case of inaccessible sections).

In section 3.7 the alternating yellowish and reddish coverbeds only tentatively matched the complete Last Glacial Cycle record ($\delta^{18}$O Stage 5e to $\delta^{18}$O Stage 1) defined by Alloway and consisting of five alternating yellowish (LLA) and reddish (paleosols) andisolic beds. Greater ambiguity was encountered at the base of the sequence overlying the lahar.

In section 3.6 the coverbeds showed a relatively unambiguous correlation with the Onaero andisolic 'type section'. Section 3.7, the number and type of andisolic coverbeds simply concluded that bench-A is older than bench-B as is obvious from altitude. Much more detailed analysis of soil structure, subtle tephra horizons and aerosolic quartz content would probably be needed to identify the age of the andisolic beds.

It is concluded that unless a full sequence of alternating andisolic beds is present, initial terrace age cannot be exactly dated (ie. assigned to a particular interstadial $\delta^{18}$O sub-stage).
Chapter Four
The Urenui-Onaero marine terraces

4.1. Introduction
4.1.1. Hay (1967) and Grant-Taylor (1964)
4.1.2. Discussion

4.2. Urenui terraces & geomorphology
4.2.1. Introduction
4.2.2. Last Interglacial Maximum Terrace (NT2)
4.2.3. Penultimate Interglacial Terrace (NT3)
4.2.4. Older marine terrace surfaces
4.2.5. Estimated age of oldest part of Urenui upland surface
4.2.6. Dissected, higher surfaces
4.2.7. Holocene river/estuary terrace, Urenui

4.3. Onaero-Urenui geomorphology
4.3.1. Drainage patterns
4.3.2. Drainage evolution
4.3.3. Other processes of landscape evolution

4.4. Summary
Chapter Four

The Urenui-Onaero marine terraces

4.1. Introduction

The Urenui terraces form the most comprehensive flight of uplifted marine terraces in Northern Taranaki. The Urenui terraces were described and mapped by Chappell (1964) in his unpublished Masters thesis. Chappell's description and classification is re-evaluated here (for reasons see section 1.3.1.).

Chappell describes the terraces thus:

"The Urenui set of terraces record 6 well marked stillstands (alternatively: oscillation maxima) of the sea. All these surfaces are mantled with 9 - 12 metres of andesite ash and while sand is seen to underlie the ash on all but the uppermost bench, the exposures are so poor that strand heights cannot be determined from the nature of these sediments on all but the two lowest terraces."

Using the altitude of the terrace surfaces (from topographic maps) and estimations of the "ash" mantle thickness, Chappell derived "stillstand heights" for each of the terraces (see Table 4-1). Stillstand height being the altitude of transition from marine to non-marine coverbeds. Chappell individually labelled the Urenui terraces 'U#' and related these to the more extensive North Taranaki/Waikato terraces.

**TABLE 4-1:** Urenui Terraces; terrace surface altitude (A), and maximum altitude of water-laid sediments (B). From Chappell (1964).

<table>
<thead>
<tr>
<th>Urenui Terraces</th>
<th>(A) Terrace altitude</th>
<th>(B) Stillstand heights</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1 ↔ Terrace 1</td>
<td>3 metres (converted from feet)</td>
<td>1.8 metres (converted from feet)</td>
</tr>
<tr>
<td>U2</td>
<td>18</td>
<td>---</td>
</tr>
<tr>
<td>U3 ↔ Terrace 2a</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>U4 ↔ Terrace 2</td>
<td>68 (&quot;strand not known&quot;)</td>
<td>55 (max)</td>
</tr>
<tr>
<td>U5 ↔ Terrace 3</td>
<td>120</td>
<td>110 (max)</td>
</tr>
<tr>
<td>U6</td>
<td>140</td>
<td>---</td>
</tr>
<tr>
<td>U7</td>
<td>170 (&quot;strand not known&quot;)</td>
<td>160 (max)</td>
</tr>
<tr>
<td>U8</td>
<td>210 (&quot;at outer edge&quot;)</td>
<td>197 (min)</td>
</tr>
</tbody>
</table>
4.1.1. Hay (1967) and Grant-Taylor (1964)
The 1:250,000 Geological map for Taranaki (Sheet 7; Hay, 1967) shows the terrace forming formations in the Urenui area, with increasing age as 'Rapanui' Formation, 'Ngarino' Formation, 'Brunswick' Formation, Inglewood Lahars, Eltham Lahars, and New Plymouth Lahars. The three highest units are laharic andesite agglomerates, believed to have originated from the extinct Kaitake Volcano. Hay proposed that;

"marine benching and cliffing " occurred "between the periods of volcanicity marked by the deposition of the Inglewood, Eltham, and New Plymouth Lahars. In these early events the mapping does not differentiate these periods of marine benching and lahar building."

4.1.2. Discussion
It is difficult to reconcile the mapping of Chappell (1964) and Hay (1967) with each other, and with observations of aerial photographs by the present author. Obviously the mapping of Hay (1967), based on Grant-Taylor (1964), is simplistic given the scale at which it is depicted. Moreover, the linear coast-parallel boundaries implied between the Inglewood and Eltham, and Eltham and New Plymouth lahars are topographically subtle features. However, as will be discussed in the following section, two possible terrace risers were tentatively identified from a vantage point on Mataro Road.

Being at a larger scale, Chappell's map (1964) is much more detailed than Hay's, but the subdivision of the older Urenui upland surface/s into different levels (U5, U6, U7, U8) seems to be at least partially based on differences in coverbed thickness rather than any relationship to terrace strandlines. Moreover, the distribution of Chappell's higher 'terrace' surfaces (U5, U6, U7, U8) does not suggest a pattern characteristic to most flights of marine terraces, with implied terrace risers tending to follow topographic contours rather than being abandoned coast lines. Chappell's (1964) mapping of the flight of Urenui terraces above the "U4" terrace is therefore considered to be ambiguous by this author.
4.2. Urenui terraces & geomorphology

4.2.1. Introduction

In this study at least three distinct uplifted Pleistocene marine terrace formations and one uplifted Holocene river/estuary terrace are recognised.

PHOTO 4-1: Oblique aerial photograph taken from an altitude of c. 550m. Four terrace surfaces of the Urenui sequence separated by three terrace risers are seen to left of the Onaero river valley.

4.2.2. Last Interglacial Maximum Terrace (NT2)

(a) The NT2 Terrace (Chappell, 1975; subsequently Alloway, 1989) is equivalent to the Rapanui Terrace (Pillans, 1983), and it is very reliably constrained by the soil accession at Onaero (see section 3.4) as being initially formed during δ18O Stage 5e, the LIGM. This is the terrace which Chappell (1964) called "Terrace 2a".

Between the Onaero and Urenui rivers the NT2 Terrace is c. 2.0km wide and widens to the west of the Onaero (see figure 4-1).

The inner edge of the NT2 Terrace is delineated by a prominent terrace riser. The NT2 Terrace riser is crossed by most inland bound roads heading off S.H.3 between Waitara and Urenui (eg. about 1.3km up Kaipikari Road from the S.H.3 turnoff). The base of the NT2 terrace riser in the Urenui-Onaero area is at an altitude of 50-60 m and is the surface
expression of a buried fossil sea cliff and strandline. It was noticed that further west of Urenui, the sigmoidal profile of the NT2 terrace-riser is more subdued (see photo 4-2), and the NT2/NT3 surface offset is of a smaller amplitude. This suggests greater burial of the fossil sea cliff by the terrace coverbeds as the distance to the Mt Taranaki volcanlastic source decreases.

PHOTO 4-2: The NT2 terrace-riser (also buried seacliff and strandline) Ngatimaru Road [Q19/198,420], near Waitara c. 8km west of Onaero.

The actual NT2 strandline is nowhere exposed in the Urenui-Waitara area but using an average uplift rate of 0.29±0.01 m.ka⁻¹ calculated from the altitude of the NT1 strandline at Turangi Road, a NT2 strandline altitude of 39.8±1.2 m is predicted.

(b) Between the Onaero and Urenui river mouths is a well defined, but very narrow terrace surface, 200 to 300 m wide, and separated from the higher NT2 terrace surface by a prominent continuous terrace riser about 10m high (see photo 4-1). Thus, the outermost terrace surface between the Onaero and Urenui river mouths is topographically lower than the terrace surface immediately inland (the NT2 Terrace), as well as the coastal terraces south of Onaero as far as the NT1 strandline at Turangi Road. However, the difference in terrace surface altitude, rather than reflecting differences in the underlying WCP, actually reflects differences in coverbed thickness. The coverbeds do not contain a basal marine
unit, nor do they contain Motunui Lahar. The author believes this terrace to be underlain by a WCP cut during the LIGM transgression, but during its subsequent history the coverbeds must have been stripped, perhaps by an old river course of the Urenui or Onaero.

4.2.3. Penultimate Interglacial Terrace (NT3)

The next terrace above the NT2 Terrace is relatively narrow at c. 1.1km in the Urenui-Onaero area, but rapidly widens west of the Onaero River to c. 3.0km.

This terrace is (informally) named NT3 Terrace by Alloway (1989) and was tentatively correlated by him with the Ngarino Terrace in the South Taranaki/Wanganui district. The Ngarino Terrace strandline has an age of 210ka B.P. (Pillans, 1990). Chappell (1964) named this terrace "Terrace2" as he believed it to be close in age to his "Terrace 2a" since shown to be the LIGM terrace, NT2.

The base of the NT3 terrace riser in the Urenui-Onaero area is at an altitude of about 70m. The NT3 Terrace is separated from the higher Urenui upland terrace surface/s by a very prominent, relatively steep, terrace riser which is about 50m high (see photo 4-3).
The NT3 Terrace coverbeds were nowhere seen exposed in the Urenui-Onaero area. However the strandline altitude of the NT3 was calculated at 61 metres. Several assumptions were made; the NT1 Terrace 80ka average uplift rate of 0.29m.ka⁻¹ was extended to the last 210ka, and the Penultimate Interglacial highstand of sea level was assumed equal to that of the present day (Pillans, 1983). A strandline altitude of 61m only allows for about 10m of coverbeds which seems too thin, when the known thickness of the andisol accession alone on the NT2 Terrace is at least 15m. This may suggest that either average uplift rate for the last 210ka is slightly less than 0.29 m.ka⁻¹, or that paleo-sea level was in fact lower than that of the present day.

4.2.4. Older marine terrace surfaces

On the basis if aerial photographs (high altitude vertical commercial photographs, and my own low altitude oblique aerial photographs) it was only possible to recognise one distinct surface above the NT3 Terrace, although there is clearly a lot of topographic undulation. This surface extends inland a width of 2-2.5 km in the vicinity of Kaipikari Road, and is referred to as the Urenui upland terrace surface. The Urenui Upland terrace surface is composed of the NT4 Terrace and probably other older terrace formations.

From aerial photographs and topographic maps it is seen that the Urenui upland surface is generally highest in the centre of interfluve areas and reduces in altitude toward the edges of valleys where coverbeds (lahars and andisols) are being stripped.

A terrestrial based vantage point from the south side of the Onaero River valley on Mataro Road (Q19/292 373) shows the Urenui upland surface in profile. Two terrace risers are tentatively identified, and may be the basis for the boundaries mapped by Grant-Taylor (1964), which separate the Inglewood and Eltham, and Eltham and New Plymouth lahars, and shown on the Taranaki Sheet: (Hay, 1967).

Coverbeds of older marine terraces

Small 'windows' are accorded into the coverbed stratigraphy of the Urenui upland surface/s in scattered road cuttings. Notable exposures (in ascending stratigraphic succession) include:

(1) "Soap stone": Overlying Urenui Formation siltstones at the outer edge of the Urenui upland surface, in the road bank of Kaipikari Road as it ascends the 50m NT3 terrace riser, occur very weathered laharic or tephric material (basal contact obscured). This material is referred to by farmers in the area as "soap-stone" as it becomes very
sticky like soap would when worked in the hand (this implies a very high clay content, probably from feldspar weathering). This c. 15m thick unit is overlain in places by lignite with tephra interbeds, and finally thick undifferentiated andisols.

(2) **Andesitic lahar:** Thick weathered ancesitic volcaniclastics, probably laharic, occur in a Mataro Road cutting (Q19/299 371) at an altitude of c. 140m. The laharic unit contains rounded clasts in laminated pumiceous, highly weathered feldspathic sands, with coarser bands.

(3) i) **Rangitawa Tephra** was seen at several places in the road cutting towards the end of Kaipikari Road (unsealed section), near to the innermost margin of the Urenui upland terrace surface. Its occurrence at this locality (~Q19/332 390-330 394) was first brought to my attention by Pillans (pers. comm. 1991). The Rangitawa Tephra is dated at 350±40 ka B.P. (Pillans *et al.*, 1992) and its age has been the subject of much debate and research. Along this stretch of road is also seen the "soap stone" mentioned above, it also closely overlies Urenui Formation (and underlies Rangitawa Tephra), but again the contact is obscured.

(ii) A rhyolitic tephra was also found at one locality on upper Mataro Road at Q19/302 369 at an altitude of c. 160m. It was found c. 300m inland along the road from the laharic deposit mentioned above and is assumed to stratigraphically overlie it. The rhyolitic tephra is c. 15cm thick and contains abundant plagioclase and β-quartz, especially in the coarser crystal-rich middle zone.\(^1\) It is assumed to be the Rangitawa Tephra on the basis of its thickness and general similarity to the Rangitawa Tephra as seen on neighbouring Kaipikari Road, and also shown to the author by Brad Pillans in Waverley, south Taranaki.

**4.2.5. Estimated age of oldest part of Urenui upland surface**

Near Q19/330 380 the strandline altitude at the inner margin of the Urenui upland terrace surface was estimated from 1:50,000 topographic map contours (Q19-Waitara Sheet) at c. 200±20 m (photo 4-4). Based on a 0.3m.ka\(^{-1}\) uplift rate and the strandline altitude age is 670±70 ka B.P. Thus it may correspond to Piri or Marorau terraces, the two oldest known from the south Taranaki/Wanganui area and correlated with \(^{18}\)O stages 15 and 17 respectively. The terrace coverbeds reach c. 50m in thickness which also implies a considerable Quaternary age.

**4.2.6. Dissected, higher surfaces**

An even higher surface, or surfaces, probably once existed, but these are now completely dissected by erosion (see section 10.4). The past existence of a higher, possibly marine

\(^1\) OU 42568
terrace is suggested by an abrupt rise in summit heights from an altitude of about 200-300 m in the vicinity of Kaipikari Road, about 4.5km inland from the NT3 abandoned sea cliff.

4.2.7. Holocene river/estuary terrace, Urenui

It is known from the work of Gibb (1986) that the post-Glacial Holocene transgression reached the height of modern day sea level at around 7ka B.P. The Holocene river terrace height (also cited by Chappell, 1964 for his "Terrace 1") is about 1.8m above modern mud-flats along the banks of the lowermost Urenui River. Assuming the terrace formed around 7ka B.P., and that its elevation above the modern analogue purely represents uplift, then the implied average Holocene uplift rate is 0.26 m.ka\(^{-1}\).

4.3. Onaero-Urenui geomorphology

4.3.1. Drainage patterns

The area defined by the Onaero and Urenui rivers and their tributaries ie. the Onaero-Urenui catchment, exhibits three distinctive and contrasting patterns of drainage (figure 4-1):

**Orthogonal trellis**

The purple area exhibits an oriented, orthogonal trellis pattern of drainage. These streams are part of the highly dissected inland hillcountry in which streams are entrenched into siltstones and mudstones of the Urenui Formation. The parallelism and regularity of the drainage pattern presumably results from structural (and hence, ultimately tectonic) control, and probably reflects strong regular jointing sets within the Urenui Formation. The dominant orientation of the trellis (orthogonal and oblique) drainage is 210-230°.

**Dendritic**

The orange area shows a less regular, dendritic (branching) pattern, with the bifurcation of tributaries in a direction either roughly perpendicular or parallel to the terrace risers/strandlines.

These streams dissect the poorly consolidated, unjointed coverbeds of the NT2 and NT3 terraces and the outer edge of the 'Urenui upland terrace surface' (see section 4.2.4.). These streams are not as entrenched as those which dissect the older, higher, inland surfaces. The drainage pattern reflects the nature of the material it is formed upon:

"Fluvial drainage networks in homogeneous structureless materials typically have a randomly branching, space-filling dendritic pattern common to many stream systems in homogeneous structureless materials."
Notable alignment of drainage systems, and the pervasive parallelism of tributary orientation over large geographic areas suggests some degree of joint and/or fault control" - Laity et al., 1985.

**Oblique trellis**

The green area is similar to the purple area, in that the streams and tributaries are deeply entrenched into the underlying Urenui Formation and exhibit an obvious degree of tributary parallelism. In this area the drainage pattern can be described as oblique trellis drainage with a bifurcation angle of c. 60°.

**4.3.2. Drainage evolution**

Drainage development, or terrace dissection, always increases inland with each progressively older terrace (see figure 10-2, after Pillans 1988). In the Urenui-Onaero area, dissection of terraces clearly follows such a pattern, and increases until at a distance of c. 9km from the coast any terraces that may have once existed are completely dissected, and adjacent valley sides converge to knife-ridges. The depth of valley incision and valley width are other aspects of terrace dissection which increase with terrace height/age.

Streams which dissect the Urenui-Onaero terraces all lead either to the Urenui or Onaero rivers. This simple observation has some interesting possible connotations. The drainage divide between the Tuahu and Mangaonga streams, tributaries of the Onaero and Urenui rivers respectively, is a knife-ridge (highlighted at lower right of figure 4-2).

This Onaero/Urenui drainage divide extends coastwards from the Tuahu/Mangaonga knife-ridge as a less immediate, more subtle physical expression, which nevertheless clearly partitions streams draining westward to the Onaero, and eastward to the Urenui.

This subtle drainage divide can be visualised as the axis along which the present-day Tuahu/Mangaonga knife-ridge will extend as dissection (and tectonic uplift/eustatic regression) proceeds in future. It is possible that the Onaero/Urenui drainage divide implies very subtle anticlinal warping about the general trend of its axis, a possibility that was briefly explored with structural dip information.

Strikes and dips were measured on the west side of the Urenui River mouth and at the east end of the beach c. 600m distant. Apparent dips were found to be between 0 and 2°, so it was very hard to determine strike and true dip using the stereonet (strike was roughly SW). Planar joints, commonly conjugate, were found to have very similar orientations at both Urenui sites. From a small sample the average strike/dip of the joints
was 240/(75 °SW, 65°NW). This strike of the joints is close to that of the dominant orientation of inland trellis drainage (see previous section). Strike and dips at Onaero were not possible because of massive siltstone.

The drainage divide is the most abiding feature in the Urenui-Onaero landscape, for it is the axis of least geomorphic activity. The streams whose branching tips are closest to the 'subtle' drainage divide will cease to extend laterally when the area of first-order stream catchment is no longer sufficient to allow advance of the channel head by surpassing the critical threshold of overland flow (Willgoose et al., 1991).

Although the stream channels become fixed as they approach some limiting distance close to the drainage divide, incision may still proceed in response to the lowering of relative base-level. Gradual lowering of relative base-level may be achieved by tectonic uplift during stable sea level. Rapid lowering of base level may be achieved by the fall of sea level during the onset of cool-cold climatic phases. It is surmised that the onset of cool-cold climatic phases will result in a period of quickening rates of geomorphic activity due to an increase in potential energy, the source of 'work' for erosion (perhaps also vegetation change). There will of course be negative feedbacks from climate change as well, such as decrease in rainfall and chemical weathering, which will serve to oppose the 'work' afforded by a change in base-level.

It was observed that larger valleys have relatively wide and flat valley-floors allowing river meanders, but also have sharp and rectilinear valley-sides. Presumably during periods of low sea level, with increased potential stream-power ('work'), these valley-sides projected downwards to a narrow constrained stream channel. During periods of high sea level, the rise in base-level decreases potential stream power resulting in aggradation and partial infilling of river valleys. It is further submitted that some stream valleys without infilled valley floors must be single-cycle valleys, especially those of lowest order.

4.3.3. Other processes of landscape evolution

Groundwater sapping in the Onaero-Urenui area primarily takes place at the level of the wave-cut platform, where relatively impermeable, consolidated siltstones and mudstones of late Miocene age and quartzofeldspatic composition (Urenui Formation), underlie highly permeable, more poorly consolidated coverbed sediments of mid-late Quaternary age and andesitic derivation (Pillans 1985, 1988).
Pillans (1985, 1988) proposed that groundwater seepage which occurs at the wave-cut platform level in valleys dissecting a terrace, results in liquefaction and/or saturation at the base of the poorly cemented coverbeds. This then leads to undermining and slope-instability, with the tendency for loss of coverbed material at sites of groundwater seepage, either by slumping or smaller scale forms of enhanced mass diffusivity. This process results in recession of coverbed sediments from the dissected periphery of a terrace with the resultant formation of cuspate alcove-shaped valley landforms (see figure 4-2). The rate of recession of coverbed sediments from the dissected periphery of a terrace is probably limited by the rate of retreat of the underlying, relatively impermeable, Urenui Formation rocks.

Relatively impermeable Miocene rocks which generally underlie the terrace coverbeds also retreat, but probably via a mechanism different from groundwater sapping. Judging from the fluted, knife-ridged form of first-order stream valleys (see photo 4-4) that descend to the main valley floor with concave profiles, this mechanism is probably direct erosion resulting from overland flow.*

* The profile of first order stream valleys is concave. Ahnert (1988) used computer modeling to investigate the relationship of hillslope form to the processes acting on it. He found that a concave slope profiles implies the dominance of "wash-slope" and "long-lasting runoff producing rainfall events".
PHOTO 4-4: 'Carved' landscape looking inland (east) from the junction of Kaipikari and Matapo Road, Urenui. Truncated mudstone/siltstone of the Urenui Formation is overlain by thick coverbeds (c. 50m max.). Strandline altitude is at c. 200 ±20 m above MSL. Beyond lies completely dissected 'North Taranaki Surface'. The distinctive erosional landforms consist of knife-ridge 'buttresses' with scalloped flanks and faceted spurs. This extreme topography partly results from artificial straightening of the originally meandering stream channel further downstream. This steepened grade and induced erosion in the upper watershed by disturbing the dynamic equilibrium of the stream channel, thus demonstrating that the landscape system responds rapidly to disturbances such as base-level lowering.
FIGURE 4-1: Map drawn from aerial photographs showing three major kinds of drainage patterns (purple: orthogonal trellis, green: oblique trellis, orange: dendritic).
FIGURE 4-2: Map drawn from aerial photographs showing drainage and drainage divides. A drainage divide may be defined between streams which drain west (arrows) toward the Onaero river and those which drain east toward the Urenui. Infilled river valleys (yellow), and undissected terrace surfaces (red) are shown.
4.4. Summary

Previous work in the Urenui area was reviewed.

At least three Pliocene uplifted marine terraces are recognised: NT2, NT3, and the Urenui upland terrace surface (which is comprised of possibly three terrace formations).

The most coastal terrace surface between Onaero and Urenui River mouths is thought to be partially stripped NT2 Terrace.

The NT2 Terrace is c. 2km wide and widens to the west of Onaero. The NT2 strandline is not known to be exposed in the Urenui-Onaero area but the base of the terrace riser lies at an altitude of 50-60 m above MSL.

The NT3 Terrace is relatively narrow in relation to the NT2 (c. 1km in the Kaipikari Rd. area). The base of the NT3 terrace-riser lies at an altitude of c. 70m. It was tentatively suggested that either average uplift rate for the c. 210ka NT3 Terrace is slightly lower than that calculated for the c. 80ka NT1 Terrace at Turangi Road (0.29 m.ka⁻¹), or; that paleo-sealevel during the 210ka highstand was lower than that at present.

Several prominent units within the coverbeds of the Urenui upland terrace surface were described including a 10-15 cm thick rhyolitic tephra near the innermost part of the Urenui upland terrace surface thought to be the 350±40 ka Rangitawa Tephra.

About 4.5km inland from the outer edge of the Urenui upland terrace surface an abrupt rise in summit heights from c. 200 to c. 300 m occurs. This change is thought to indicate the presence of an older, completely dissected, palimpsest planar erosion surface.

A Holocene river terrace near the mouth of the Urenui River is tentatively used to imply an uplift rate of 0.26 m.ka⁻¹ for the last c. 7ka.

Three distinctive drainage patterns were recognised in the Onaero-Urenui catchment. The deeply dissected hillcountry exhibited an orthogonal trellis drainage pattern and suggested structural control from joint sets within the Urenui Fm. A dendritic drainage characterised the less entrenched streams on the NT2 and NT3 terrace surface, reflecting the homogeneous structureless nature of the coverbeds in which the drainage is evolving. Oblique trellis drainage in the upper Onaero River-Mangapoua stream, west of the orthogonal drainage, also reflects strong structural influence from the Urenui Fm.
It was observed that (terrace) dissection, valley incision, and valley width all increase inland with surface altitude and thus age. The Tuahu-Mangaonga stream drainage divide continues seaward as a more subtle geomorphic element which partitions streams draining westward to the Onaero and east to the Urenui. the drainage divide is the most abiding feature as it is the axis of least geomorphic activity.

The process of landscape dissection and drainage evolution was examined in the Urenui area, which provides a good example of drainage pattern characteristics on successively older surfaces from the NT2 Terrace through to the completely dissected NTS. In contrast to the palimpsest NTS1, Pleistocene marine terraces and Holocene coastal features may be directly related to tectonic uplift and eustatic sealevel change.

Effects of base-level lowering were considered. It was proposed that larger river and stream valleys with wide flat floors but rectilinear sides are infilled V-shaped valleys formed during a sea-level low stand. Lower order V-shaped stream valleys are probably single (climatic) cycle. Effects of artificial base-level lowering (several metres) were seen in the Urenui area where straightening of a meandering stream induced erosion in the headwaters.

1 There is a problem with providing a geologically rigorous definition of the "North Taranaki Surface", but the concept is nevertheless retained for the sake of discussion within this thesis. A possible partial description is that: (1) The NTS is the envelope of ridge-crest concordance in the completely dissected inland hillcountry. (2) The coastal boundary of the NTS is a westward migrating front of maximum dissection.
Chapter Five
NT2 Terrace and other sections north of Urenui .................. 63

5.1. Main Introduction .......................................................... 63
5.2. NT2 Terrace, Wai-iti Beach ............................................. 63
  5.2.1. Introduction .......................................................... 63
  5.2.2. Wave-cut platform ................................................... 64
  5.2.3. Marine/Estuarine coverbeds ....................................... 64
  5.2.4. Non-marine coverbeds .............................................. 65
  5.2.5. Environmental interpretation/conclusion ....................... 65
5.3. Pukearuhe ................................................................. 68
  5.3.1. Introduction/description ........................................... 68
  5.3.2. Coverbeds ............................................................ 69
5.4. NT2 Terrace & Holocene feature, Tongaporutu River mouth .... 73
  5.4.1. Introduction .......................................................... 73
  5.4.2. NT2 Terrace .......................................................... 73
  5.4.3. Abandoned Holocene riverside cave and borings ............. 74
  5.4.4. Conclusion .......................................................... 74
5.5. NT2 Terrace, Mohakatino .............................................. 76
  5.5.1. Introduction .......................................................... 76
  5.5.2. Road cutting, north of Mohakatino bridge ..................... 77
  5.5.3. Road cutting, south of Mohakatino bridge ..................... 79
  5.5.4. Age of sediments ................................................... 80
  5.5.5. Holocene Sediments, Mohakatino ............................... 80
5.6. Summary ..................................................................... 83
Chapter Five

NT2 Terrace and other sections north of Urenui

5.1. Main Introduction
Coverbeds of the NT2 Terrace at Wai-iti beach, Pukearuhe, Tongaporutu and Mohakatino are described (sections 5.2, 5.3, 5.4, and 5.5 respectively). Holocene features/deposits at Tongaporutu and Mohakatino are also described.

5.2. NT2 Terrace, Wai-iti Beach
5.2.1. Introduction
An entire NT2 Terrace coverbed sequence, totalling some 30m in thickness, is exposed in a large slip (Q18/373 515) along the coastal cliffs, about 1km south of Wai-iti Beach. The exposed coverbed sequence lies some 2km seaward of the NT2 strandline. The wave-cut platform (WCP), with overlying marine and non-marine coverbeds are briefly described.

PHOTO 5-1: Oblique aerial view of Wai-iti slip site and surrounding landscape, including abandoned seacliffs of the LIGM transgression, from an altitude of c. 550m. The undulating (NT2) terrace surface results from Last Glacial dune deposits. Dune crests in the vicinity of the slip-site trend sw/ne oblique to the NT2 strandline, whereas closer to the strand appear dunes(?) whose crests are parallel to it.
5.2.2. Wave-cut platform

The wave-cut platform (WCP) is cut into Urenui Formation (fig. 5-1). The Urenui Formation at this site consists of massive, blue-grey, silty-mudstone. The WCP was formed during the LGM (δ18O Stage 5e); and is roughly 10m above HWM at a distance of c. 2km from its strandline.

The morphology of the WCP is smooth and gently undulating, with amplitudes of a few tens of centimetres and wavelengths of a few tens of metres. Groundwater seepage forms a steady trickle in fine-weather and is concentrated in the troughs, with attendant precipitation of bright orange iron-oxide/algae.

5.2.3. Marine/Estuarine coverbeds

(1) Shallow marine coverbeds

The coverbeds are c. 2m thick, unconsolidated, and immediately overlie the WCP (figure 5-1). The basal layer is gravelly and consists of rounded quartz and andesite pebbles, with larger mst/sst cobbles exhibiting boring. The gravel fines upward into well-sorted, olive-brown, medium sands. The sands are massive to poorly laminated with occasional large pebbles. The uppermost 0.3m consists of coarse sand/grit and larger pebbles, and also contains large black hornblende crystals (shiny black cleavage faces).

(2) Alternating very shallow marine (?) and estuarine coverbeds

Immediately overlying the marine gravels and sands is a wood-bearing grey-clay layer c. 2m thick. The clay is capped with a thin lignite which readily splits to reveal grassy-leaf impressions. A second lignite occurs further up the sequence within dominantly marine sands. The lignites obviously record estuarine or swampy conditions.

Overlying the first lignite are some 8m of iron-cemented (?)marine) sands. The second lignite occurs approximately mid-way within these sands. The sands show internal deformation structures suggestive of either post-depositional slumping or perhaps coseismic shaking (fig. 5-1, especially centre). The original sedimentary structure appears to have been cross-bedded to wavy-horizontal (ripple-lamination?).

A down lapping structure is seen just below the second lignite at the left (north) of figure 5-1. In sequence stratigraphy, down-lap is taken to indicate the progradation of sediments as relative sea level rise slows, however whether this applies on the relatively small scale here is doubtful (pers. comm. C.A. Landis, 1993). Nevertheless, the implications of the

---

[1] Pillans (pers. comm. post-thesis) thinks this sounds like a dunesand. The fact that no pebbles were noted may support this.
lignite directly above is of shoaling and supra-marine conditions. The cross-bedding suggests progradation in a general north to south direction.

Oxidation of iron-bearing minerals intensifies toward the top of the very shallow marine sands. The partially cemented iron-stained character of these sands probably indicates the presence of oxygenated groundwater (ie. close to the water table) at some stage.

5.2.4. Non-marine coverbeds

(1) Aeolian dune sands

The sands abruptly pass into non-oxidised, non-cemented sands some 12m in thickness (fig. 5-1). The abrupt boundary between cemented and uncemented sands is irregular but basically horizontal, and probably erosional. This is indicated by the contrast between laminated to cross-bedded (marine) sands below, and large scale, high angle (aeolian) cross-bedding above.

The aeolian sands at Wai-iti slip can be subdivided into four 'phases' on the basis of prominent internal discontinuities. According to Alloway (1989), major dune building only occurred during the Last Glacial $\delta^{18}$O Stage 2 (see section 3.4); so the four phases may indicate smaller scale (probably local) fluctuations within this interval (note the paleosol formed on top of phase 3 dune sand, indicates brief stabilisation and vegetation, perhaps due to climatic amelioration).

On the Pouakai ring plain, the andesitic dune sands are named Katikara Formation and have an estimated age range of 20-13 ka B.P. (Neall, 1975). It therefore seems likely that the Wai-iti aeolian sands are a direct correlative of the Katikara Formation in coastal central Taranaki.\(^2\)

(2) Loess-like Andisols and paleosols

Overlying the aeolian deposits (fig. 5-1) is a yellow/brown loess-like andisol (LLA) unit, exhibiting only poor soil structure - nature and climatic affinities unresolved, but probably from the Last Glacial (ie. Sy1, $\delta^{18}$O Stage 2).

5.2.5. Environmental interpretation/conclusion

The rapid transition from very shallow marine to aeolian sands across a sharp, probably erosional and hydrogeological boundary, seems to fit well within the following scenario:

\(^2\)Pillans (pers. comm. post-thesis) points out that major glacial period dune building only occurred away from the coast and thinks that the Wai-iti dune sands are likely to be interglacial (ie. not Katikara Formation).
Progradation occurred during the LIGM high sea level with abundant andesitic detritus coming from the proto-Taranaki/Egmont Volcano. With the ensuing cool stadial, sea level rapidly fell, in turn lowering the water table and perhaps triggering internal slumping. Deposition may then have occurred upon the now subaerially exposed sands, but during \(^{18}O\) Stage 2 (or possibly Stage 4, the only other period of full glacial climate in the Last Glacial Cycle) the strengthening of aeolian processes could have stripped these coverbeds, and exhumed the old water table (more cemented). This process of stripping coverbeds down to the level of the water table was coined "ventiplanation" by Fleming (1953). Ventiplanation is the process leading to the formation of extensive plains of low relief by deflation of dunes down to the level of the watertable, implying "a reduction or cessation in the supply of sand from the beaches". The increased source area and windy arid conditions during the Last Glacial, combined with local topographic controls, may explain the thick aeolian sand deposits.
FIGURE 5-1: NT2 Terrace coverbeds c. 1km south of Wai-iti Beach at Q18/373 515. The coverbeds are fortuitously exposed in a large coastal slip. Note the thickness of aeolian deposits.
5.3. Pukearuhe

5.3.1. Introduction/description

At the Pukearuhe end of the White Cliffs walkway, a section (Q18/423 561) close to the front of a 'terrace-front valley' (Pillans, 1985) is exposed. A small unnamed stream emerges from the front of the abandoned LIGM seacliff, marking the position of the NT2 strandline (altitude c. 30m). As it crosses this line the stream changes in several of its characteristics.

![Diagram showing the stream channel and its relationship to the LIGM abandoned seacliff, and the position of the outcrop described in the text.](image)

**FIGURE 5-2** Precis location map showing the stream channel and its relationship to the LIGM abandoned seacliff, and the position of the outcrop described in the text.

**Up-stream** of the fossil NT2 seacliff, a gravelly stream-floor is developed, with a very low gradient towards the front of the valley. Fine weather stream-flow occurs over a width of 2 to 3 m. The stream-floor is composed of rounded sandstone and mudstone cobbles, pebbles, grit and silt, with the notable absence of andesite or quartz lithologies.

**Down-stream**, past the abandoned front of the seacliff, the stream runs over smooth, bare Mt Messenger Formation sandstone, and is deeply incised into a very narrow channel with steep-sided walls.
The difference between up and down-stream reaches partly reflects recent aggradation in the upstream reach, and degradation in the downstream reach. This recent aggradation/degradation results from the construction of a culvert to allow stream-flow to continue beneath the track where it crosses the stream. This man-made barrier has effectively dammed sediment transport through to the downstream reach.

There is a prominent natural difference between the relatively 'open' valley upstream of the strandline, compared to the channel immediately downstream which is narrow and steeply incised. This indicates that the upstream valley is much older. Below the culvert, at the head of the downstream reach, very hard, rounded, concretionary boulders occur in outcrop. They were also seen in a similar nearby setting at Q18/419 555. The concretions are very similar to those that weather from the uppermost Mt. Messenger Formation cliffs on the modern beach, and which are left deposited on the beach as the cliff retreats. Although they may have been weathered from the erosive action of the stream they may also be remnant from cliff retreat during the LIGM.

5.3.2. Coverbeds
(1) Abraded platform and basal conglomerate

The stream has down-cut some 5m through the abraded sandstone surface of the Mt Messenger Fm. at the entrance to the terrace-front valley (see fig. 5-3). This irregular abraded surface slopes gently upward from the stream for some 30m before levelling off, and is overlain by coverbeds containing a basal conglomerate. Directly overlying the sloping surface near to the stream only sandstone/mudstone cobbles and pebbles were seen. Whereas on the higher levelled surface, porphyritic andesite cobbles and pebbles occur in conjunction with sedimentary lithologies.

The basal conglomerate on the higher, level, abraded surface is believed to be shoreline deposit which formed close to the old seacliff during the LIGM. The rounded, porphyritic andesite and quartz cobbles/pebbles present evidence of long-shore drift from sources further south. Contrastingly, the mono-lithology of sandstone cobbles/pebbles on the lower, streamward sloping surface indicates isolation from such a source of andesite (and quartz) and may be attributed to a local inland source.

The streamward-sloping surface possibly represents the migration of the paleo-stream channel towards its present location, in response to a gradual lowering of eustatic sea-level and/or tectonic uplift of the coast (ie. lowering base-level).
An ensuing, more rapid fall of sea level may then have caused the stream to down-cut rapidly, 'locking' the stream into its present position. Geomorphology suggests that the stream once emerged from the terrace-front valley slightly further south than its present position, as suggested from the northward bend in the stream just before emerging from its valley (figure 5-3).

(2) Beach sands

Several metres of well-sorted, ferromagnesian-rich sands overlie the strandline conglomerate, but were not seen overlying the fluviatile conglomerate (fig. 5-3). The lower 0.5-1.0 m of sand are orangey in colour, and 'dusty' in texture.
FIGURE 5-3: Stratigraphic column for the 120ka shoreline sequence at the base of the abandoned LIGM sea cliff (right background) / inner margin of the NTZ Terrace, Pukearuhe. The inset sketch shows the outcrop exposed in a track at the start of the White Cliffs walkway (see text for discussion).
Recognisable hornblende and weathered feldspar occur as dark and light flecks within the orange, dusty sands. Some ferromagnesian minerals have preferentially oxidised and disintegrated to form an orange, iron-oxide.

Up-section the iron-stained sands give way to fresher dark-grey ferromagnesian sands with a common, ubiquitous feldspar component. The ferromagnesian component consists almost entirely of dark-green hornblende and transparent olive-green augite, very similar to modern north Taranaki beach sands. The crystals are often broken along cleavage planes into prismatic shapes, often one side of the crystal, or less commonly the entire crystal is abraded (frosted appearance), but with the original euhedral crystal form still visible. The fractured and abraded character of the grains is very similar to that found on the modern beaches of north Taranaki, testifying to the high energy surf environment. In the lower parts the sand is horizontally laminated but higher up appears structureless.

Towards the middle of this fresh sand unit a prominent band of pale, whitish sand occurs. The layer is 30 to 50 mm thick, horizontally continuous, and sharply defined. It contains hornblende and augite, but is overwhelmingly dominated by feldspar crystals. Many of the feldspars are quite fresh exhibiting twinning and zoning, other crystals are more weathered and disintegrate easily to a powder giving a 'chalky' character. It is probable that the feldspar-rich layer records an andesitic eruption from the early Mt. Taranaki/Egmont Volcano that occurred during a southeasterly wind, causing the tephra to be deposited directly into the immediate environment. These feldspars are thus primarily regarded as pyroclastic phenocrysts. To minimise mixing with other beach-sand components the air-fall tephra must have only been briefly worked in the beach environment. The feldspar component throughout the rest of the sands is obviously from tephras more thoroughly worked by long-shore drift from areas south.

(3) Andisolic units

Overlying the sand is a sequence of andisolic units, subdivided into yellowish, Sy beds, and reddish-brown, Sr beds (after Alloway et al. 1992; see section 3.4). The lower Sy bed contains a layer of rounded mudstone cobbles and quartz pebbles. The Sy bed is overlain by a Sr bed. The field relationship of Sr beds implies deposition of a second Sy bed over the first Sr bed, followed by erosion, then deposition of a second Sr bed, followed by deposition of the final Sy bed (see figure 5-3).
5.4. NT2 Terrace & Holocene feature, Tongaporutu River mouth

5.4.1. Introduction
Two separate features are discussed; the NT2 Terrace coverbeds on either side of the lower Tongaporutu River, and an abandoned Holocene riverside cave.

5.4.2. NT2 Terrace

5.4.2. South side of river:
The NT2 WCP and its marine coverbeds are exposed in Clifton Road as it ascends from the Tongaporutu riverside batches onto the NT2 Terrace surface (Q18/461 637). The WCP is formed in fine grained micaceous sandstone of the lowermost Mt Messenger Formation. It is overlain by a c. 0.25m thick basal conglomerate consisting of well rounded cobbles and pebbles of andesite, quartz, greywacke, and mudstone/sandstone lithologies. The lowermost 1-2 cm consists of a veneer of small pebbles. The basal conglomerate is overlain by at least 4m of black, laminated, dominantly ferromagnesian sands (lamination implies near beach environment). Higher units are mainly obscured, but probably consists of aeolian sand then andisols.

At Ohanga Stream near the start of the White Cliffs Walkway, and c. 1.5km southwest of the outcrop described above, a similar sequence of NT2 Terrace coverbeds is exposed (Q18/471 625). Ohanga Stream has incised several metres into the Mt Messenger Formation, exposing the WCP and its lowermost coverbeds for c. 50m to the outer edge of the terrace surface. In at least one place the WCP exhibits small holes obviously bored by a marine organism. The WCP is again overlain by rounded quartz, andesite and greywacke pebbles, with larger mudstone/sandstone clasts.

The altitude of the WCP at Clifton Road relative to MSL was determined using vertical angle measurements with known baseline, to the nearby hilltop trig station "Tongaporutu N" (153.9m). It was found that at a distance of ≤0.2km from the LIGM strandline, the WCP has an altitude of 30.9 ± 2 metres above MSL (see appendix I for method). As noted above, the WCP is overlain by ≥4m of shallow marine to paralic sediments.

5.4.3. North side of river
On the north side of the Tongaporutu River, the NT2 WCP and its marine coverbeds are exposed. The outcrop occurs about 100m west of a roadside rest area, which conveniently harbours a geodetic benchmark, 'EC57' (21.82m above MSL). The altitude
of the WCP at 30.4 m above MSL was thus easily determined using theodolite stadia methods.*

The WCP has a thin basal conglomerate of rounded quartz, andesite and greywacke pebbles and grits; overlain by c. 2.0m of strongly cross-bedded, black ferromagnesian sands which grade into c. 4.5m of laminated sands. The top of the paralic sands is thus at an altitude of c. 37m above MSL.

5.4.3. Abandoned Holocene riverside cave and borings
Cemented, rounded andesite cobbles were found in a small abandoned cave in the riverside cliffs (south side) of the lower Tongaporutu river/estuary c. 300m from the river mouth. An adjacent modern riverside cave contains uncemented rounded andesite cobbles at the back, c. 1m below the level of those cobbles in the abandoned cave (photo 5-2). The andesite cobbles were either derived from the river erosion of the NT2 Terrace marine coverbeds along the lower river valley, or from longshore drift during the Holocene from sources further south.

At the base of the riverside cliffs (uppermost Mohakatino Formation) is a dense zone of intertidal borings occupied by the isopod crustacean Sphaeroma quoyanum. Approximate HWM is indicated by a band of green algae. Above HWM is a zone of weathered, but almost identical holes, inferred to be the abandoned dwellings of Sphaeroma quoyanum. The top of these weathered holes lies c. 1.0m above the top of the modern occupied bore holes.

The abandoned holes are younger than the raised cemented cobbles. This statement is based on the fact that it is only the back of an abandoned cave which remains, indicating several metres of retreat of the riverside cliff since the cave was active; whereas the abandoned bore holes occur on the present surface of the riverside cliff.

5.4.4. Conclusion
The height of the uncemented cobbles relative to their modern analogue, cannot easily be used to make inferences about Holocene uplift and/or eustacy. This is because the coastline is retreating under wave attack, meaning the paleo-river mouth probably lay westward of its present position. According to Gibb (1986) the post-glacial transgression culminated at present sea-level at around 7 ka B.P. (see footnote, pg.22). Thus, with a more westerly river mouth, river tread would be higher at the position of the riverside

* Nb. The height of the WCP relative to the river/estuary floor (datum) was determined using base-line measurements. The height was found to 28.0m above datum implying that the estuary floor at Q18/ 482 641 is at an altitude of c. 2.5m above MSL at a distance of c. 600m from the river mouth
cave, hence by-passing the need to invoke Holocene uplift. As coastal erosion proceeded, the level of the river tread would then be expected to be lower.

PHOTO 5-2: Cemented rounded andesite cobbles are seen in this small riverside cave c. 300m from the Tongaporutu River mouth at low tide. A modern cave containing uncemented rounded andesite cobbles occurs at left (in darkness). Note the intense borings by *S. quoyanum* at lower right, with the higher abandoned holes (above CAL's head) inferred to be of the same origin. See overlay.
5.5. NT2 Terrace, Mohakatino

5.5.1. Introduction

The NT2 WCP is cut into Mohakatino Formation. The height of the WCP exposed in coastal cliffs is c. 0.75km from the LIGM strandline is c. 8 to 9m above HWM.

The NT2 Terrace coverbeds total 15+m in thickness. Two sections c. 0.5km apart are described.

(1) Just north of Waihi Stream (R18/500 750), c. 2km north of the Mohakatino River mouth, the WCP is overlain by a rounded pebble conglomerate which grades up into laminated sands. The basal conglomerate contains abundant quartz pebbles and andesitic material. The higher sands are laminated and up to 8+m thick. A prominent horizontally continuous iron-pan separates the predominantly laminated sands from steeply cross-bedded aeolian sands above (note similarity to Wai-iti beach sequence). The dune sands are overlain by a succession of andisolic units, often with a basal grey/black carbonaceous/lignitic unit.

(2) About 600m due south (R18/500 744) the aeolian unit appears to be missing and an andisolic succession is formed directly upon laminated pale-grey shallow marine sands (photo 5-3). A dark-brown/grey carbonaceous andisol grades up into a paler reddish-brown andisol. A relatively thin, pale whitish layer then intervenes beneath a second reddish-brown paleosol. This is overlain by a very prominent whitish layer. The layer has a sharp contact with the underlying andisol and is most intense near its base with several patches of pure white. The chalky coloured layer then diffuses up into a pale brown (tephric/sandy?) andisol (Holocene?). The whitish bands are likely to be andesitic tephric loesses (thickness probably precludes a rhyolitic origin).

PHOTO 5-3: NT2 Terrace coverbeds exposed in coastal cliffs north of the Mohakatino River mouth. The WCP is at a height of c. 9m above HWM (beach sand at base).
5.5.2. Road cutting, north of Mohakatino bridge

A road cutting at the side of S.H.3 (R18/507 743)c. 0.7km north of the the Mohakatino River bridge (and 290m north of geodetic BM, EC66) exposes wood bearing clays and muds which are overlain by laminated and cross-bedded variegated well sorted fine sands (fig. 5-4). The sands are overlain by lignite followed by andisols formed in clay/mud overlying the lignite.

At R18/505 741 is a roughly conical hill c. 90m high. This is situated c. 200m southwest and lies some 200 m coastward of the outcrop. From the position of hill coastward of the abandoned LIGM sea cliff it is thought that during the LIGM the hill was probably an island. However it is so close to the inferred LIGM coast, that during this period it may have connected with the mainland at low tide (such as the Sugar Loaf islands at New Plymouth).

The fine laminated sands at R18/507 743 are silty and predominantly grey-white quartzofeldspathic at the base (overlying mud/clay with angular mudstone clasts). The sands become clearly laminated towards the top, with an increase in the frequency of titanomagnetite-rich bands. These sands are fine and very well sorted (photo 5-4). The sands are sharply terminated by an ironpan and overlain by carbonaceous clay. The top of the sands is at an altitude of 29.3m above MSL (measured relative to geodetic BM, ‘EC66’, using a Sokkisha total station).

PHOTO 5-4: Variegated, laminated sands (fine, well sorted), with scour and fill channel at top right. Metallic blue-black bands are titanomagnetite-rich, grey-white bands are dominantly quartz and muscovite, while orange-brown bands are compositionally intermediate.
FIGURE 5-4: Sketch of road section outcrop at R18/507 743, about 700m north of the Mohakatino River bridge.
5.5.3. Road cutting, south of Mohakatino bridge

Uplifted river sediments occur about 130m south of the Mohakatino River bridge (c. 1km south of the above outcrop) at R18/504 734.

FIGURE 5-5: Section exposed in road cutting south of Mohakatino River bridge (R18/505 734). Shows conglomerate lens (note andesite pebbles), overlain by dominantly laminated sands, then andisol/s. A nearly identical sequence is seen in a river side cliff c. 130m west.

A nearly identical sequence is seen in a river side cliff c. 130m west. Lower down in the sequence (not exposed at R18/505 734 above), are wood bearing clays and muds. There is no sign of Mohakatino Formation above low tide level in the the lower river/estuary.

It is obvious that the lower mud/clay sediments are river deposits as they contain no andesitic material. An andesitic component arises up sequence, and also coincides with a transition to coarser, better sorted, sandy sediments showing cross-bedding and lamination. The andesitic conglomerate at c. 14m above MSL, is probably indicative of a river mouth bar facies, or some similar environmental setting.

This up-sequence increase in andesitic detritus is interpreted as indicating an increase in coastal influence due to marine transgression, the transgressing coastline eventually connecting the locality with andesitic sediments transported north by longshore drift from the Taranaki Peninsula. It seems probable that the sequence records infilling of a low
stand river valley as base-level rose during a significant phase of global climatic amelioration.

5.5.4. Age of sediments
The actual timing of this event is not clear, but is almost certainly of the last 125 ka B.P. An altitudinal comparison of the uppermost limit of water-laid sediments in this section (R18/ 505 734), with those in the northern section (R18/ 507 743) may provide a clue to age. The northern sands are at an altitude of c. 29m, compared to c. 15m on the southern side; hence the southern river deposits would seem to be younger, and/or associated with a lower high stand of sea level.

5.5.5. Holocene Sediments, Mohakatino
Holocene sediments are exposed in the modern river bank just inland of the north side of the Mohakatino River bridge (R18/ 505 735). The section is c. 650m inland from the coast.

The sediments exposed in the bank above the modern tidal mud flat are crudely laminated ferromagnesians sands, and are overlain by a pumiceous (rhyolitic) layer c.1m thick. The pumiceous layer is a pale purple-grey colour at the base and consists of pumiceous sands and scattered pumice pebbles. The top 30cm of the pumiceous layer is brown to black and contains much charcoal, with common large rounded pumice clasts up to cobble size. The pumiceous layer is horizontally continuous over some 30m of exposure (see photo 5-5 & 5-6). The relatively thick pumiceous sediments most probably originate from the Taupo eruption: 1850±10 years B.P. (Froggatt & Lowe, 1990).

An umu (maori oven) was seen in one localised area and contained shattered rounded andesite cobbles and charcoal. The umu was confined to the burnt part of the pumiceous layer. Overlying this layer is c. 50cm of micaceous sands containing angular mudstone/clasts.

Surveying
Relative to geodetic bench mark, EC66, the topographic surface of the Holocene river terrace is at an altitude of 3.2m above MSL (measured using total station, see Appendix I), and the top of the pumiceous layer is at 2.7m above MSL. The modern tidal mud flat is at an altitude of c. 1.5m above MSL and is inundated at high tide due to constricted river mouth flows. Just west of the bridge, and only 50m west of the pumice section, driftwood and black sand occur at an altitude of 2.3m above MSL. Hence these sediments are only 0.4- 1.2 m above the modern tidal estuary.
Interpretation

The elevated pumiceous sediments most likely indicates some degree of Holocene uplift (since Taupo eruption of 1850±10 years B.P.). The charcoal-rich upper part of the pumiceous unit is probably a result of human occupation (Maori?), this could be easily clarified by radiocarbon dating. The higher unit is probably a result of road construction by European farmers. The S.H.3 overbridge has constricted local river flows around this site, and probably is driving bank erosion. There are too many unknown variables involved to make any valid inferences from the above fieldwork.
PHOTO 5-4: Holocene river terrace coverbeds exposed in the eroding northern bank of the Mohakatino River, just inland from bridge (photo taken from bridge). Note the modern mud-flat being inundated by the rising tide. See below for detail.

PHOTO 5-6: Pumiceous sands with charcoal-rich upper part. Overlain by clay-soil with relatively fresh mudstone/sandstone clasts, probably layered down during recent times as a result of human activity (note: farm road in above photo).
5.6. Summary

Wai-iti: Shallow marine gravels and sands overlying the WCP give way to a thicker sequence of alternating estuarine, and by association, very shallow marine sands (showing post-depositional slumping - earthquake triggered?). The two lignites indicate shoaling and supra-marine deposition. A small-scale downlapping structure below the second lignite supported a standard sequence stratigraphic interpretation of progradation within a regime of slowing relative sea level rise. Aeolian sands (c. 12 m) were correlated with the Katikara Fm. in coastal central Taranaki of Last Glacial ($\delta^{18}$O Stage 2) age. The process of ventiplanation was invoked to explain the sharp hydrogeological and erosional boundary between marine and aeolian sediments.

Pukearuhe: Coverbeds overlying an abraded surface close to a small stream near the front of the LIGM sea cliff were described and related to other features such as stream morphology. The basal unit of the higher, level, platform contained andesite and quartz lithologies, and beach sand indicating a shoreline origin. Only sedimentary lithologies were found on the lower platform indicating a local inland provenance. Migration of the stream channel was inferred and was further taken to suggest the influence of gradual (?) base-level lowering followed by rapid fall of eustatic sea level.

Tongaporutu: The NT2 WCP and lower marine coverbeds from sections on either side of the river were described: The WCPs of the NT2 Terrace, on either side of the Tongaporutu River have many similarities: Both WCPs lie at c. 30 m above MSL, at a similar distance from the LIGM abandoned sea cliff, and are overlain by a similar thickness of shallow marine to paralic sediments. The maximum height of water-laid sediments is c. 37 m above MSL indicating c. 32 m of uplift since the LIGM (note +5m paleo-sealevel at c. 120 ka B.P.). The inferred average uplift rate for the last 120ka is therefore 0.27 m.ka$^{-1}$.

Holocene features were also described: Cemented andesite cobbles found in an abandoned riverside cave were argued to be Holocene, deposited when river tread was higher and the rivermouth coastal cliffs further westward. Abandoned holes c. 1 m above bore holes of S. quoyanum are much younger than the cemented cobbles. If these holes are the weathered borings of S. quoyanum (ie. intertidal) they must indicate a relative fall in base-level (tectonic and/or eustatic) in relatively recent Holocene times. There is also the possibility that these borings are not intertidal and must have formed by some other process. This latter explanation is favoured.
Mohakatino: Two sections north and south of the Mohakatino bridge were described: Wood bearing clays and muds at the northern road cutting were overlain by laminated sands, whose character suggested an up sequence increase in coastal influence. The top of these sands at an altitude of 29.3 m indicates that they were probably deposited during the LIGM. At the southern section, thick muds and clays are overlain by andesitic sands and conglomerates inferred to be a river mouth bar facies (maximum altitude of 15.3 m). On an altitudinal basis the north and south sections were deposited during different (highstand) phases of the Last Glacial cycle ($\delta^{18}$O stages 5e and 5c(?) respectively).

Pumiceous (probably Taupo eruption genesis i.e. 1850±10 years B.P.) and charcoal-rich sediments exposed in the eroding bank of the Mohakatino River were described. Charcoal sediments are assigned to the period of human (Maori) settlement and the highest surficial sediments to European activity. A small amount of late Holocene uplift is inferred.
Chapter Six
Non-Marine Terraces

6.1. Introduction
6.2. 'Non-marine' terraces above Waikiekie Stream, Tongaporutu
6.3. Terraces not of marine origin
6.4. Possible mode of formation
6.5. Mokau non-marine terraces
6.6. Other non-marine surfaces
6.7. Two models for the formation of non-marine surfaces in north Taranaki
   6.7.1. Preamble
   6.7.2. Hypothesis I: Groundwater sapping
   6.7.4. Hypothesis II: The Pukearuhe Landslide
6.8. Summary/Conclusions
Chapter Six

Non-Marine Terraces

6.1. Introduction

Terraces and elevated sub-planar surfaces which occur above the NT2 coastal marine terrace between the Tongaporutu River mouth and White Cliffs, superficially appear to be of uplifted marine origin, but are more likely the result of some subaerial process. It is submitted that all terraces above the main coastal marine terrace north of White Cliffs were formed sub-aerially under stratigraphic/structural control.

6.2. 'Non-marine' terraces above Waikiekie Stream, Tongaporutu.

Above the main NT2 coastal marine terrace near Waikiekie Stream (Q19/470 612), are two terrace surfaces with altitudes of c. 160-200 m and 220-250 m respectively. These two terraces are separated by a linear, north-striking, approximately shore-parallel cliff (photographs 6-1 & 6-2).

PHOTO 6-1: The main coastal terrace (Q18/460 605) is underlain by an uplifted wave-cut platform at c. 30m altitude, and is backed by the prominent abandoned LIGM sea-cliff. Above this is an extensive, shore-parallel sloping surface, which in the northern area (left) is clearly separable into two terraces by a linear riser.
FIGURE 6-1: Slope-profile of the two high non-marine terraces at Q18/469 612. Surveyed using a theodolite and stadia.
PHOTO 6-2: View north from north end of WhiteCliffs (~Q18/445 581): Main coastal terrace is the uplifted NT2 marine terrace, separated from higher non-marine terraces by its abandoned LIGM seacliff. The two higher terraces are non-marine (~Q18/469 612) are lithologically/structurally controlled surfaces, separated by a linear riser (c. 20 m high). Closer to the viewer, only one surface is recognisable, and appears to be an extension of the lower non-marine terrace seen to the north at ~Q18/469 612.
6.3. Terraces not of marine origin

Superficially the two terraces resemble a remarkably well preserved pair of significantly elevated uplifted marine terraces. Upon closer inspection however there are several characteristics which suggest an entirely different origin, and also age.

(1) Firstly the excessive degree of terrace slope and its pronounced sideways tilt: The slope of both terraces has a main cliff-normal component (which is also approximately shore-normal), and a more minor cliff-parallel component. The cliff-normal slope is 4 to 6°, while the cliff-parallel slope is 2 to 3° (figure 6-1).

The anticlinally warped South Taranaki/Wanganui terraces have a maximum measured shore-parallel tilt of 0.23° (Ball Terrace), and an average shore-normal tilt on the Ball Terrace WCP of 1.05° (Pillans, 1990). Thus it seems unlikely that any North Taranaki marine terraces of Ball age (520ka) would have tilts an order of magnitude larger than the demonstrably deformed South Taranaki/Wanganui terraces.

(2) Secondly, the absence of any outcrop of coverbeds of marine origin. Poor outcrop only exposed massive clay-rich soils.

(3) Thirdly, the parallelism of bedding in the Mt Messenger Formation with the boundary between the Mt Messenger Formation and the terrace soil-coverbeds shows lack of truncation by a WCP (photo 6-1).

(4) Fourthly, and importantly, the lack of dissection of the terrace surfaces under discussion is not in line with their implied age if a marine origin is assumed (assuming a moderate rate of uplift suggested by the NT2 strandline altitude).

6.4. Possible mode of formation

The linear riser/cliff which separates the two non-marine terraces must therefore have an alternative mode of formation to that of ancient coastal cliffing. Although no field evidence for faulting was seen, it is possibly an exhumed fault-plane which offsets by some 20m a surface within the Mt. Messenger Formation which was itself being exhumed by erosion. This scenario raises the question of; what is the mechanism of erosion and what initiated it?

If the surface upon which erosion took place (resulting in the two terraces) was a poorly consolidated and permeable layer; a type of groundwater sapping process could be invoked.
If such a mechanism exists, then sapping (and terrace formation) was probably initiated during the LIGM when the NT2 seacliff was cut. Once initiated at the NT2 seacliff, sapping would then be able to proceed up-dip, with a step at the presumed fault plane, and continuing on the upper offset surface. The highest terrace is therefore the youngest (inverse to the normal altitude-age relationship on a flight of uplifted marine terraces).

6.5. Mokau non-marine terraces

The NMT above the main coastal marine terrace in the Mokau-Awakino area is obviously structurally controlled. The outer edge near Pahaoa is at an altitude of c. 160m, and decreases to c. 100m above Mokau township, some 2km to the south (photo 6-3).

![PHOTO 6-3: Oblique aerial photo taken from an altitude of c. 550m. The NT2 Terrace forms the coastal plain below the abandoned LIGM sea cliffs, a silver of Holocene coastal plain may also be seen. Pahaoa Hill lies above the ascending track at left. The high non-marine terrace is obviously structurally controlled, as seen from the parallelism of the sloping surface with Mohakatino Fm. bedding.]

6.6. Other non-marine surfaces

Inland from the coastal terraces, gently sloping surfaces similar to the non-marine terraces just described, occur as basins within the rugged hill country. Often these sloping surfaces are found on the sides of stream valleys, and slope gently towards the stream.
6.7. Two models for the formation of non-marine surfaces in north Taranaki

6.7.1. Preamble

These landforms are obviously not of marine origin but must evolve through some sub-aerial process which proceeds in conjunction with a particular lithological/structural configuration (predetermined by the mid-late Cenozoic geological history of the North Taranaki Basin). Two possible mechanisms are discussed to try and account for non-marine terraces and related landforms such as 'basins'. The first involves groundwater sapping, the second involves land-sliding.

6.7.2. Hypothesis I: Groundwater sapping

Introduction

This hypothesis proposes that wherever lithological and structural conditions are right, there is the potential for groundwater sapping processes to come into play:

Two conditions seem necessary for this potential to be activated. Firstly, groundwater recharge from some inland surface source into a permeable, mechanically weak unit. And secondly, an exposure down-dip from the source which allows groundwater discharge at the level of the permeable/impermeable contact between the overlying aquifer and an underlying aquiclude. It is proposed that when both these conditions are met, erosion by groundwater sapping may occur.

Structural configuration depends on gently dipping surfaces of several degrees. Lithological configuration is more speculative, but as outlined above it is thought likely to be a permeable layer overlying an impermeable indurated layer. See photos 6-4, 6-5, and 6-6.

Model

A simple model of the formation of a non-marine terrace via groundwater sapping will now be outlined. As already mentioned, the potential orientation of the non-marine terrace is structurally predetermined, but its actual topographic exhumation as it were, is controlled by the evolution and superimposition of drainage. See figure 6-2 for schematic description of model.

In this example, truncation of coastal strata during the LIGM sea level highstand provides the second condition. Then, in response to falling base-level during the ensuing regression, streams rapidly incise. When the stream downcuts to the level of the permeable weak unit the first condition is met and groundwater sapping occurs simultaneously with accelerated stream channel incision.
The whole process may stop when the stream begins cutting a channel into the underlying impermeable layer, leaving high non-marine terraces in coastal areas, and "back-basins" further inland as shown in figure 6-2.

**Existence of fracture permeability?**

A possible (small-scale) analogue which supports the groundwater sapping hypothesis for the formation of a non-marine terrace (NMT) was seen in Mohakatino Formation rocks exposed in low coastal cliffs just north of the Mohakatino River mouth spit (Q18/500 739).

It is proposed that pervasive jointing which is inferred to occur within some layers, not only mechanically weakens the rock but also creates a relative permeability serving to concentrate groundwater flow.

**Description**

A rock platform occurs at c. 2.5m above fair weather HWM. The platform is c. 30m long and 2 to 4 m wide (see photo 6-9).
The platform occurs at a sharp lithological boundary in the Mohakatino Formation between non-volcanogenic interbedded sandstone and mudstone below, and pale-grey tuffaceous siltstone with interbedded coarse tuff layers, above.

The tuffaceous siltstone/sandstone is pervasively cracked and jointed in a haphazard polygonal fashion. The cracks and joints mechanically weaken the unit, and hence aid erosion and thus platform formation. It is envisaged that in addition to being mechanically weak, intense fracturing would also create a relatively high permeability in the unit.

The platform is c. 2.5m above fair weather HWM, but during heavy surf at high tide is probably washed by large waves. In fine weather, small amounts of debris continually flake off, and presumably are removed periodically by storm waves. About 6m of overburden has been removed between the platform and the LIGM WCP which truncates the Mohakatino Formation at c. 9m above HWM. Obviously there is a different mechanism by which erosion occurs for non-marine terraces.

Summary (or, "what analogue?")

The platform analogy simply demonstrates that sharply contrasting mechanical properties, can potentially be differentially acted upon by a given erosional process (such as groundwater sapping) to form a planar topographic surface. In this particular example, the pervasively shattered tuffaceous unit is being preferentially eroded to the underlying non-shattered, non-tuffaceous unit. The erosive mechanism is a combination of subaerial weathering and mechanical storm-wave action. The gently westerly dipping (c. 140°/6°W) boundary between the two units is being erosionally exploited to form a planar topographic surface (a miniature NMT of sorts).
FIGURE 6-2: Schematic diagram outlining a model for the development of coastal non-marine terraces and their inland equivalents—"back-basins", through the interplay of drainage development and lithological (and structural) configuration. Stream (1) downcuts through relative base-level lowering, when the stream starts to dissect a more permeable layer it provides a new groundwater source to aid the sapping process downdip. The downdip sapping process ceases when another impermeable layer is reached (stream 2) and the inland recharge source is 'disconnected'.
6.7.4. Hypothesis II: The Pukearuhe Landslide

Introduction

The Pukearuhe Landslide is described, and its possible mechanism of formation considered as a general mechanism for the formation of non-marine terraces.

Description

A large landslide with an estimated volume of \( \sim 10^7 \) m\(^3\) is seen in photo 6-10, centrefield. Debris from the landslide has piled out over the LIGM sea cliff, burying \(-0.25\)km\(^2\) of the NT2 Terrace. An older landslide scar is seen immediately south.

PHOTO 6-10: Oblique aerial view of Pukearuhe area from an altitude of c. 550m with Pariokariwa Point at lower left. The NT2 coastal marine terrace terminates abruptly here before the White Cliffs start just to the north. Note the large landslide which is discussed in detail in the text. Also note thick Last Glacial dune deposits in the coastal cliffs.

The younger landslide has created a broad shovel-shaped hanging valley. The older landslide has a prominent sloping floor. It appears that this sloping floor is coplanar with the floor of the younger landslide. The implied planar sloping surface also closely parallels other planar topographic surfaces seen further inland (eg. left mid- & background, photo 6-10). All surfaces are the topographic expression of structural dip within the North Taranaki Basin sedimentary rocks.
The above example from Pukearuhe strongly suggests that gently dipping planar topographic surfaces may be created through landslides (into space created by marine coastal erosion or river valley incision).

Other landforms which are likely to have formed by a similar mechanism are seen at Tongaporutu (especially photo 6-11, as well as Mokau (photo 6-3) and Awakino (photo 6-4).

PHOTO 6-11: A gently inclined, seaward sloping, basin-shaped, cirque-like landform occurs centre-field, and may have been formed by a landslide. A prominent, pale-grey mudstone horizon appears to underlie the surface that has formed by erosion. The pale-grey horizon facilitates correlation with another higher surface up-dip (upper left of photo). This in turn allows the basin to be linked with the non-marine terraces slightly further north (refer to photo 6-1). 

Model

The landslides excavate material above certain amenable gently dipping horizons within the (uplifting) sedimentary sequence. The gently dipping horizons upon which planar sliding of overburden occurs are evidently inherently weak, locally extensive layers.

One of the simplest types of rock-slope failure results from sliding on an inclined plane within a given rock mass, as shown in figure 6-3. Planar sliding is kinematically feasible when the dip of the internally weak horizon (B) or discontinuity is greater than its angle of
internal friction (\(\varnothing\)), and less than the slope of the exposed rock face (\(i\); in roughly the same dip-direction as \(\beta\)). Actual (dynamic) failure occurs when the resistive forces (primarily cohesion and friction) are exceeded by the driving forces of gravity driven mass. If the rock-slope system is in a finely tuned metastable state then slight extrinsic changes which serve to decrease resistive forces (e.g., climatically induced decrease in cohesion), or to increase driving forces (say coseismic shaking), may precipitate a dynamic transition to a more stable state.

This simplistic yet elegant planar sliding model seems adequate in explaining the qualitative features observed at Pukearuhe, however quantitatively there are difficulties, since it would be expected that the angle of internal friction of the Urenui Formation (silty mudstone; assume \(\varnothing>25^\circ\?\)) would be much greater than the dip of the assumed weak horizontal internal layer (c. 5-8° SW). A catastrophic event such as a moderate to large earthquake may have to be invoked for the planar sliding model to remain viable. It is envisaged that many such planar sliding events (in conjunction with other less catastrophic types of erosion) would lead to the development of extensive sub-planar sloping surfaces.
6.8. Summary/Conclusions

It was shown that certain terrace and other related surfaces cannot be marine in origin because of four main factors: (1) Excessive degree of terrace slope and pronounced sideways tilt. (2) Absence of marine coverbeds. (3) Parallelism of bedding with the coverbed/Miocene rock boundary (i.e., lack of truncation). (4) Lack of dissection of non-marine surfaces cf. lower marine terraces.

It was observed that the gently southwest dipping layered sedimentary strata (interbedded sandstone, siltstone and mudstone) control the orientation and surface slope of the non-marine surfaces. Erosional mechanisms which exhume a lithological surface were then considered, and two simple models were put forward: (Model 1) Exhumation by groundwater sapping or related process. (Model 2) Exhumation by repeated large scale periodic landsliding.

Lack of outcrop evidence allowed only surmisal as to the lithological configuration which could allow groundwater sapping processes to occur. Evidence was seen for landsliding partially exhuming sub-planar surfaces within the Miocene sequence. However the dips seem to be too low for a planar sliding model to apply unless an extreme external event such as an earthquake is invoked (which is considered likely). A more complex hypothesis may be needed to more closely model the actual situation, but the planar sliding model seems promising.
PHOTO 6-4: Inland from Awakino, just past "Junction Garage": Elevated non-marine terraces in the lower Awakino River valley. The terraces are obviously formed along a single stratigraphic horizon dipping at c. 6° SW (see photo 6-6).
PHOTO 6-5: View south from non-marine terrace above Tongaporutu (-Q18/470 615): Boundary between Mt. Messenger Formation and Quaternary andisolic coverbeds perfectly parallels bedding planes in the former (note marked vegetation line due to groundwater seepage at the contact). The lack of truncation of the Mt Messenger Fm. (dipping c. 3-4° SW) strongly suggests that the terrace is not of marine origin. Note: White Cliffs in right mid-background, and the broad out-jutting NT2 coastal marine terrace beyond at Pukearuhe. Also see figure 6-1.
PHOTO 6-6: Panorama from Pahoa trig (258 m), looking NE into Awakino River Valley below:

Mid-ground: Extensive, elevated and remarkably planar surface which Chappell (1964) identified as low angle dip-slopes "developed on siltstones of the Mokau Group", and that dip 6°SW towards the Mokau River (see photo 6-4). The mechanism by which a dipping horizon can be exploited to form a sub-planar non-marine surface is of interest here.

Geometry of scarps: ridges coming off the edge of the non-marine dip-slope surface in the mid-foreground are angular and faceted cf. the higher scarps at the rear of the dip-slope surface which are substantially more subdued (suggesting upper rocks are more erodable).

Left, mid-background: Curvilinear, parallel, grooved stream-valleys which deeply dissect dipping terraces and end in valley heads (follow up right valley and can see theatre-head). The right and left valleys are 1.3 and 2.0 km long respectively. Note the wavy ridge-crest formed by the intersection of first-order side-valleys.
PHOTO 6-7: Part of the Tuahu Farm "back-basin" (Q19/340 360), just behind Tuahu trig. According to the farmer, the land within the back-basin was recently recontoured to stop the ponding of water which used to occur during heavy rain, but which would then drain quickly into the ground to emerge at the edges causing slipping into the gullies (pers. comm with farmer March 1992).

PHOTO 6-8: Oblique aerial view of White Cliffs, near Waipunga Stream mouth, from an altitude of c. 550m. The cliffs are c. 200m high and are formed of Mt Messenger Formation. A "back-basin" seen in background, occurs within the Mimi River valley (Q18/460 560). Note that the slope of this surface is aligned with regional dip.
Chapter Seven
Holocene and older features at Aria Beach, Mokau

7.1. Introduction 
7.1.1. General description of the coast north of Mokau 
7.1.2. Introduction to Aria Beach 
7.2. Possible fossil wave-cut notch and associated borings 
7.3. Origin of the holes 
7.3.1. Introduction 
7.3.2. Possible formative processes 
7.3.3. Description of borings/holes at Aria Beach 
7.3.4. Origin of the holes by analogy to borings at Tongaporutu 
7.3.5. Conclusion 
7.4. Origin of the coastal notch at Aria Beach 
7.4.1. Possible formative processes 
7.4.2. Description of notch features 
7.4.3. Coastal Notches - literature summary 
7.4.4. Summary 
7.5. Other Holocene features 
7.5.1. Stranded Holocene headlands/stacks 
7.5.2. Holocene coastal strip 
7.6. NT2 Terrace 
7.6.1. Wave cut platform 
7.6.2. Terrace coverbeds 
7.6.3. Tectonic implications
Chapter Seven
Holocene and older features at Aria Beach, Mokau

7.1. Introduction

7.1.1. General description of the coast north of Mokau
Typical of this coast is a 3-4 m high sand-dune, a spatially enduring feature along much of the Mokau-Awakino coast. The dune lies just behind the storm-surf zone and is vegetated with 'ice-plant' (a coastal succulent). Inland of this dune lies a flat strip at 3-4 m below the dune-crest, typically vegetated with maram grass, box-thorn and ice-plant. Inland of the strip is a 10 to 20 m cliff/steep slope, mostly covered in flax. The strip forms an elongated coastal depression between the dune and cliff. Cliff exposures reveal a wave-cut platform of sandstone/mudstone at a relatively low-level compared to that south of the Mokau river. The terrace coverbeds overlying the wave-cut platform (WCP) are typically rounded quartz pebbles at the base, then laminated dark sands overlain by steeply bedded dune-sands, capped with andisols. Generally only the upper soil and sand-dunes are exposed, while the lower parts are steep (about 45°), vegetated talus slopes. The sub wave-cut platform rocks belong to the Mohakatino Formation (Purupuru Tuff Member) and are generally exposed in small headlands, spaced every few hundred metres.

7.1.2. Introduction to Aria Beach
Aria beach (R18/508 778) is found at the northern end of the township of Mokau and is accessible via a track which leads off from Aria Terrace Rd. See figure 7-1.

The main features of interest which will be discussed here are;

(1) A notch (possibly an uplifted fossil marine notch) and associated holes (possibly fossil intertidal borings).

(2) The NT2 Terrace coverbed sequence overlying the WCP.

(3) Other Holocene features including a narrow coastal strip backed by a Holocene sub-fossil sea cliff (probably representing the post-glacial transgression culmination strandline) and abandoned Holocene headlands and stacks.
PHOTO 7-1: The notch feature at Aria beach, Mokau (location 'A', see figure 7-1). Intense borings can be seen on the face below the notch base (note 1m rule). The NT2 WCP truncates the top of the Mohakatino Fin. The notch base coincides with a subtle lithological change from grey to orange micaeous sandstone.
7.2. Possible fossil wave-cut notch and associated borings

A prominent notch occurs in Mohakatino Formation sandstone at the seaward edge of a rock outcrop (photo 7-1). The notch can easily be found at the end of the access track to the beach and it lies c. 15m inland from the edge of the beach sands. On the sandstone walls immediately below the notch is a zone of what appear to be biological borings, but will for the time-being be referred to by a non-genetic descriptive term; simply “holes”.

The notch occurs at 2.75m above the carpark datum and at 4.2m above the high tide scum mark of 13th of Feb 1991 (3m reported tide), which is taken to roughly approximate HWM. Approximately 0.3m below the notch is a zone of intense holings giving the rock a honey-combed appearance. The hole zone has a vertical width of c. 1.3m.

The origin of the holes and the implications will now be considered, followed by a similar consideration as to the origins of the notch form (section 7.4).

7.3. Origin of the holes

7.3.1. Introduction

The Aria Beach holes occur on the sides of abandoned headlands and stacks. Since these headlands and stacks were formed by coastal erosion of an uplifted WCP (plus its coverbeds), their age sets the upper limit for the age of the holes (and the notch).

The modern coastline has formed through processes which can only have operated since the post-glacial transgression reached the height of present sea-level about 7000 years B.P. (Gibb, 1986). Thus the maximum age of the stacks and headlands, now disjunct from the active shoreline is 7000 years.

The holes, although weathered, appear relatively fresh and it seem unlikely that they could remain so well preserved for the greater part of the Holocene. Banks of sand and soil are commonly seen partially or totally covering the cliffs and stacks beyond the active modern shoreline. Recent uncovering may well explain the preservation of the holes, as will be discussed further.

7.3.2. Possible formative processes

The morphology, orientation and distribution of the holes are such that the only plausible explanation for their genesis would seem to be that a marine or terrestrial organism bored living spaces into the relatively soft micaceous sandstone. Other explanations such as differential weathering controlled by relatively cemented/uncemented zones within the rock, or groundwater sapping seem implausible.
7.3.3. Description of borings/holes at Aria Beach

Location 'A' (see photo 7-1): End of beach access track.

The base of the notch occurs at 2.75m above the ground surface (carpark datum) and at c. 4.2m above HWM. A zone of dense holes occurs abruptly at 0.3m below the notch base. The zone of holes extends for c. 1.3m and occupies a zone between 2.6-3.9m above HWM. The dense holes give the rock surface a honey-combed texture. The opening diameter of individual holes ranges from only 1mm up to 6mm. Lengths of holes within a small area were measured by inserting a piece of wire as far in as possible. For holes of diameter 1.5mm measured lengths were between 1-2cm, for holes with openings of between 4-6mm measured lengths were between 4 to 5cm (length = 10*diameter). In the measured areas typical diameters were ≥ 4mm. The very small holes (c. 1mm diameter) often had white webs around their openings suggesting insect occupation (these holes are probably very recent).

Location 'C': ~50m south of 'A'.

At this more sheltered location, holes occur below the notch base but seem to be much more weathered and not as continuous in their distribution. An important difference is the presence of abundant, relatively large, sub-rounded to elliptical, smooth-surfaced, crater-like depressions up to 6cm in diameter. They are often seen merging into each other as if one were growing at a faster rate consuming a neighbouring 'crater' in the process. The relationship of 'craters' and 'holes' implies that the craters are the weathered remnants of certain holes which have for some reason become morphologically unstable and radiated outwards in a ripple-like manner.

Location 'D'

See section 7.4.2.

7.3.4. Origin of the holes by analogy to borings at Tongaporutu

The holes seen at Aria beach, Mokau, appear very similar to active bore holes exposed in the sandstone/mudstone cliff walls of the Tongaporutu river-estuary (and which are fully accessible at low tide). At Tongaporutu the bore holes are very dense, laterally continuous, and occupy a vertical zone about 1m wide. It was seen that a small crustacean was the occupier of each borehole, which when disturbed rolled itself into a tight, pea-size ball. With reference to Morton & Miller (1968) the animal was identified as *Sphaeroma quoyanum*, an isopod crustacean that bores "galleries" in soft rock by rasping. It occupies a definite position in relationship to sea-level and is found in a zone which extends from medium tide level (MTL) to high water neaps (HWN). Thus it has
potential as a paleo-intertidal indicator if it can be identified in areas away from the modern seashore.

The holes seen at Aria Beach, Mokau, are very similar morphologically to modern borings seen at Tongaporutu though more weathered. However they were unoccupied by any such marine organisms or the remains thereof. Careful searching, both at Mokau and of a zone of definite abandoned bore holes at Tongaporutu did not reveal fossilized remains of *S. quoyanum* or secondary inter-tidal occupants such as the juvenile black mussel (*Modiolus*), however the possibility of them occurring cannot be ruled out. Unfortunately the chitinous shell of the crustacean would not be amenable to radiocarbon dating. In one hole at Aria beach, modern insect eggs and larvae were seen but nothing else. (Unoccupied holes are also evident on stack-1).

7.3.5. Conclusion

Holes at the Tongaporutu River/estuary are demonstrably formed by a rock-boring crustacean. By analogy, similar looking holes at Aria beach, Mokau, are also possibly of this origin. If they are attributed an intertidal genesis, the present height of these holes above modern HWM has important tectonic implications.

From the work of Gibb (1986) it is known that the culmination of the post-glacial marine transgression at present sea-level occurred about 7000 years B.P (see footnote, pg. 22). The average height of the upper and lower limits of the borings at location 'A' above approximate HWM is about 3.3m. The inferred average uplift rate for the last 7000 years at Mokau is thus (assuming an intertidal origin) 0.47 mm.a⁻¹, which although only a rough estimate is considerably higher than uplift rates of between 0.2 and 0.3 mm.a⁻¹ for much older Pleistocene marine terraces. Note Holocene uplift inferred from elevated river terraces at Urenui is only 0.26mm.a⁻¹.
7.4. Origin of the coastal notch at Aria Beach

7.4.1. Possible formative processes

(1) The first hypothesis was that the notch feature at location 'A' was "obviously" wave-cut and had since been tectonically uplifted. This hypothesis seems to be a logical progression from the above discussion, which tentatively concluded that the holes were intertidal borings.

(2) Subtle lithological changes controlling erosive processes such as abrasion by wind-driven sand (sand-blasting), or perhaps groundwater seepage resulting in some form of 'sapping'.

(3) Sand-blasting above a certain level, not controlled by lithology but by the height of low dunes just behind the drift-wood HWM.

(4) A combination of sand-blasting and lithology.

7.4.2. Description of notch features

Location 'A': End of beach access track.

The base of the notch is sub-horizontal and at c. 4m above HWM and coincides with a subtle lithologic change from grey, to pale-orange micaceous sandstone (photo 7-1). Above the lithological contact the outcrop sides are smooth and gently concave, while below the contact they are vertical and honey-combed with holes (see previous section). Hence there is a ledge all the way round this outcrop at the level of the contact. The ledge is widest (c. 1.5m) and flattest at the seaward point of the outcrop forming the prominent notch, on the south side the ledge is 70cm wide and slopes outwardly at about 24°, on the north side it is 25-60 cm wide with a 26° outward slope. The grey sandstone seemed to be softer than the upper unit but this was probably a result of the honey-comb structure.

Location 'B'

Just south, and about 50m inland, a 2m wide, sloping ledge runs for some several tens of metres roughly parallel to the shore. Above the ledge is a smooth, broad, shallow concavity terminated at the top by a WCP at 5-7 m above ~HWM.

Location 'C'

About 50m south of location 'A', another prominent notch occurs (photo 7-2). The notch base coincides with a lithological change from grey to pale-orange micaceous sandstone as at locality 'A' but here it is more pronounced. The upper pale-orange sandstone appears to be slightly less cemented/indurated than the lower grey sandstone.
PHOTO 7-2: Notch-like feature at location 'C' coincides with a relatively subtle lithological change from grey to pale-orange micaeous sandstone.

Location 'D'

About 70m south of location 'A', a smooth, broad, shallow concavity occurs abruptly above a vertical face containing crater-like depressions (photo 7-3). It is apparent that the craters are very weathered holes which have become broad, and shallow in form. The holes become more weathered to the right accompanied by decreasing height of the soil bank. Suggesting that lowering of the soil-bank from left to right progressively uncovered pre-existing holes, hence explaining why they are more weathered (and crater-like) to the right.
PHOTO 7-3: Concave notch-like feature at location 'D'. Lowering of the soil bank from left to right has progressively uncovered pre-existing holes which are clearly more weathered and diffuse to the right.

Since the soil bank is probably transient, even on Holocene time-scales, this would indicate that the holes have weathered quite rapidly at this locality. The holes are abruptly terminated by the concave surface, indicating that the holes were a pre-existing feature, erased by the erosional formation of that concave surface ie. the holes and notch are not contemporaneous.

The concave surface seen here lacks a pronounced ledge and also does not coincide with any noticeable lithological change, supporting an entirely erosional formation. Hence it contrasts with the other localities which suggest the effect of lithology coupling with an erosional mechanism.
An important observation was that the bottom of the erosional concavity coincided roughly with the top of a sand dune about 10m seaward of the outcrop. This hints at a sand-blasting mechanism which implies that the sand dune is a relatively long term feature on Holocene time-scales*. Onshore sand-blasting also explains why a vertical sandstone face parallel to the direction of sand blasting shows no erosion.

In conclusion for this locality, the concave surface may be explained by sand-blasting from a base-level defined by the long-term minimum height of shore-parallel sand dunes (figure 7-1). To reconcile this mechanism with observations at locations 'A' and 'C', it is proposed that where an upward change to a slightly softer lithology occurs at the same level as the base of the sand-blasting régime, a more pronounced erosion feature resembling a wave-cut notch occurs with a sharp sub-horizontal ledge at the base.

* The coastal sand-dune is a spatially enduring linear feature along much of the Mokau-Awakino coast (c.4km of coast). An empirical geomorphic relationship called the size-persistence relationship (Ahnert, 1988; Baker, 1986) may be expressed by a power-law relationship $T = [400S]^{1.4}$, where $T$ (ka) = the 'life-span' of some geomorphic feature, and $S$ (km) = the linear size of the feature. Taking the order of magnitude of the sand dunes length (~1km), the persistence for a feature of this size according to the above empirical equation is ~4ka.
A coastal notch seen at the Tongaporutu river mouth (south head) at low tide. The notch is clearly structurally controlled, as it exhumes a large intraformational slump fold in the lowermost Mt Messenger Fm. The notch also is clearly related to sea level as the flat base coincides roughly with high tide and the higher reentrant probably corresponds to heavy surf impact.
7.4.3. Coastal Notches - literature summary

Pirazzoli (1986) discusses the morphology of erosion notches, the diverse known mechanisms of notch formation, and the value of different types of notch as paleo-sea level indicators.

"Erosion notches vary greatly in size, shape, and external appearance and may be cut at various levels by diverse processes."

"The development of a marine notch may be attributed to various processes of chemical, physical, biological, or mechanical origin. However, despite a relatively abundant literature on the subject, the mechanism of notch formation remains barely understood."

Pirazzoli defines two broad classes of coastal notches; sea-corrosion notches, and "notches of other origin":

Sea-Corrosion Notches

Sea-corrosion notches can be formed by a diverse range of physico-chemical and biological processes in the infralittoral to supralittoral range. Corrosion surfaces typically appear bioeroded, rugged and pitted. Sea-corrosion notches include midlittoral and supralittoral notches (also called "wind-blasting notches").

Midlittoral notches

Midlittoral notches formed in sheltered environments are termed tidal notches as they are cut in the intertidal zone. Midlittoral notches formed in more exposed coastal environments are termed surf-notches and they are cut at levels above that of high tide. Surf notches are characterised by a surf-bench, the height of which ranges from slightly above HTL in areas of moderate surf intensity, up to 2m above HTL in very high energy surf environments.

Supralittoral notches

Supralittoral notches, or wind-blasting notches, "usually occur in or near the spray zone ... but may also be found further inland". The formational mechanism is ascribed to disintegration due to alternate wetting and drying, and crystallization of salt spray, then removal of the weakened rock by wind-blasting, especially along lines of weakness (ie. bedding planes, joints, etc.). Wind-blasting notches have no quantitative use as sea level indicators.

Notches of other origin

Notches of other origin include abrasion notches and structural notches (see photo 7-4). Although they commonly form in a coastal environment they do not necessarily have any direct relationship to sea level.
A similar type of notch to the wind blasting notch is the structural notch: "In rock formations consisting of horizontal or gently inclined beds, differential erosion may excavate the weakest layers ... and thus produce linear reentrants with notch-like profiles".

**Conclusion**

The concave surface as seen at location 'D' is believed to have formed through a combination of sand-blasting coupled with chemical weathering of the rock from wind-driven salt-spray. The base level of sand blasting is probably controlled by the long term height of the shore-parallel sand dune, possibly through much of the Holocene. In Pirazzoli's scheme the concave surface is a supralittoral notch.

At the other localities where this feature is more pronounced into a more classic notch, the same processes as above are involved, but with the additional factor of a subtle lithological change occurring within the sand-blasting regime. Where this subtle lithological change occurs a sharp sub-horizontal ledge is formed, delineating the base of the notch. In Pirazzoli's scheme this structure is a supralittoral notch, with elements of the structural notch.

**7.4.4. Summary**

The notch at Aria Beach is not a marine notch, but a supralittoral notch. The notch post-dates the holes which occur just below it. Some evidence can be presented to argue that the holes are intertidal in origin, but the tectonic implications of this suggest a rather excessive Holocene uplift rate compared to that for the Urenui Holocene, and also the north Taranaki Late Quaternary. The origin of the holes still remains elusive.

**7.5. Other Holocene features**

**7.5.1. Stranded Holocene headlands/stacks**

Two small headlands/stacks, which were probably once lapped by non-storm waves but are now partially connected to the Holocene coastal plain can be seen immediately north of the notch (stacks #1 & 2, fig. 7-2). The stacks front onto the upper beach but are not normally exposed to wave action except during storms. The stacks are formed of micaceous sandstone with thin mudstone bands (Mohakatino Fm.). [Note that the active stacks seen at Tongaporutu are much taller due to the uplifted WCP being at a greater height, partly due to being closer to the strandline, partly to different uplift rates].

**7.5.2. Holocene coastal strip**

A narrow coastal plain lying immediately to the north of stack#2 about 100m long, 30m wide and about 1m above the edge of the beach sands.
FIGURE 7-2: Small scale map of Aria beach Mokau constructed with a Sokkisha total station. Heights are relative to the first setup labelled 'datum'.
The coastal strip is backed by a steep scrub-covered slope which represents an abandoned coastal sea cliff with banks of sand and soil. The cliff rises 23m vertically to the uplifted terrace surface on which the northern Mokau houses and highway are built. The base of the slope represents a buried Holocene strandline, probably representing the culmination of the post-glacial transgression (Gibb, 1986) which reached present sea level at c. 7ka.

The fact that the fossil Holocene sea-cliff is abandoned implies a locally prograding coastline after the inferred sea level culmination. The partially land joined fossil stacks, narrow coastal strip and modern sand dunes also indicate subsequent progradation. A small scarp (about 1m high) at the outer edge of the coastal strip and fronted by driftwood may now indicate a minor (?) receding stage. Higher coverbeds consist of andisolic units overlying aeolian sands.

### 7.6. NT2 Terrace

#### 7.6.1. Wave cut platform

The WCP terminates Mohakatino sandstone of the coastal cliffs and stacks, at a distance of c. 0.4km from an abandoned sea cliff.

Directly above notch-1 (location 'A'), the WCP is at a height of 5.5m above the high tide scum mark (~HWM) and is about 1.25m higher than the base of the notch. Along the coast in this area the WCP occurs at around 5 to 7m above HWM. This is significantly lower than the WCP immediately south of the Mokau River which has a height of c. 20m above MSL almost right at the NT2 strandline. It is believed that the WCP north of Mokau River is of the same age because its associated abandoned sea cliff sustains the linear continuity of the abandoned LIGM (ie. NT2) sea cliff from north of the White Cliffs right up to the Awakino River.

#### 7.6.2. Terrace coverbeds

The coverbeds overlying the WCP are about 20m thick, and contain several different facies, which ultimately are related to eustatic/climatic events. The coverbed stratigraphic sequence at Aria Beach may be subdivided into at least five main units. See stratigraphic column (figure 7-3) for details.

**Basal unit**

Consists of 2-3m of alternating pale sands and well-rounded pebble conglomerate. The lowest layer consists of a thin, c. 10cm thick horizon of moderate to well sorted sands. The pale sands consist mainly of weathered feldspar as well as abundant hornblende and
augite, and subangular quartz grains. The conglomerate consists of well rounded quartz, andesite (porphyritic) and greywacke pebbles.

Discussion- Origin of quartz pebbles: It has been suggested that the quartz pebbles probably were transported by longshore drift from the West Coast of the South Island when a Taranaki-Nelson land-bridge was present during major glacial phases (pers. comm. C.A. Landis via V. Neall, March 1991). When sea level rose, the landbridge disappeared, and this (metamorphic) quartz source was effectively isolated. Presumably a transgressing shoreline would shuffle a quartz rich lag landward, thereby confining quartz pebbles to the basal unit overlying the WCP.

Laminated sands
The basal unit is abruptly overlain by c. 5-8 m of laminated sands containing only scattered quartz pebbles. The sands are medium to coarse, moderately to well sorted, and consist of alternating, closely spaced, dark-grey and light-olive coloured horizons. The dark bands are rich in ferromagnesian minerals, while the light bands have a higher plagioclase and quartz content. Obviously the dark bands are more winnowed. The inferred environment of deposition is beach to very shallow marine.

The sands are layered in gently shoreward sloping sets (c. 5° W). Each set consists of parallel laminated layers, separated by slight angular disconformities. An upsection increase in feldspar was noted, the sands simultaneously acquire a more cohesive texture, which is probably due to an increase in clay, the weathering product of feldspar.

Wood-bearing clay/mud unit
The laminated sands are abruptly overlain at one locality (side of access track, fig.7-2 and left column of fig. 7-3), by c. 0.5m of wood bearing clay/mud at an altitude of c. 15m above ~HWM. The unit is grey to pale-brown in colour and has a high content of fine grained mica, which is obviously derived from micaceous mid-Miocene mudstone and sandstone so ubiquitous in the inland hill country.

The wood is partly carbonised (mainly outer part), and may or may not be within the limits of radiocarbon dating given its stratigraphic position (underlying Last Glacial dune sands, and overlying LIGM beach sands ie. c. 20 < Age [ka.B.P.] < c. 120). Amino acid racemization could possibly determine the age of the wood.

The upper part of the clay unit is iron-stained and separated from the overlying unit by an irregular limonitic "iron-pan".
Inferred depositional environment: Estuarine clay-rich micaeous muds, possibly from the ancient mouth of the Mokau or Awakino rivers. Possible modern analogues exist at the Urenui, Tongaporutu, Mohakatino, Mokau and Awakino river mouth estuaries.

Aeolian dune sand
The clay unit on the south side of the access track (fig.7-2) was seen to be overlain by grey sands with moderate to steep angled bedding. Further up the track, very prominent large scale aeolian cross-bedding occurs. The aeolian sands are c. 8m thick.

Andiolic units
Essentially unstratified and homogeneous with a coarse nut structure and scattered small pale patches (LLA?), no obvious tephras. Thickness about 3-5m.

7.6.3. Tectonic implications
The maximum altitude of marine sediments at Aria beach is the contact between the estuarine unit and the underlying laminated beach sands. Assuming the terrace is the NT2 Terrace, comparisons providing information on uplift rate can be made.

By comparing the altitude of the sand/estuarine contact at Aria beach (c. 15m at a distance of just 0.4km from the NT2 strandline), with that of the top of the very shallow marine sands in the NT2 Terrace coverbeds at Wai-iti Beach (c. 22m above ~HWM at a distance of c. 2km from the NT2 strandline), and at Tongaporutu (c. 37m above MSL at a distance of c. 0.2km from the NT2 strandline), uplift rate at Aria beach may be indirectly estimated.

Obviously the uplift rate at Mokau must be much less than at Tongaporutu and Wai-iti beach. It seems reasonable to estimate c. 10-15m less uplift at Aria beach over the last 120ka, which implies that average uplift rate is 0.08-0.13 m.ka\(^{-1}\) less than places south of Tongaporutu. Hence uplift rate at at Aria beach, Mokau is believed to be c. 0.15 m.ka\(^{-1}\)

This result compares very well with surveying performed immediately south of Mokau river mouth, where the altitude of the WCP at the base of the abandoned LIGM sea cliff was found to be 20.7±0.2m above MSL (measured relative to geodetic bench mark 'EC68'), c. 4m of beach sand overlying this puts the strandline at c. 25m above MSL implying an average uplift rate of 0.17 m.ka\(^{-1}\) for the last 120 ka.
FIGURE 7-3: Stratigraphic column for Aria Beach, mainly showing NT2 terrace coverbeds. The left and middle columns were constructed from survey measurements shown on the surveyed area of fig. 7-2.
Chapter Eight

Mokau rhyolitic deposits

8.1. Introduction

Three localities in the Mokau area are described. All contain highly weathered crystal-rich rhyolitic material which may represent the weathered remnants of a distal ignimbrite sheet that originated from a volcanic centre within the Taupo Volcanic Zone. The northernmost locality at Pahaoa Hill is c. 2km north of Mokau township and occurs at an altitude of 160-180m. Two other localities at which similar weathered rhyolitic material is found occur high on the north and south sides of the Mokau River valley at altitudes of 205 and 220 m respectively. The discussion is presented in two chapters; chapter eight is concerned with describing the outcrop, its mineralogical, and sedimentological characteristics and from this attempting to identify the origin of the deposit; and in chapter nine SEM observations of chemically weathered plagioclase feldspar, altered mica, and a diagenetic zeolite mineral are discussed.

8.2. Mokau rhyolitic localities

8.2.1. Pahaoa Hill

A highly weathered crystal-rich rhyolitic deposit consisting of thinly bedded to massive material overlies weathered Mohakatino Formation on farmland c. 2km north of Mokau township. Three outcrops occur on the non-marine terrace above the abandoned LIGM seaciff and below Pahaoa trig (258m). Grid reference R18/ 517 803 (figure 8-1).

8.2.2. Tainui (north side of the Mokau River valley)

A highly weathered crystal-rich rhyolitic deposit consisting of rounded clasts of fine-grained, rhyolitic tuff and overlain by thinly bedded crystal-rich rhyolitic material. Outcrops on the north side of the Mokau River valley at an altitude of c. 205m above MSL. Grid reference R18/ 519 783 (figure 81).

8.2.3. Tuhipakahakapo (south side of the Mokau River valley)

A highly weathered crystal-rich rhyolitic deposit containing scattered rounded clasts of fine-grained, rhyolitic tuffaceous material. Outcrops in a vehicle track just below Tuhipakahakapo trig station on the south side of the Mokau River valley, at an altitude of c. 220m. Grid reference R18/ 515 757 (figure 8-1).
Chapter Eight
Mokau rhyolitic deposits

8.1. Introduction ................................................................. 118
8.2. Mokau rhyolitic localities .................................................. 118
  8.2.1. Pahaoa Hill ............................................................ 118
  8.2.2. Tainui (north side of the Mokau River valley) ................. 118
  8.2.3. Tuhiingakakapo (south side of the Mokau River valley) ... 118
8.3. Pahaoa Hill Outcrops ..................................................... 120
  8.3.1. Outcrop 'A', Pahaoa ................................................. 120
  8.3.2. Outcrop 'B', Pahaoa ................................................ 127
  8.3.3. Outcrop 'C', Pahaoa ................................................. 129
  8.3.4. Pahaoa outcrop comparison ....................................... 130
8.4. Other rhyolitic volcaniclastic deposits in North Taranaki ...... 132
  8.4.1. Tainui (north side of the Mokau valley) ....................... 132
  8.4.2. Tuhiingakakapo (south side of the Mokau valley) .......... 134
8.5. Characterisation of the Mokau rhyolitic deposit ................. 136
  8.5.1. Petrography of Rhyolites ......................................... 136
  8.5.2. Petrography of central North Island rhyolites ............... 136
  8.5.3. Petrography of the Mokau rhyolitic deposit .................. 136
  8.5.4. Mode of deposition ................................................. 137
  8.5.5. Correlation .......................................................... 137
8.6. Mangakino Volcanic Centre Ignimbrites .......................... 138
  8.6.1. Ignimbrite A ....................................................... 138
  8.6.2. Ignimbrite B & C .................................................. 138
  8.6.3. Ongatiti Ignimbrite ............................................... 138
  8.6.4. Unit D, and Ahurua Ignimbrite .................................. 140
  8.6.5. Unit E ignimbrite .................................................. 140
  8.6.6. Rocky Hill Ignimbrite ............................................. 140
  8.6.7. Rangitawa Tephra/Whakamaru Ignimbrite ..................... 140
8.7. Discussion ..................................................................... 141
8.8. Summary/conclusion ...................................................... 141
Chapter Eight

Mokau rhyolitic deposits

8.1. Introduction
Three localities in the Mokau area are described. All contain highly weathered crystal-rich rhyolitic material which may represent the weathered remnants of a distal ignimbrite sheet that originated from a volcanic centre within the Taupo Volcanic Zone. The northernmost locality at Pahaoa Hill is c. 2km north of Mokau township and occurs at an altitude of 160-180m. Two other localities at which similar weathered rhyolitic material is found occur high on the north and south sides of the Mokau River valley at altitudes of 205 and 220 m respectively. The discussion is presented in two chapters; chapter eight is concerned with describing the outcrop, its mineralogical, and sedimentological characteristics and from this attempting to identify the origin of the deposit; and in chapter nine SEM observations of chemically weathered plagioclase feldspar, altered mica, and a diagenetic zeolite mineral are discussed.

8.2. Mokau rhyolitic localities

8.2.1. Pahaoa Hill
A highly weathered crystal-rich rhyolitic deposit consisting of thinly bedded to massive material overlies weathered Mohakatino Formation on farmland c. 2km north of Mokau township. Three outcrops occur on the non-marine terrace above the abandoned LIGM seacliff and below Pahaoa trig (258m). Grid reference R18/517 803 (figure 8-1).

8.2.2. Tainui (north side of the Mokau River valley)
A highly weathered crystal-rich rhyolitic deposit consisting of rounded clasts of fine-grained, rhyolitic tuff and overlain by thinly bedded crystal-rich rhyolitic material. Outcrops on the north side of the Mokau River valley at an altitude of c. 205m above MSL. Grid reference R18/519 783 (figure 8-1).

8.2.3. Tuhingakakapo (south side of the Mokau River valley)
A highly weathered crystal-rich rhyolitic deposit containing scattered rounded clasts of fine-grained, rhyolitic tuffaceous material. Outcrops in a vehicle track just below Tuhingakakapo trig station on the south side of the Mokau River valley, at an altitude of c. 220m. Grid reference R18/515 757 (figure 8-1).
FIGURE 8-1: Locations of three rhyolitic deposits in the Mokau area: Pahaoa (outcrops; A, B, and C), Tainui, and Tuhiingakakapo (just off map). Inset (1) is from a sketch of an oblique aerial photograph looking east from an altitude of 550m (author). Inset (2) is a sketch map from a vertical aerial photo taken at an altitude of 7800m (NZ Aerial Mapping).
8.3. Pahaoa Hill Outcrops

Three outcrops occur on the non-marine terrace above the abandoned LIGM seacliff and below Pahaoa trig (258m). Grid reference ~R18/517 803.

Pahaoa outcrop location

Three exposures were found within 300m of one another (figure 8-1).

- Outcrop 'A' lies 150m south of the farm track which ascends onto the non-marine terrace from the NT2 coastal terrace below. It is associated with a distinctive cluster of conical shaped hillocks at an altitude of about 180m. An exposure in the side of one hillock reveals a bedded deposit of rhyolitic origin.

- Outcrop 'B' occurs at an altitude of about 170m in the cutting of the farm track which ascends onto the non-marine terrace from the lower NT2 coastal terrace.

- Outcrop 'C' forms part of a natural exposure along the top edge of the cliff, at an altitude of about 160m, and lies about 70m north of the farm-track.

8.3.1. Outcrop 'A', Pahaoa

Outcrop 'A' and its associated cluster of distinctive conical shaped hillocks (photo 8-1) lies 10-15 m above Mohakatino Formation which is exposed in the cutting at outcrop 'B'. An exposure in the side of the most prominent hillock looks superficially like blocks of limestone (photo 8-2), but close-up is suggestive of ignimbrite (photos 8-3 & 8-4). In hand specimen (O.U.42563) the rock is dry and light-weight with high porosity. The rock is white to pale-orange in colour with scattered brown spots and blotches, and contains many euhedral, coarse-sand grade, transparent crystals in a fine-grained white matrix.

Matrix

In thin-section (O.U.42561 & O.U.42562), the matrix is volumetrically dominant and appears to be devitrified glass. SEM photos 9-9 & 9-13 show what may be altered glass shards. The matrix appears cloudy and/or isotropic under cross-polarized light, and very dusty and stained under plane-polarised light. In some areas shard texture is obvious. Electron microprobe analysis of the matrix was inconclusive because of extensive alteration, and the rough polished surface. From microprobe analysis it is known that the matrix is rich in alumina and silica with minor iron and trace potassium, calcium and sodium (Table 8-1). Silica values are lower than one would expect for a rhyolitic material, but this may be attributed to leaching.
PHOTO 8-1: another perspective on the unusual hummocky topography. Here looking north from the lower end of a small farm supply dam seen in lower right. The most prominent hillock is that of photo 8-2. Weathered Mohakatino Fm (pale-grey) can be seen in track coming up from dam (reddish-brown is andisol).

PHOTO 8-2: Outcrop 'A': Blocks of thinly bedded, crystal-rich, sandstone-like rhyolitic material exposed in the side of a small conical hill.
PHOTOGRAPHS 8-3 & 8-4: Successive close-ups of outcrop 'A'. The weathered surface shows thin laminar bedding (resistant beds were seen to be slightly more crystal-rich and therefore coarser). Brown spots mottle the rhyolitic material and are thought most likely to be completely altered mafic minerals of unknown identity. The pinky-brown discoloration is secondary but probably also mineralogically controlled.
TABLE 8-1: Electron Microprobe analysis of weathered matrix. Outcrop 'A'.

<table>
<thead>
<tr>
<th>Oxide</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>TiO$_2$</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>H$_2$Ocat</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix</td>
<td>45.09</td>
<td>38.13</td>
<td>0.00</td>
<td>0.84</td>
<td>0.00</td>
<td>0.10</td>
<td>0.07</td>
<td>0.12</td>
<td>-</td>
<td>84.42</td>
<td></td>
</tr>
</tbody>
</table>

Volcanic Quartz

Quartz grains are typically subhedral to euhedral, generally showing either slight polishing or rounding of crystal faces. The crystal form is bipyramidal indicating the high-temperature paramorph of quartz i.e. β-quartz. The abundance of β-quartz suggests a rhyolitic origin. In thin-section quartz grains have a sharp curvilinear outline and are often fractured, which is typical of high-temperature β-quartz after it has inverted to its low structural state.

Feldspar

The surface of feldspars is generally highly etched but the actual mineral seems to be unaltered. The feldspars are typically water-clear. Pale clay material is sometimes seen filling voids left by dissolution within the feldspar. In thin-section feldspar has an irregular outline and may show straight lamellar twinning, or less commonly concentric zoning. Feldspar from outcrop 'A' was analysed using the electron microprobe (Table 8-2):

TABLE 8-2: Recalculation of feldspar components from microprobe analysis.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Na (Ab)%</th>
<th>Ca (An)%</th>
<th>K (Or) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67.87</td>
<td>29.22</td>
<td>2.91</td>
</tr>
<tr>
<td>2</td>
<td>67.81</td>
<td>29.23</td>
<td>2.96</td>
</tr>
<tr>
<td>3</td>
<td>64.30</td>
<td>32.43</td>
<td>3.27</td>
</tr>
</tbody>
</table>

(All analyses contained minor amounts of ferric iron)

The composition is that of relatively sodic andesine, and is probably of high-temperature structural state (but see below) based on its association with high-temperature volcanic quartz. Sodic-andesine (and oligoclase) is the typical feldspar of rhyolites.
Extinction angle measurements on several feldspars from outcrop 'A' that exhibit sharp lamellar twinning and symmetrical extinction gave a maximum (from five grains) of 22.5°. For high temperature plagioclase this corresponds to andesine (Ab66/An34), and for low temperature plagioclase to more calcic andesine (Ab58/An42). Electron microprobe analysis (~Ab65/An35) agrees with extinction angle measurements for the high-temperature form of plagioclase.

Altered Phyllosilicates

A common to minor mineral found within the Mokau rhyolitic deposit at Pahaoa, Tainui and Tuhingakakapo has many features of a phyllosilicate that has undergone diagenetic alteration through weathering.

At Pahaoa mineral grains are elongate, have a segmented vermicular form and flake easily into plates with pseudo-hexagonal faces (the basal 001 cleavage). The plates are of variable thickness and may be either pale-bronze or dark-brown. Thicker segments are typically pale-bronze in colour. Vermicular mineral grains without clay-coating thus often appear striped when viewed side-on. Each plate can be seen to be formed of many fine sheets (not all of which are the dominant colour of the particular individual plate). Within the dominantly dark-brown plates, pale-bronze sheets have swollen differentially causing warping of adjacent dark-brown sheets.

Three methods were used to identify the original composition of this highly altered but very distinctive mineral.

Electron Microprobe: Highly altered phyllosilicate was probed. All that could be deduced was that it is iron-rich and is undergoing a kaolinization or chloritization alteration process (see Table 8-3). It is probable that the mineral was original juvenile biotite (pers. comm. Dr Y. Kawachi, 8 June 1992).

<table>
<thead>
<tr>
<th>Oxide</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>TiO2</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>H2Ocal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phyllo</td>
<td>41.38</td>
<td>33.51</td>
<td>0.35</td>
<td>5.49</td>
<td>0.00</td>
<td>0.66</td>
<td>0.07</td>
<td>0.00</td>
<td>0.39</td>
<td>4.05</td>
<td>85.92</td>
</tr>
</tbody>
</table>
X-Ray Diffraction: The least altered mineral grains were handpicked containing pages of dark brown obviously micaceous material sandwiched in between more voluminous pale bronze coloured, very fine-grained material.

The 2θ plot (figure 8-2) contained peaks that fairly closely matched illite-mica (ie. fine-grained mica) and also kaolinite (both identified using the XRD computer database). Evidently the dark-brown 'pages' are relatively unaltered mica, while the pale bronze material is its kaolinite alteration product. It is not possible to specify what kind of mica it is, but the colour strongly suggests biotite.

![Figure 8-2: XRD of dark brown 'pages' from altered phyllosilicate.](image)

**FIGURE 8-2: XRD of dark brown 'pages' from altered phyllosilicate.** Sharp peak at 8.9° (10.0Å) is believed to be that of illite-mica (ie. fine-grained mica).

Scanning Electron Microscope (SEM): Before SEM preparation, hand-picked phyllosilicates were observed under the binocular microscope. The grains were seen to be striped in alternating dark-brown and pale-bronze coloured bands, perpendicular to the basal (001) cleavage. From observations under both light and electron illumination, it was seen that cleavage traces are being distorted and bent by differential expansion of phyllosilicate layers. In SEM photos 9-10 to 9-13 it is evident that as the basal layers have parted, tiny elongate crystallites of diagenetic clay have become oriented perpendicular to the direction of basal-layer divergence. This strongly suggests that the phyllosilicate layers have been slowly expanding *in situ* within the Mokau rhyolitic deposit at Pahaoa.

Conclusion: It seems most likely that the highly weathered mineral is altered original biotite. Dr R. Briggs (pers. comm. Dec 1992), pointed out the dangers of "attributing a
highly altered golden-coloured phyllosilicate to 'biotite' because these phyllosilicates can occur in rhyolites due to weathering and may not necessarily indicate juvenile original biotite". However despite this warning it seems that the highly weathered phyllosilicate is an original constituent of the deposit. This is a useful distinguishing characteristic for correlating the Mokau rhyolitic deposit with central North Island ignimbrites (see section 8.6).

Lithics

Lithic clasts (coarse to very coarse sand grade) are fairly common. In thin section lithics are characteristically well-rounded and appear to be divided into three populations:

Coarse grained dark-brown lithics (unknown composition). Primary origin probably volcanic (andesitic?).

Fine grained, well-rounded, yellow-brown (unknown composition). Primary origin possibly Miocene sedimentary rocks, possibly volcanic.

Rare, poly-crystalline quartz with individual grains showing undulose extinction. Primary origin probably low-grade metamorphic.

Lithic clasts are most prominent in the 0.5 to -1.0 \( \Phi \) grainsize fraction and consist mainly of fine-grained pale-brown to grey rock. It is possible that they represent volcaniclastic fragments of a welded ignimbrite

Grain-size

A sample from the middle part of the bedded rhyolitic unit at outcrop 'A' was gently disaggregated and dry-sieved. In the pulverization process artificial grains were produced and thus the graph does not depict a natural grainsize distribution. It does however facilitate the estimation of the size-frequency relationship of quartz, and to a lesser extent, feldspar phenocrysts within the sample.

\( \beta \)-quartz phenocrysts lie entirely within the range from 2.0\( \Phi \) to 0.0\( \Phi \) with no gradual tail-off. Plagioclase phenocrysts lie within the range of 2.5\( \Phi \) through to 0.5\( \Phi \). Mean grain-size is somewhere within the 1.5\( \Phi \) range, and frequency tails off fairly rapidly either side of this value. Plagioclase is much less durable than quartz, especially so in this case where the feldspars are severely corroded. Hence the size-frequency distribution of feldspar as shown in figure 8-3 is influenced by the analytical disaggregation process ie. shattering large crystals which in turn boosts smaller grainsizes.
FIGURE 8.3: Bar graph of grainsize versus % (weight percent). Each column also shows the weight ratio of quartz:feldspar: matrix.

**Phenocrysts in the 0.0 to 2.0 \( \phi \) sand fraction:** Abundant quartz. Quartz dominates in the 0.0 & 0.5 \( \phi \) fractions. Feldspar dominates over quartz in the 1.0 & 1.5 \( \phi \) fractions. Quartz and feldspar are subequal in the 2.0 \( \phi \) fraction.

**Phenocrysts in the 2.5 to 3.0 \( \phi \) sand fraction:** Feldspar and quartz become minor. Magnetite obvious, and more abundant in the 3.0\( \phi \) fraction (but still <1%).

Finer fractions (<4\( \phi \)) are dominantly crushed matrix.

### 8.3.2. Outcrop 'B', Pahaoa

Outcrop 'B' occurs near the outer edge of the non-marine terrace and overlies weathered Mohakatino Formation (Purupuru Member) at an altitude of c. 160m (estimated from 1:50,000 map contours). Outcrop 'B' consists mainly of unconsolidated rhyolitic sands, containing abundant plagioclase and B-quartz phenocrysts. The deposit is typically about 1-2m thick within hollows in the Mohakatino surface and thins-out completely between hollows. At this locality coherent, semi-consolidated unstained material sometimes occurs as pods within mainly unconsolidated arid iron-stained sands (photo 8.5). Overlying the rhyolitic sands is a dark greyish-red andesitic paleosol. At the base of the rhyolitic sands, a grey and orange mottled clay containing angular weathered mudstone fragments, and separated from the underlying Mohakatino Fm. surface by a c. 10cm thick iron-stained flakey layer, was found. The angular mudstone fragments are possibly rip-up clasts.
PHOTO 8.5: Outcrop 'B': Unconsolidated, damp, crystal-rich rhyolitic sands surrounding internally coherent blocks of consolidated, crudely laminated, crystal-rich rhyolitic sandstone (note intense brown mottling). O.U.42560 is the pod c. 10cm below hammer head.

A brick-sized sample (O.U.42560) of more consolidated material was found as a pod within very pale-orange to yellow-brown sands. In hand specimen, the rock is a semi-consolidated coarse-textured, crumbly sandstone, consisting of angular, coarse-sand grade, transparent crystals, in a pale fine-grained matrix. Prominent dark brown spots mottle the pale rhyolitic sandstone and are densely concentrated in horizontal bands above and below a relatively spot-free middle part. The mottles are 1-7 mm in diameter, roughly spherical, and appear to be a coating on mineral grains. Under the binocular microscope the sandstone consists of subhedral to euhedral crystals of high-quartz (up to 1.5mm) and water-clear but often corroded feldspar reminescent of melting ice, and up to 2mm in length. These crystals are embedded in a white, devitrified glass-shard matrix, having the appearance of interpenetrating flakes and sheaves.

Volcanic Quartz

The quartz crystals are paramorphs of high-temperature B-quartz. The more euhedral crystals often show the characteristic hexagonal bipyramidal symmetry. The quartz crystals often hold large fluid inclusions containing daughter minerals with potential for determining the homogenization temperature (pers. comm. Dr Dave Craw, June 1992).
For a deposit so rich in $\beta$-quartz it would be normal to assume a rhyolitic origin, and hence to expect sodic andesine to oligoclase feldspar (but see below).

**Feldspar**

The feldspar phenocrysts, in contrast to the quartz phenocrysts, have intricate etched surfaces. Some are deeply corroded and skeletal and as a consequence, loose in their 'sockets' (moulded in the devitrified matrix), but nonetheless are very clear and internally unaltered. There is a tendency for thin parallel sheets, separated by an air-gap (sometimes with pale clay filling) to remain, perhaps suggesting weathering of twinned plagioclase, and differential preservation of alternate twin planes but no other evidence was seen to support this (see section on feldspar weathering).

**Feldspar composition:** Refractive indices (RI) for the fast and slow vibration directions were found using white light (Tsuboi Method). Coarse feldspars from outcrop 'B' were hand-picked and crushed. Fragments perpendicular to (010) showing symmetrical lamellar twinning were viewed under oils calibrated in refractive index increments of 0.002. The fast and slow vibration directions were found using the sensitive tint plate then rotated into the plane of the polariser where relief, and sense of Becke line movement were observed. The slow (γ) RI is 1.555, the fast (α') RI is 1.547 (ie. δ = 0.008). This corresponded to a plagioclase composition of sodic andesine (Ab64/An36±1), for both high and low temperature plagioclase series.

**Altered phyllosilicate:** See section 8.2.1.

**8.3.3. Outcrop 'C', Pahaoa**

Outcrop 'C' occurs at the top edge of the abandoned LIGM sea-cliff, c. 70m north of the farm-track. It is well exposed for several hundred metres along the top edge of the cliff (see figure 8-1, photo 8-6).

Unconformably overlying weathered Mohakatino Formation is nearly 4m of pale, coarse feldspar and $\beta$-quartz rich, volcanic sandstone and loose sands. The volcanic sandstone is generally laminated and intact at the base. Above this it typically occurs as unconsolidated and massive sands. These sands are overain by a greyish-red paleosol, then a loess-like andisol. The sequence is the same as at outcrop 'B', except for a greater thickness of sand and sandstone.
PHOTO 8-6: The pale-orange appearing sediments which outcrop along the top edge of the LIGM abandoned sea cliff constitute outcrop 'C'. The closest, most prominent exposure is c. 4m thick.

8.3.4. Pahoa outcrop comparison

Rhyolitic material of all three outcrops contain clear plagioclase feldspar and high-temperature quartz (β-quartz) phenocrysts set in a very pale-orange (10YR 8/2) matrix. However differences occur between outcrops in the proportion of phenocrysts and in the texture of the surrounding matrix. Differences in matrix texture may be diagenetic, reflecting the effect of different long-term moisture environment on porosity.

Outcrop 'A': (a) The 2.0m thick bedded sequence has a lower crystal content than outcrop 'B'. The texture is relatively fine-grained and not at all open. It is denser in hand specimen. At the base of the sequence crystals appear slightly coarser; very coarse sand cf. coarse-medium sand.

The fallen rhyolitic sandstone block (fcre-ground of photo 8-2) looks very similar to outcrop 'C' except that it is not as phenocryst rich and the matrix is not as open (but more so than outcrop 'A' described above).

Outcrop 'B': Directly overlies weathered Mohakatino Formation. A consolidated sample within loose sands is highly crystal-rich in β-quartz, and especially feldspar. The matrix
texture is very open, consisting of interpenetrating flakes and sheaves. In hand specimen it is very light-weight.

Outcrop 'C': Directly overlies weathered Mohakatino Formation. Consists mainly of unconsolidated $\beta$-quartz and feldspar sands. It is certainly the same deposit as outcrop 'B' since both overlie weathered Mohakatino Fm. and contain coherent, consolidated blocks or pods.

Rocks and sediments in outcrops 'B' & 'C' were moist (and thus relatively heavy), whereas rocks in outcrop 'A' occurred as dry, low density blocks. The relationship between the rhyolitic sandstones which overlie weathered Mohakatino Formation at outcrops 'B' and 'C', and the higher deposit (outcrop 'A') which does not appear to rest on Mohakatino Formation is not clear, however they are likely to be of similar origin.
8.4. Other rhyolitic volcaniclastic deposits in North Taranaki

In addition to the rhyolitic deposit found near Pahaoa Hill, two other rhyolitic volcaniclastic deposits were found, one on either side of the Mokau River. Like the Pahaoa deposit both directly overlie weathered Mohakatino Formation and occur on non-marine surfaces inland of the abandoned LIGM sea-cliff, at an altitude well above that of the coastal marine NT2 Terrace. Figure 8-4.

FIGURE 8-4: Outline map of the Mokau area showing the location of the Tainui and Tuhiŋgakakapo outcrops. Note the (LIGM) NT2 Terrace, with the sloping non-marine terrace above. The map is sketched from a vertical aerial photo taken at an altitude of 7800m (NZ Aerial Mapping).

8.4.1. Tainui (north side of the Mokau valley)

A highly weathered rhyolitic deposit consisting of rounded clasts of fine-grained, rhyolitic tuff and overlain by very highly weathered bedded crystal-rich rhyolitic material. Outcrops on the north side of the Mokau River valley at an altitude of c. 205m.

The outcrop just north of the Mokau River is areally small in extent, and stands as an isolated 'stack' of rhyolitic material about 5m thick, and overlying weathered mudstone/sandstone at an altitude of c. 205m. The deposit probably represents a small remnant of a once more extensive deposit. The altitude of the deposit was determined
using an electronic theodolite by baseline/vertical angle measurements from a sports field then tied into a near-by geodetic benchmark, 'EC66' (see Appendix I for method).

The lower part of the deposit consists of well rounded clasts (large pebble size) of reworked fine-grained rhyolitic tuffs and/or ignimbrite (photo 8-7). The clasts have a characteristic concentric weathering rind separating the clasts into an outer weathered shell and fresher core. XRD analysis showed the composition to be dominantly kaolinite and quartz.

PHOTO 8-7: The Tainui outcrop is found at an altitude of c. 205-210 m above MSL, on the north side of the Mokau River valley, and consists of weathered conglomerate containing abundant fine-grained rounded clasts of rhyolitic origin.

The upper part of the deposit lacks these rounded reworked clasts and consists of subhorizontal, bedded material containing β-quartz and plagioclase phenocrysts embedded in a devitrified matrix (photo 8-8). The upper Tainui unit is very similar to the Pahaoa outcrop 'A' except that the matrix is stained a golden-brown colour and has a more 'open' texture. It also contains less feldspar which may be due to the obviously more weathered state than at other localities. This also may explain the more open, porous texture. The Tainui unit also contains highly weathered vermicular phyllosilicate identical to that found in the Pahaoa deposit, and thought to be altered original biotite.

1 OU 42564
2 OU 42565
Feldspar was also found to be almost identical to that described from Pahaoa, both in its external highly etched appearance, and in its composition. The Tainui outcrop is believed to be part of the Mokau rhyolitic deposit documented from Pahaoa.

PHOTO 8-8: Thin, sub-horizontal beds consisting of crystal-rich weathered rhyolitic material, and overlying the rhyolitic conglomerate seen in 8-7 above.

8.4.2. Tuhingakakapo (south side of the Mokau valley)
A highly weathered crystal-rich rhyolitic deposit containing scattered rounded clasts of fine-grained, rhyolitic tuffaceous material. Outcrops in a vehicle track just below Tuhingakakapo trig station on the south side of the Mokau River valley, at an altitude of c. 220m (estimated from 1:50,000 map contours). Grid reference R18/515757.

The Tuhingakakapo deposit outcrops at the side of a track providing access to the trig station (see figure 8-5), and overlies weathered Mohakatino Formation. The lower unit consists of feldspar and β-quartz phenocrysts in a semi-consolidated white matrix. It appears massive and sedimentary structures were not seen. This lower unit is separated from the overlying unit by an unconformity which possibly represents an erosional scour channel. The overlying unit consists of cross-bedded coarse sands and rounded clasts. The rounded clasts are reworked rhyolitic clay-tuffs. The clasts show no obvious

1 OU 42566
2 OU 42567
obvious imbrication, although cross-bedding suggests a paleo-current flowing from the northeast to southwest.

FIGURE 8-5: Sketch of the Tuhingakakapo outcrop (from photos) showing the weathered rhyolitic material overlying Mohakatino Formation, and its sedimentary characteristics.
8.5. Characterisation of the Mokau rhyolitic deposit

8.5.1. Petrography of Rhyolites

Williams, Turner, and Gilbert (1982) discuss the typical petrography of rhyolites and dacites: In rhyolites the typical plagioclase phenocrysts are sodic-andesine or oligoclase. In dacites the typical plagioclase phenocrysts are calcic-andesine and sodic-labradorite but compositions can range as widely as oligoclase and bytownite. In rhyolites, quartz typically represents greater than 20% of the felsic component and greater than 10% of the total volume (modal or normative). In dacites, modal quartz is not necessarily present, but if it is tends to be "deeply embayed". In rhyolites, minor accessory minerals almost always present are zircon, sphene, magnetite and ilmenite. In dacites, minor accessory minerals include fayalite, apatite, magnetite, ilmenite, garnet, and cordierite.

8.5.2. Petrography of central North Island rhyolites

Ewart (1967 & 1968) documented the petrography of Central North Island rhyolitic "lavas" (from the four main centres of the Taupo Volcanic Zone), with emphasis on the phenocryst assemblages. All rhyolites contain plagioclase and (titano-?)magnetite phenocrysts and usually contain modal quartz. The central North Island rhyolitic lavas are unusual in that none (out of 246 samples) contain alkali feldspar (sanidine). On the basis of ferromagnesian phenocrysts, Ewart delineated three major, generally discrete assemblages:

- Orthopyroxene (and augite).
- Orthopyroxene and calcic-hornblende.
- Biotite, calcic-hornblende and orthopyroxene.

Biotite-bearing rhyolites have the highest mean total crystal content (with a mean modal % of 18.1, s.d.=9.3). They are characterised by relatively abundant modal quartz resulting in low plagioclase:quartz ratios (P/Q; mean =2.5, s.d.=1.8).

8.5.3. Petrography of the Mokau rhyolitic deposit

The Mokau rhyolitic deposit at Pahaoa is crystal-rich in sodic-andesine (An35-40), as well as only slightly corroded B-quartz phenocrysts. Feldspar and quartz comprise at least 10% of the total volume, at an approximate feldspar/quartz ratio of 1. Ferromagnesian phenocrysts include a common, highly altered biotite, ubiquitous titanomagnetite and minor dark-green (calcic?) hornblende. Minor accessory minerals include very rare zircon and garnet (separated from the 3Ø sieved fraction using the Frantz EM separator).
These characteristics suggest that the Mokau deposit is derived from an eruption of biotite-bearing rhyolite, that probably originated from somewhere within the Taupo Volcanic Zone.

The possibilities of the deposit being dacitic in origin are considered unlikely on the basis of late Pliocene ages of the two possible dacite sources, and provisionally rejected on the basis of mineralogy (too rich in quartz phenocrysts, plagioclase too calcic). Also, the two possible known sources, involving relatively small erupted volumes were:

The c. 1.75Ma New Plymouth dacite cumulodomes 65km to the south.

The c. 1.8Ma Waikeria dacite 90km to the north.

Also, current direction implied by other rhyolitic deposits is not from either of these directions.

8.5.4. Mode of deposition

Assuming a distant vent, deposition as an airfall tephra is precluded. On the ground of thickness (2 to 4 metres) and the relatively coarse grain size characteristics of the Mokau rhyolitic deposit. The deposit is fairly well sorted and contains no clasts larger than several millimetres (the largest clasts appear to be composed of highly weathered, fine-grained, rhyolitic tuff similar to rounded pebbles found in other rhyolitic deposits above the Mokau River- see section 8.4).

The Mokau rhyolitic deposit attains a thickness of 4m in places, often just as 'loose sand' but at one locality as sandstone blocks, possibly displaying columnar-jointing, and with mm-cm scale sub-horizontal laminations (indicative of high velocity flow?). Exposure at outcrop 'A' is restricted to one side of an unusual conical hillock (one of an extremely localised cluster of several dome-shaped hillocks). It is interesting to note that in a geomorphological paper Selby et al. (1988) showed similar hillocks, formed at the boundary between welded and unwelded ignimbrite (Whakamaru Ignimbrite). Thus it appears feasible that the Mokau rhyolitic deposit is a distal rhyolitic ignimbrite. Possible correlative ignimbrites are discussed in the following section.

8.5.5. Correlation

The Mokau rhyolitic deposit at Pahaoa is confined to the non-marine terrace c. 100 m above the coastal NT2 Terrace. This distinctive deposit therefore has great potential for chronological constraint of the terrace if it can be correlated with a known rhyolitic eruption. Some possible known tephras and ignimbrites will now be considered to try and establish a correlative deposit.
8.6. Mangakino Volcanic Centre Ignimbrites

A large negative gravity anomaly is centred 5 to 10 km north of the Mangakino township and covers about 500 km$^2$, marking the Mangakino Volcanic Centre (MVC). The MVC is a large extinct rhyolite volcano that was active in the early to mid-Quaternary. The MVC is probably analogous to the Taupo Volcanic Centre, which was active throughout the late Quaternary, and still is. Descriptions of the MVC ignimbrite succession by Wilson (1986) are used to consider likely correlatives of the Mokau Rhyolitic deposit(s). Age estimates are from the recent work of Soengkono et al. (1992).

8.6.1. Ignimbrite A

Although this is a widespread early ignimbrite of "energetic emplacement" the description does not fit (i.e. colour, lithic clasts, texture, not crystal-rich).

8.6.2. Ignimbrite B & C

These are both poorly exposed and believed to be restricted to the immediate MVC area.

8.6.3. Ongatiti Ignimbrite

This is the most widespread and voluminous MVC ignimbrite and one of the largest known in the entire history of the Taupo Volcanic Zone. The Oparau Tephra of Pain (1975) which occurs on the Kawhia coast some 70 km north of Mokau is believed to be a probable distal deposit of the Ongatiti Ignimbrite (Pain, 1975 and Wilson 1986).

Descriptions by Pain of the Oparau Tephra (a member of the Kauroa Ash Formation) are of rocks which sound similar to the Mokau rhyolitic deposit. The reference site is Oparau, near Kawhia (70 km north of Mokau). Oparau lies 80 km WNW of Mangakino township. Mokau lies 105 km WSW of Mangakino (as well as the same distance due west of Lake Taupo's western bay).

Pain describes the Oparau Tephra at its reference site, as a lens of rhyolitic tephra with a maximum thickness of 3 m, consisting of small weathered angular to subangular clasts (<3 cm), in a white (5YR 8/1) sandy-clay matrix. Sand grains include abundant quartz, some magnetite, plus rare glass and zircon.

The Ongatiti eruption consisted of an earlier and a later erupted facies. The earlier erupted part is more widespread to the west and south of the MVC and travelled at least 70 km from the vent in a "single, voluminous and energetic flow" (Wilson 1986).

Age: 1.25 ± 0.09 Ma (K-Ar by Soengkono et al., 1992). Note, reverse magnetization.
8.6.4. Unit D, and Ahuroa Ignimbrite
These seem fairly easily discounted due to their distribution, size and other characteristics.

8.6.5. Unit E ignimbrite
This ignimbrite occurs over a wide area of the King Country but is only poorly exposed. Walker et al. (1983) correlated Unit E with a very extensive non-welded ignimbrite called the Morrinsville Ignimbrite. If this correlation is correct, a travel distance of at least 150km is indicated. Little descriptive information is given by Walker et al.

Age: Based on the stratigraphic position between the Ongatiti and Rocky Hill ignimbrite, Unit E is c.1.1 Ma in age. Note reverse magnetization.

8.6.6. Rocky Hill Ignimbrite
According to Wilson this is the youngest deposit seen in the King Country which can definitely be attributed to the MVC. As mentioned above, the Rocky Hill Ignimbrite is one of the three largest eruptions in the history of the TVZ. In addition to being crystal-rich it also contains original biotite (Bruce Houghton, pers. comm. August 1992).

Age: 1.06± 0.09 Ma (K-Ar by Soengkono et al., 1992). Note, reverse magnetization.

8.6.7. Rangitawa Tephra/Whakamaru Ignimbrite
The Rangitawa Tephra is a rhyolitic airfall tephra found widely preserved on the older parts of the South Taranaki/Wanganui terraces and is also reported from Urenui in North Taranaki (Pillans & Kohn 1981). The youngest terrace on which it occurs is the 400 Ka Ararata terrace and the tephra has a fission track age of 350±40 Ka (1 sd.). It has recently been shown that the Rangitawa Tephra and the Mt Curl Tephra are most likely the same deposit (Pillans et al., 1992).

Field identification (Pillans & Kohn 1981) is aided by; i) The “presence of a distinctive dark brown weathered andesitic ash which overlies the Rangitawa Pumice at many localities”. ii) Pale colour. iii) Characteristic coarse, sandy, basal layer (dominantly plagioclase feldspar). iv) Ferromagnesian mineralogy dominated by hypersthene with lesser amounts of hornblende. Biotite, which is a bronze colour when weathered is also present (Pillans, pers. comm.) It also contains only minor quartz. Distal samples of the Rangitawa Tephra seen at Urenui and near Waverly (shown by Dr Brad Pillans) are not at all similar either mineralogically, texturally, or volumetrically. Thus this correlation seems unlikely. Also see section 4.2.4.
8.7. Discussion

On the 1:250,000 geological map of Taranaki (Hay, 1967), remnants of the Ongatiti Ignimbrite are shown to be much closer to Mokau than the Rocky Hill Ignimbrite, though still rather distant from the coast (closest remnant about 40km NE of Mokau).

The Ongatiti Ignimbrite seems a likely correlative for the Mokau rhyolitic deposit as it is extremely voluminous, crystal-rich, and is thought likely to have reached the coast of the Tasman Sea. However there is a problem in that biotite does not reportedly occur within the Ongatiti Ignimbrite (Bruce Houghton, pers. comm. August 1992), whereas an altered phyllosilicate in the Mokau deposit is most likely weathered original biotite. Biotite however, is a component of the other two extremely large, crystal-rich ignimbrites - the Rocky Hill and Whakamaru. Hence it seems that either the altered phyllosilicate in the Mokau rhyolitic deposit is derived from a diagenetic biotite, or that the Mokau rhyolitic deposit originates from the Rocky Hill or Whakamaru, or another very large biotite bearing ignimbrite.

8.8. Summary/conclusion

Pahaoa outcrops 'A', 'B', and 'C' are crystal-rich weathered rhyolitic deposits. All outcrops contain abundant, coarse sand-grade, high temperature sodic-andesine plagioclase (An35-40) and sub-euhedral β-quartz in a highly devitrified very pale orange to white matrix. These outcrops also contain minor to common highly altered biotite, ubiquitous fine magnetite, as well as sub-angular to rounded lithics (1-2 mm) of probable rhyolitic tephra/ignimbrite origin (probably other lithologies as well).

Pahaoa outcrops 'B' and 'C' both unconformably overlie weathered Mohakatino Formation and occur as mainly loose, damp sands. Remnant coherent blocks showing lamination indicate some degree of in situ destruction of internal sedimentary structures, most likely due to the saturated state which occurs due to infiltration of meteoric water from free-draining soils.

Outcrop 'A' outcrops at a slightly higher altitude as laminated coherent blocks, and although its stratigraphic relationship with the other two Pahaoa outcrops is not exposed they are expected to grade into each other.

The two other rhyolitic deposits at Tainui and Tuhungakakapo have many similarities to the outcrops at Pahaoa in that both are crystal-rich in plagioclase (highly etched morphology identical to Pahaoa), as well as sub-euhedral β-quartz, all in a highly devitrified clay-rich matrix. Sedimentologically there are differences between these two
outcrops and Pahaoa, in that they also contain rounded pebble-size clasts of fine-grained, crystal-poor, rhyolitic tuff material, and show evidence of strong currents (presumably river currents as they both occur high on the sides of the Mokau River valley).

These deposits must have travelled to the North Taranaki coast across a plain of low relief, in contrast to the highly dissected relief of the present day. It is suggested that the Tainui and Tuathingakakapo outcrops were deposited along the sides of an ancestral Mokau River at some unknown distance from its original river mouth. The Mokau rhyolitic deposit implies the existence of an extensive plain of low relief existing in the early to mid-Quaternary, which must have continued into the Waikato area. This implication is reciprocately supported by the ridge-crest concordance of the North Taranaki Surface (NTS) which has long been attributed to a dissected peneplain (through simple theoretical considerations in chapter ten, the altitude of the NTS envelope is shown to be only indirectly related to the rate of tectonic uplift).

There are too many assumptions required to make useful age calculations from the c. 200m altitude of the rhyolitic river deposits (ie. sufficiently long term average uplift rates, distance from the paleo-river mouth at time of deposition, the rivers paleo-baselevel and aggradational/degradational regime, etc.), but a general consideration of these variables leads the author to believe that the deposit is unlikely to be younger than half a million years old.

From the thin planar bedding and other sedimentological characteristics of the deposit at Pahaoa it is believed that it is a distal ignimbrite, probably originating from the extinct Mangakino volcanic centre. The Tainui outcrop also contains thin planar bedded crystal rich material almost identical to that seen at Pahaoa (especially outcrop 'A').

The Mokau rhyolitic deposit/s is at this stage not able to be uniquely correlated with any one large known ignimbrite eruption, but it is thought likely to be either the Rocky Hill or one of the older Whakamaru Group ignimbrites (oldest member is K-Ar dated by Soengkono et al., 1992; at 0.61±0.13 Ma).
Chapter Nine
Alteration of minerals within the Mokau rhyolitic deposit.....142

9.1. Chemical weathering of feldspars.................................142
9.2. Chemically weathered minerals from the Mokau rhyolitic deposit.........143
9.3. Etched plagioclase feldspars from the Mokau rhyolitic deposit.........144
9.4. Altered phyllosilicates from the Mokau rhyolitic deposit.............144
9.5. Zeolite (?) on mineral surfaces within the Mokau rhyolitic deposit .......145
9.6. Clay transformation rates in tephras........................................146
   9.6.1. Age control.........................................................146
   9.6.2. Environmental controls...........................................147
Chapter Nine

Alteration of minerals within the Mokau rhyolitic deposit

Etched plagioclase feldspar, altered phyllosilicate (originally biotite), and diagenetic zeolite and clay minerals from the Mokau rhyolitic deposit are discussed with emphasis on scanning electron microscope (SEM) images.

9.1. Chemical weathering of feldspars

The Mokau rhyolitic deposit contains abundant plagioclase feldspar phenocrysts (see earlier sections), almost all of which exhibit etched and dissolved surfaces, yet internally are almost totally unaltered. The surface form of the feldspars became of interest for two reasons: Firstly their aesthetic appeal, and secondly, I suspected there could be a relationship between the degree of plagioclase dissolution, and the age of the deposit combined with the local site environment (eg. leaching history). Plagioclase surface morphology would also allow comparison, and possibly strengthen correlation, between the Mokau rhyolitic deposit at Pahaoa and two other very similar rhyolitic deposits several kilometres to the south. In other words, using surface morphology of feldspars to check whether it was likely that the individual rhyolitic deposits were of the same age or not.

Chemical weathering of silicate minerals - literature review: Etch-pits are common on a diverse group of silicate and other minerals which have undergone aqueous dissolution. The morphology of etch-pits is typically polyhedral and their orientation consistent with the crystalline structure of the host mineral. Severely etched minerals are common in such diverse environments as soils, diagenetically developed secondary porosity and hydrothermally altered rocks (Blum et al., 1990).

Etch-pits develop at the intersection of dislocations with the mineral surface. Dislocations are line defects along which the crystal lattice is distorted, introducing strain-energy. Dislocations are present in virtually all crystalline solids, and typically form at low densities during crystal growth, or at very high densities during plastic deformation (Blum et al., 1990).

The mechanism of dissolution and the rate-limiting step in the process of chemical weathering of minerals has been the subject of intense debate in the literature and has still not been fully resolved (Mogk, 1990). For example, some of the key questions that remain unresolved are:
Does dissolution occur strictly through "surface"-controlled reactions (scale of tens of angstroms) or through the development of "leached-layers"? (2) Are weathering reactions laterally heterogeneous on mineral substrates, and if so, what is the nature of the preferentially weathered sites? Mogk (1990).

Chemical weathering of feldspar - literature review: For feldspars, the "surface-reaction hypothesis" (Helgeson et al., 1984) is the only theory consistent with scanning electron microscope (SEM) and X-Ray photoelectron spectroscopy (XPS) studies of the surfaces of etched feldspar grains (the other two general hypotheses are the "armouring precipitate" and the "leached-layer" hypothesis).

From observations of feldspars in soils, Berner & Holdren (1979) outlined the development of surface morphology: In the early stages of weathering, shallow "almond-shaped" etch-pits occur on the surface of the feldspar. During later stages of weathering, "square-shaped", prismatic etch-pits develop. In the final stages of weathering, the grains become fragile honeycomb-like shells. Holdren & Berner (1979) concluded that the mechanism regulating the weathering of feldspar is a surface reaction at the mineral/aqueous solution interface.

9.2. Chemically weathered minerals from the Mokau rhyolitic deposit

Introduction

Whole phenocrysts and fragments/remnants of larger crystals (plagioclase feldspar, quartz, and altered phyllosilicate) were hand-picked from sieved fractions of the Mokau rhyolitic deposit. The crystals were mounted on SEM stubs and vacuum coated, first with carbon and then with gold. Observations were conducted on the Medical Schools JEOL 360 scanning electron microscope. The nature of the samples, and the manner in which they had been coated enabled very high resolutions to be obtained. Details of even the smallest features (e.g. individual clay-mineral crystallites coating quartz phenocrysts at about 80,000 times magnification) were easily obtainable.

Whole rock samples were also inspected. These samples did not require vacuum coating as their relatively large size negated a major problem in SEM work, that of surface "charging". Uncoated samples however do not have the same potential for very high resolution images as is possible for coated samples.
9.3. Etched plagioclase feldspars from the Mokau rhyolitic deposit.

Large phenocrysts are sometimes shaped like irregular doughnuts and possess a large central hole (photo 9-1). These doughnut-shaped feldspars may have had a compositionally different core (e.g. more anorthite-rich) which was more prone to chemical weathering than the remaining feldspar. The surface morphology of the inner zone of the feldspar crystal is rougher (more pitted) than more peripheral zones (e.g. photo 9-2). Small, square to rectangular, prismatic etch-pits (Berner & Holdren, 1979), having linear dimensions of roughly 1 to 20 µm can be seen forming on the surface, close to the central hole, of photo 9-2.

Other large feldspar crystals do not possess the “doughnut” form, and it seems apparent that they were originally lamellar-twinned phenocrysts. The etch-pits that form on the twin plane are irregular (photo 9-4), to “almond-shaped” (Berner & Holdren, 1979) as in photo 9-3. It would seem from photo 9-3, that etching proceeds by the consumption of external layers which are seen to be more pitted, or surfaces exposed to formational fluids (also see photo 9-5).

Some smaller crystals showed square to rectangular prismatic etch-pits (e.g. photo 9-7 & 9-8 pits show linear dimensions of up to 80 µm on photo 9-7; up to 110 µm on photo 9-8, and from 20 to 150 µm on photo 9-9. In particular, photo's 9-9 & 9-7 show that the prismatic etch-pits are tunneling, at a roughly perpendicular angle, into the twin-plane, with the lamellae seen exposed on the side walls.

Yet another feldspar weathering morphology is shown in photo 9-6; grooved striations (“terrace-front valleys”) are forming at right angles to a linear "riser". Both structures apparently follow crystallographically defined orientations.

9.4. Altered phyllosilicates from the Mokau rhyolitic deposit

Before SEM preparation, hand-picked phyllosilicates were observed under the binocular microscope. They were seen to be striped in alternating dark and pale-bronze coloured bands, perpendicular to the basal (001) cleavage. From observations under light and electron-beam illumination, it was seen that cleavage traces are being distorted and bent by differential expansion of phyllosilicate layers. In SEM photo's 9-10 to 9-13 which successively zoom in on a clay filled fissure, it is seen that as the basal layers have parted, tiny elongate crystallites of diagenetic clay have become oriented perpendicular to the direction of basal-layer divergence (especially see photo's 9-12 and 9-13). These oriented crystallites, some up to 5µm long, strongly suggest that the phyllosilicate layers have been slowly expanding in situ within the Mokau rhyolitic deposit, as also evidenced on
the macro-scale by the curved altered phyllosilicate in photo 9-14 within its surrounding matrix.

9.5. Zeolite (?) on mineral surfaces within the Mokau rhyolitic deposit
Diagenetic crystallites coat the surfaces of many crystals within the Mokau rhyolitic deposit. At reasonably high magnifications (upwards of about 1000 times), "matts" and "forests" of elongate crystallites can be seen covering the surfaces of many crystals within the rhyolitic unit. "Matts" of crystallites, as seen in photo 9-15 (coating a quartz grain), consist of flat-lying, randomly-oriented, elongate, flat, tabular crystallites with blunt terminations. Typically they are about 2 \( \mu \text{m} \) in length, and about 0.2 \( \mu \text{m} \) wide. "Forests" of these elongate, tabular crystallites are also seen on the surface of the altered phyllosilicate discussed in the previous section. See also photo 9-16 for a closer view of these crystallites. From the individual crystallite morphology it is apparent that the 'matts' and 'forests' are composed of the same mineral, but with a different collective orientation.

It is notable that significant coatings were never seen on the surfaces of feldspars. An explanation for this may be that aqueous dissolution which is occurring at the feldspar surface and resulting in etching, is providing cations in solution, predominantly aluminum and silicon. Crystallites then form by co-precipitation onto other minerals, such as quartz and phyllosilicate, undergoing less rapid dissolution.

Initially the crystallite coatings were assumed to be clay minerals and efforts were made to identify them using its SEM morphology. The high halloysite-7Å content of the matrix naturally led me to suspect that the crystallites were halloysite. Halloysite however has a tubular or spherical form (Sudo & Shimoda, 1978). No SEM photos were found for halloysite. Emeritus Professor D.S Coombs (pers. comm. July 1993) suggested that the zeolite minerals mordenite and erionite were likely candidates - both having fibrous habits and commonly reported from rhyolitic tuffs.

**Erionite:** "The morphology is quite simple, with rare hexagonal prisms..., but usually erionite occurs as thin fibres, often forming a compact felt, but sometimes tufts with delicate woolly aspect..." - Gottardi & Galli (1985).

"Genesis in a hydrologically open system, mainly by slow percolation of meteoric water through the porous tuffaceous sediments was invoked by Barrows (1980) for explaining the presence of erionite..." (ibid.).
Mordenite: Is an orthorhombic zeolite with eight sides, the, "morphology is always characterised by needles, fibres with c-elongation; radial aggregates, from loosely bound to compact, are common" (ibid.).

Photo 9-16 shows some of the diagenetic crystallites almost end-on. At the lower mid-left of photo 9-16 one crystallite was clearly seen to have a hexagonal cross-section (other similar hexagonal shaped crystallites can also be seen). Hexagonal morphology thus rules out the eight-sided mordenite and suggests erionite. An XRD analysis to back up this observation was attempted but not enough material was able to be collected.

9.6. Clay transformation rates in tephras

Length of weathering time, primary mineral composition, and past and present site weathering conditions influence types and amounts of clay minerals present (Lowe, 1986).

9.6.1. Age control

Clay-sized material generally increases with age, as glassy and other components are broken down and transformed to authigenic clay minerals. In New Zealand tephras are generally weathering under temperate and humid conditions. A general relationship between clay-content and age applies to New Zealand rhyolitic tephras which are weathering under similar environmental conditions (Table 9-1).

<table>
<thead>
<tr>
<th>Age (ka B.P.)</th>
<th>Clay Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 3ka</td>
<td>&lt; c. 5% clay minerals</td>
</tr>
<tr>
<td>3- 10 ka</td>
<td>5- 10 % clay minerals</td>
</tr>
<tr>
<td>10- 50 ka</td>
<td>10- 30 % clay minerals</td>
</tr>
<tr>
<td>&gt; 50ka</td>
<td>&gt;30% clay minerals</td>
</tr>
</tbody>
</table>

For rhyolitic tephras a widely adopted weathering sequence is:

$\text{glass} + \text{allogphane} \rightarrow \text{allogphane} \rightarrow \text{halloysite}$
The glass/allophane transition in New Zealand is estimated to occur after about 3ka, with the allophane/halloysite transition occurring after 10 to 15 thousand years. In one Japanese study the allophane/halloysite transition was shown to occur at about 6ka, and it was demonstrated that with time the halloysite crystals enlarge and become more well ordered, attaining a diameter of up to 1\(\mu\)m in about 250ka. Based on the high percentage (significantly >60%) of halloysite-7Å in the matrix of the Mokau rhyolitic deposit (figure 9-1, also fig. 8-3), it is probably significantly older than 50ka.

![FIGURE 9-1: XRD analysis of white clay-rich matrix of the Mokau rhyolitic deposit (Pahaoa outcrop-A): Halloysite-7Å (H) and quartz standard (Q) are clearly seen. The sharp peak at 21.6° (4.09Å), as well as small peaks at 40.2° (2.24Å) and 42.3° (2.12Å) were not able to be identified.](image)

### 9.6.2. Environmental controls

The environmental controls on weathering may be divided into macro- and micro-environmental factors: Macroenvironmental factors are regional rainfall and temperature, both past and present. Microenvironmental factors include degree of leaching, drainage, pH of percolating water, tephra thickness, burial depth, vegetation, and other organic cycle factors. Environmental factors that are most important are those that affect the concentration of silica in solution (pH of the solution is important here), the movement and availability of alumina, and their opportunity for co-precipitation. The predominant environmental controlling factors on weathering are leaching regime, organic cycle and vegetation type; which are themselves dependant upon climate, drainage and tephra thickness.

**Temperature effect:** Climosequence studies have shown clay-content is related to mean temperature. During the Late Pleistocene glacials average temperatures were several
degrees lower than at present. Conditions however were drier, hence rates of silica leaching were reduced, and therefore the role of paleotemperature in clay formation cannot be evaluated with certainty.

**Drainage effect:** Impeded or slow drainage tends to favour the formation of halloysite and silica-rich allophane (Si: Al = 1) because of the minimized loss of soluble silica and other cations. Good drainage promotes loss of silica and formation of low silica allophane (Si:Al = 1/2) and imogolite.

**Tephra thickness and burial depth effect:** Burial of a surface horizon reduces the organic input, and in time, allows previously humus-bound aluminum to be released and to ultimately co-precipitate with silica to form allophane or imogolite. A thick sequence (>2 m) potentially provides a silica-rich environment for a buried tephra, favouring the formation of halloysite through resiliﬁcation.
Feldspar - pitted and etched.

Etch pit in feldspar crystal.
Feldspar - relatively unetched.

Feldspar - striated
clay? coating altered phyllosilicate.

Feldspar.
Prismatic etch-pits in feldspar.
clay? coating altered phyllosilicate.
Altered phyllosilicate in matrix.
Chapter Ten
Landscape: a theoretical and quantitative approach..................158

10.1. Fractals and landscape evolution.................................................158
10.1.1. Introduction ........................................................................158
10.1.2. Chase Synopsis.................................................................158
10.1.3. Quantifying the irregular (self-similarity and self-affinity)......159
10.1.4. Proposed analysis of the North Taranaki hill country ..........160
10.1.5. Laplacian Growth and the property of "directedness"........160

10.2. Landscape evolution on the South Taranaki/Wanganui marine
terraces .....................................................................................161
10.2.1. Drainage Initiation .....................................................161
10.2.2. Terrace evolution...........................................................162
10.2.3. Valley and side-slope evolution ......................................163

10.3. A theoretical approach to landscape evolution in northern Taranaki.....163
10.3.1. Introduction.............................................................163
10.3.2. Systems in geomorphology...........................................163

10.4. Summary/Synthesis...............................................................165
Chapter Ten

Landscape: a theoretical and quantitative approach.


10.1. Fractals and landscape evolution

10.1.1. Introduction

Non-euclidian or irregular branching geometry pervades nature (over a wide range of scales) and is expressed in the organisational pattern of diverse biological and physical phenomena; from tree branches and veins, to dendritic river channel networks and their corresponding valleys and ridges. Benoit Mandelbrot's inspired conception of fractal geometry; "Mountains are not cones, coastlines are not circles, bark is not smooth, nor does lightning travel in a straight line" (1982), was in the mathematical sense a revelation, for it provided science with a tool by which to quantify the 'irregular' and to begin contemplating the possibility of a unifying mechanism of process, growth and form.

10.1.2. Chase Synopsis

Chase's (1992) "precipiton" model of landform evolution provides valuable insights into the relationship of topographic complexity (quantified using the surface fractal dimension, D) and generalizations of the three main processes which sculpt the landscape; erosion, diffusion, and deposition. Erosion roughens the landscape, while diffusion and deposition attempt to smooth it. Erosion is a scale-free (ie. self-similar) process and therefore roughens the topography at all scales. The other two processes are scale-dependent; diffusion balances roughening at small scales with its smoothing effect, while at larger scales depositional processes buffer erosional roughening.

Chase's model successfully predicts that the landscape is multifractal, with D being less at short wavelengths (ie. at the small scale landforms appear smoother) and increasing with longer wavelengths (ie. on larger scales the landscape appears rougher). This smoothing at short wavelengths is caused by diffusive processes (eg. mass wasting, slope-wash, soil creep, and slumping), and which are more effective in wet climates than dry ones.

The precipiton model found that although the fractal dimension generally increases with the horizontal length scale, it is not a function of relief (vertical length scale), nor is it
particularly correlated with the rate of tectonic uplift. Rather, it is climatically controlled factors which are most clearly related to the fractal dimension of topography.

For example, Chase's model predicts that at small scales a relatively low diffusion rate (corresponding to arid climate) results in rougher topography than wet-humid climates which produce smoother landforms at the small scale (this is assuming similar erodability of the rocks, another model variable). In particular, Chase found that the model variable he calls "maximum effective storm size" is; "perhaps the most important climatic variable in determining the landforms that develop", and that it is, "related less to total amount of precipitation than to how it is distributed in time"; also, "higher carrying capacitites are more erosive and favor (sic) larger fractal dimensions for both long- and short-wave length models".

10.1.3. Quantifying the irregular (self-similarity and self-affinity)

Fractal dimension of a 'curve': Most of the fractals found in nature possess a statistical rather than exact self-similarity or self-affinity. Exact self-similarity is a property of the deterministic "mathematical monsters" of the early 1900s like the Koch Curve and Sierpinski's Gasket (Voss, 1989).

Self-similar fractals can be characterized by only one exponent (D, the fractal dimension), whereas self-affine structures require at least two scaling exponents for different directions. "The contours of a landscape may be isotropic and self-similar, whereas the vertical ones may be anisotropic and not self-similar" (Matsushita and Ouicha, 1989).

The method proposed by Matsushita and Ouicha is a flexible and powerful method which allows any 'curve' embedded in two dimensions, such as a contour line or vertical cross-section, to be analysed for its scaling exponents in the x- and y-direction (Vx and Vy). If the curve is self-affine then Vx≠Vy≠1. If Vx=Vy then the 'curve' is self-similar and the fractal dimension is D=V⁻¹. The self-affinity parameter (H) is defined as Vy/Vx, and using generalizations of fractional Brownian motion can be used to simulate strikingly realistic self-affine 'curves' which resemble transect profiles of mountainous landscapes (as well as higher dimensional shapes such as landscapes and clouds - see Voss, 1989).

To analyse a curve using the method of Matsushita and Ouicha, the horizontal and vertical standard deviations (X and Y) are found for a set of points (xi, yi) along a certain 'length' of curve (N.s) where s is the unit length and N is the number of units along the curve at this scale. N is then changed by changing the step-length scale, s. The standard deviations X and Y are then plotted on a log-log graph against N, with the slope of the
resulting regression line yielding the self-affine exponents $V_x$ and $V_y$. If there is only one line then the curve is self-similar.

![Diagram](image)

FIGURE 10-1: Analogy between Laplacian growth described in Vicsek (1989) and the branching pattern of a river network.

10.1.4. Proposed analysis of the North Taranaki hill country

It was proposed to digitize a profile of the dissected inland hill country behind the marine terraces from a 1:50,000 topographic map and to try and find the self-affine parameters using the 'Matsushita method'. This could then be compared with a similar analysis of dissected hill country in the South Taranaki/Wanganui area behind the marine terraces, and used to compare the state of equilibrium and/or the balance between erosion, diffusion and deposition processes in the two areas. However it was not easy to obtain digitized topographic data for this area, at least not in the public domain. A cross-section from 1:50,000 topo map was started by hand but it was decided that it would take too much time to digitize a long enough transect. See section 10.4 for further details.

10.1.5. Laplacian Growth and the property of "directedness"

The similar shape of Laplacian growth phenomenon described by Vicsek (1989); including dielectric breakdown, viscous interfingering, ballistic deposition etc.; to stream and river networks (especially in the Urenui-Onaero area) was noticed by the author.

Laplacian Growth is a common phenomenon in nature and leads to branching (self-affine) fractal structures with deep "fjords" between the branches (Vicsek 1989). Growth takes place from a "seed" and moves in a direction pointing away from the initial
configuration. "The branches tend to grow outward and practically there are no branches developing in a direction of the seed. Thus there exists a directedness inherent to Laplacian patterns" - Vicsek (1989). The fractal properties of Laplacian growth arise from the instability of the growth process at the interface between a propagating fractal tip (ie. stream channel head) and the surrounding space. Directedness is also known as "self-avoidance" (Stark, 1992).

Several analogies were noticed between real examples of river networks and deterministic, recursive computer models discussed by Vicsek (see figure 10-1): Firstly, the "directedness" of the river network away from the coast. The "seed" of the river network is obviously the river mouth, and the present coastline is the "substrate" upon which the seed is located in space. Strict Laplacian growth can only proceed in an unrestricted medium having no predetermined directions of preferred growth. In the Urenui-Onaero area for example, this condition is only approximately met for streams dissecting the unjointed Quaternary coverbeds. For the more entrenched inland streams which dissect the Urenui Formation, a certain degree of predetermined pattern is imposed on stream growth by inferred joint sets and/or faults (see section 4.3).

10.2. Landscape evolution on the South Taranaki/Wanganui marine terraces

10.2.1. Drainage Initiation

Pillans (1985) detailed the general mechanism by which streams on a terrace evolve, and outlined three main stages:

The first stage of drainage network evolution, occurs during a regression cycle. The seaward dipping wave cut platform results in predominantly shore normal drainage. At the same time as drainage starts to evolve on the emergent platform, terrestrial sediments begin to accumulate in the interfluve areas and both erosion and deposition continue concurrently.

The second stage begins with the following transgression cycle. The drainage system is truncated by cliff formation. The cliffing causes an increase in local relief along which renewed valley initiation and/or dissection can occur. The effect of this truncation is that the smallest streams discharge into the sea via waterfalls and/or hanging valleys. Larger streams however lack these features, which suggests that the rate of down-cutting is in dynamic equilibrium with the rate of cliff retreat during the highstand (c. 0.7 m.a\(^{-1}\) for Hawera-Wanganui, J.G. Gibb pers. comm. with C.A. Landis).
The third stage begins with abandonment of the cliff during the following regression. This results in valley initiation along the terrace front, and valley growth and lengthening via headward sapping. The upstream ends of valleys and their tributaries are characteristically large basin shaped amphitheatres with steep headwalls and gently sloping floors. Immediately downstream the valley floor is swampy with no defined stream channel. In the lower reaches streams have well defined channels and may be locally eroding into the underlying wave cut platform.

The streams in south (and north) Taranaki have constant flow all year round, largely derived from groundwater seepage via small springs at the permeable/impermeable boundary of the coverbed/wave-cut platform interface where it intersects the valley sides or base. Groundwater is largely derived from springs at the valley head. Pillans believes that the bifurcation of the drainage network is largely controlled by groundwater flow which is in turn controlled by such factors as tectonic tilting. This third stage of drainage network evolution then continues irrespective of further transgression/regression cycles until terraces are completely dissected. Pillans (1988) hypothesized that the stage of complete dissection may be characterised by drainage network stabilisation, perhaps due to a balance being reached between uplift and fluvial downcutting. This hypothesis is supported by computer modeling by Willgoose et al. (1991), and is discussed in more detail in section 10.3.2.

10.2.2. Terrace evolution

Pillans (1988) recognised the fact that each dated marine terrace represents a nearly ideal initial surface upon which subaerial processes will have operated for a knowable period of time. The initial surface is probably almost identical for terraces formed at different times, thus a flight of terraces presents an evolutionary sequence of nearly “ideal landscapes in which to quantify long term rates of landscape change”. Pillans found that:

(1) Drainage densities increase inland on each progressively older terrace until at some distance inland the terrace surface is completely dissected. From this discrete data Pillans constructed a continuous relationship (see figure 10-2 from Pillans 1988) which is strongly linear.

(2) Interfluve area (remaining original terrace surface) decreases in sympathy with an increase in drainage density so that the terrace is completely dissected after c. 560ka and drainage densities are about 3km.km\(^{-2}\).
(3) Accumulation rate of non-marine coverbeds (dunes, loess and soil) is also highly linear at an average of 1/16 m.ka\(^{-1}\).

### 10.2.3. Valley and side-slope evolution

From detailed study of terrace-front valleys, Pillans (1988) also found that:

1. The mean rate of headward retreat of a terrace front valley is c. 2 mm.a\(^{-1}\).
2. The mean rate of stream downcutting is c. 0.2 mm.a\(^{-1}\).
3. Valley length is proportional to stream discharge.
4. Valley side-slopes are approximately rectilinear with a noticeable slope break associated with the wave-cut platform.

### 10.3. A theoretical approach to landscape evolution in northern Taranaki

#### 10.3.1. Introduction

When a wave-cut platform (and its marine cover-beds) is first abandoned by the sea it represents an approximately planar, essentially euclidian, geomorphically ideal, ‘initial’ surface. Through the processes of erosion the initial surface then evolves towards a distinctly non-euclidian form which more closely resembles the forms of fractal geometry (see section 10.1). Resulting in progressively increasing dissection which is always observed with increasing age and therefore altitude of uplifted marine terraces.

#### 10.3.2. Systems in geomorphology

Uplifting marine terraces, or any landscape undergoing tectonic uplift can be approached as a system involving the flux and transformation of energy: “In energy terms, the potential energy of the system (ie. elevation) is being dissipated by the transport of energy out of the catchment by erosion”.

At the same time energy is being externally fed into the system via tectonic uplift, which raises another characteristic of many natural systems that of 'openness'. “In energy terms, the tectonic uplift is a source of potential energy for the system and opposes the dissipation of energy”- Willgoose et al., 1991.

Tectonic uplift opposes erosion of the catchment, or at least, the decrease in elevation by erosion. This tension between the dissipation and input of energy, raises the possibility of geomorphic dynamic equilibrium: “At dynamic equilibrium the elevation at every point in the catchment is constant with time ...Catchments where net deposition or erosion are taking place, ... cannot be in dynamic equilibrium. If a catchment is not in
dynamic equilibrium, then either the mean channel network or the mean elevations must be changing with time" - Willgoose et al., 1991.

Marine terraces which have not yet been completely dissected by erosion are obviously not in "dynamic equilibrium". However, there reaches a stage in the evolution of marine terraces, where the remnants of any planar surfaces are totally destroyed by erosion. As discussed in section 10.2.2., in south Taranaki total destruction of the original initial surface occurs after c. 560ka (Pillans, 1988).

FIGURE 10-2: Percentage undissected terrace vs. time (ka. B.P.) for the South Taranaki/Wanganui uplifted marine terrace sequence. [Modified from fig. 2, Pillans 1988].
Once this stage has been reached, the only hint that remains of the former planar surface is a concordance of ridge-crest altitudes, the envelope of which forms an imaginary planar surface. In north Taranaki this concordance is characteristic of a large area of land lying inland which occurs inland of the uplifted marine terraces (see sections 1.1 and 1.10 for further description). Chappell (1964) named this concordance of ridge-crests the "North Taranaki Surface" (NTS). It is possible that this concordance of ridge-crest altitudes represents a state of dynamic equilibrium, where neither the "mean channel network", or "mean elevations" are changing with time (ie. both attributes are in a 'steady-state').

Willgoose et al. (1991) showed by computer modelling, that drainage density initially increases in a linear manner (as Pillans categorically showed for the south Taranaki area, see section 10.3), but then levels-off as the channel network becomes constrained, through negative feedback, by its own areal growth (which Pillans 1988 hinted at). Within the NTS all ridges meet in knife edges, so it seems reasonable to assume that the mean channel network has reached a steady-state. The second condition for "dynamic equilibrium" is that elevations are in a steady state, which is somewhat harder to evaluate. If uplift is equally balanced by erosion, at all points, then elevations will have attained a steady-state, and the NTS is thus in a state of "dynamic equilibrium".

Thus the altitude of the ridge-crest envelope cannot be used as an estimate of the altitude of former uplifted marine terraces even though the planar form of the envelope may be inherited from the wave-cut platform/s which underlie the possible former marine terrace/s. Obviously this is because tectonic uplift rate will not purely result in uplift of mass, but energy from this force will be simultaneously dissipated by erosion. The high rate of erosion within the NTS probably easily balances or exceeds tectonic uplift.

10.4. Summary/Synthesis
Matsushita's method for the fractal analysis of a curve, and Chase's precipiton model of topographic complexity were summarised. A proposal for the analysis and interpretation of a topographic profile from the north Taranaki hillcountry was outlined based on the above schemes.

Although it did not eventuate, the proposal to analyse a profile of the rough inland hill country for its roughness parameter (H) was given. It was envisaged that multifractal behaviour (H as a function of horizontal scale) could be related to the relative importance of diffusion, deposition and erosion at various scales within the NTS. It would perhaps be possible to see from this data whether todays landscape has equilibrated to the present
PHOTO 10-1: Degraded LIGM sea cliff between Tongaporutu and Mohakatino. Note the smooth appearance which is taken to imply the dominance of diffusional smoothing over erosional roughening at small scales.
Observations in the north Taranaki field area clearly show that at the small scale (< \(10^2\) m), individual hills, terrace risers, scarps etc; are relatively smooth in appearance, and this is obviously due to the dominance of diffusion at short wavelengths, especially in wet-humid climates (see photo 10-1 of degraded LIGM cliff). At the larger scale (~\(10^3\) m) the landscape appears much rougher and more complex (photo 10-2). In Chase's scheme this is due to the dominance of erosional roughening over depositional smoothing over at large scales (diffusional smoothing operates only at small scales). In north Taranaki it is obvious that deposition is not sufficient to balance erosional roughening. Erosion therefore dominates, with the relatively impermeable rocks causing high run-off during the frequent heavy rains, and the relatively soft sedimentary rock able to be easily removed. In addition the high drainage density provides an efficient network for removing eroded material out to sea.

The similarities between the dendritic pattern of a typical north Taranaki river catchment and the branching fractal structures of Laplacian growth described by Vicsek were noted. The departure from an ideal Laplacian growth pattern was linked to structural heterogeneity within the rocks in which drainage is 'growing'.

The evolution of landscape in South Taranaki/Wanganui elucidated by Pillans (1985, 1988) was summarized. The rates of landform evolution in South Taranaki/Wanganui are probably roughly similar to rates in north Taranaki.

The landscape as an evolving system in more general terms was then considered. It was argued that drainage density may have stabilised (i.e. steady-state), but that mean elevation over the NTS is not necessarily in a steady-state. In fact mean elevation may even be decreasing if rates of vertical erosion exceed the rate of tectonic uplift (c. 0.3- 0.15 mm.a\(^{-1}\)). for this reason the altitude of the ridge-crest envelope (or "concordance") cannot be used as an estimate of the altitude of possible former uplifted marine terraces.
PHOTO 10-2: Vertical aerial photo (NZ Aerial Mapping) from an altitude of c. 7800m above Rapanui Stream (at left) showing the rough and complex appearance of the landscape inland of the coastal marine terrace (NT2 Terrace) at this scale (roughly 1:35,000). Erosional roughening dominates at this larger scale.
Chapter Eleven

Late Quaternary tectonics ............................................................ 169

11.1 Rates of tectonic uplift ............................................................ 169
Chapter Eleven

Late Quaternary tectonics

11.1 Rates of tectonic uplift

At least four Pleistocene uplifted marine terraces occur in the north Taranaki area. These are the NT1, NT2, NT3, and an older terrace formation (informally named 'Urenui upland terrace surface'). The average uplift rate for the Late Quaternary was inferred from Last Glacial Cycle marine terrace strandline altitudes at several localities. The altitude of the NT1 and NT2 terrace strandlines or features near to this were used to calculate average uplift rates at several localities (Table 11-1). The uplift rates show a clear decrease from south to north (figure 11-1). Nearly constant uplift rates are implied for the interval between Motunui and Tergaporutu River mouth for the duration of the Last Glacial Cycle. Uplift rates then begin a rapid, almost linear decline north of the Tongaporutu River. The intersection between these two trend lines of figure 11-1 predicts that the beginning of uplift rate diminuition occurs c. 5km north of the Tongaporutu River.

TABLE 11-1: Summary of tectonic uplift rates for the late Quaternary in north Taranaki. These values are plotted in figure 11-1 below (except for the NT3 and Holocene estimates).

<table>
<thead>
<tr>
<th>Marine Terrace</th>
<th>Tectonic uplift rate (m.ka⁻¹)</th>
<th>Average over (ka B.P.)</th>
<th>Location</th>
<th>Reference chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT1</td>
<td>0.29</td>
<td>81</td>
<td>Turangi Rd.</td>
<td>2</td>
</tr>
<tr>
<td>NT2</td>
<td>0.27</td>
<td>120</td>
<td>Tongaporutu</td>
<td>5</td>
</tr>
<tr>
<td>NT2</td>
<td>0.20</td>
<td>120</td>
<td>Mohakatino (n.)</td>
<td>5</td>
</tr>
<tr>
<td>NT2</td>
<td>0.17</td>
<td>120</td>
<td>Mokau (s. side)</td>
<td>7</td>
</tr>
<tr>
<td>NT2</td>
<td>~0.15</td>
<td>120</td>
<td>Mokau (n. side)</td>
<td>7</td>
</tr>
<tr>
<td>NT3</td>
<td>slightly &lt;0.29?</td>
<td>210</td>
<td>Urenui</td>
<td>4</td>
</tr>
<tr>
<td>River (Holocene)</td>
<td>~0.26</td>
<td>7</td>
<td>Urenui</td>
<td>4</td>
</tr>
</tbody>
</table>

Some underlying regional scale tectonic mechanism must be responsible for this spatial distribution of uplift rates (for example- thrusting of Torlesse basement along the Taranaki Boundary Fault).
References cited


Pillans, B. (1990b). Late Quaternary marine terraces, south Taranaki-Wanagnui. NZGS misc. map 18 (Map and notes). Wellington, New Zealand. DSIR.


Vertical angle measurements with known baseline to determine height differences over long distances:

This method was found useful in determining the height difference between the theodolite and an object of interest. This method was used in the case of the Mokau rhyolitic deposit at Tainui, and for the NT2 WCP at Tongaporutu (south side). In the Mokau case, it was most useful to calculate the height from a distance of over 1km because of several factors:

1. A local football field allowed a long baseline to be set up on a relatively level surface, and it was easily accessible.

2. A nearby geodetic bench mark allowed the height difference between the theodolite setup and the point of interest to be determined with respect to MSL by accurately tying the setup into the benchmark using electronic distance measurement (EDM).

3. A relatively steep line of sight between the theodolite and the deposit.

In the Tongaporutu case, the point of interest was easily accessible but not close to any benchmark. A trig station Tongaporutu 'N' was visible with uninhibited line of sight from a locality nearby which allowed a moderate baseline to be setup. A relatively steep line of sight between the theodolite and the trig station also existed.

Accuracy may be improved by lengthening the baseline and/or taking many observations of vertical angle to reduce systematic errors (standard error reduces as \( n^{-1/2} \), where \( n \) is the number of observations). If the trig is too distant, or does not have a large enough height difference relative to the point of observation, an impractically large base-line is required and this method breaks down.
Measure:

\[ \Theta_1, \Theta_2, v, \text{ and } h. \]

Calculate:

\[ s = \sqrt{h^2 + v^2} \]

\[ \alpha = \tan^{-1}(v/h) \]

\[ A = s \sin(180° - \Theta_1 + \alpha) / \sin(\Theta_1 + \Theta_2) \]

\[ B = s \sin(\Theta_2 - \alpha) / \sin(\Theta_1 - \Theta_2) \]

From these calculate the height difference:

\[ Z = B \sin \Theta_1 = A \sin \Theta_2 \]

Definitions: \( \Theta_1 \) and \( \Theta_2 \) are the vertical angles from two theodolite setups (1 and 2) separated by a horizontal distance \( h \) and vertical distance \( v \), which constitute the baseline (between the optical centre of the theodolite).