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.
Cyclostratigraphy of late Oligocene – early Miocene strata:

An example from the Waiau Basin, western Southland, New Zealand.

Regan Dillon, 2006
Abstract
A section of marine strata in the Waicoe sub-basin (Waiau Basin), Southland, New Zealand records the Oligocene – Miocene (O-M) epoch boundary and the Waitakian to Otaian New Zealand Stage boundary. The sedimentary succession is cyclic, is 470m thick and ranges in age from 24Ma at the base to 18-19Ma at the top as indicated by biostratigraphy. The section comprises alternating lithologies of siliciclastic sand and mud beds in the lower 1/3 of the section and alternating lithologies of bioclastic sand and mud beds in the upper 2/3 of the measured section.

Facies analysis indicates a deep marine depositional environment that sourced sediment loads from the shelf margins. Shelf margins are interpreted to have been narrow margins which were vulnerable to destabilisation at the shelf break when sediment exceeded accommodation space on the shelf. Destabilisation of the shelf break is interpreted to have generated turbidite flows that were deposited in the deep marine depositional environment.

Relative sea level change is interpreted to be a significant control on accommodation space on the shelf. A low relative sea level is interpreted to account for extended periods of shelf exposure that enhanced turbidite generation. Spectral analysis of cyclically varying visual grain size estimates indicates coincidence of turbidite generation with changes in Earth’s orbit on 40-400kyr timescales. This suggests that glacio-eustasy was a significant influence on turbidite deposition across the O-M boundary in the Waiau Basin.

The 400kyr cycle was identified by Zachos et al. (2001) as coinciding with the Mi-1 event (first glaciation in the Miocene) and a period of low amplitude in the variability of obliquity and also suggested that Mi-1 may account for an Antarctic ice sheet at this time. Grain size derived glacio-eustasy across the O-M boundary in the Waiau Basin confirm significant sea level lowering co-incident with the Mi-1 oxygen isotope event.
Acknowledgements

Many people have helped in getting this thesis finished. Firstly I have to recognise Kirsty Tinto as being the key figure that helped me a great deal with this thesis in the field and in the lab. Thanks Tinto, for what appeared to be an endless amount of time you had available for me and thanks for the positive support you gave me.

I would also like to thank Gary Wilson, my supervisor, who gave me direction and encouragement when I needed it most and was a proponent of many new ideas this study contains. Thanks Gary, for putting up with my dodgy first drafts and casual approach to research. Special mention needs to be made to Hugh Morgans from GNS in Lower Hutt who gave me a great deal of assistance with the biostratigraphy used in this study. Thank you Hugh, for all the help you gave me, this project would have been nearly impossible on my own.

Acknowledgement needs to be given to my field assistants Tim Popham and Claudio Tapia, who braved the blazing Southland Sun in summer and the frozen temperatures in the depths of winter. Thanks fellas, for taking time out of your own schedules to help me drill rock and look at mud. I also need to thank Christian Ohneiser who gave me a lot of help with interpreting paleomagnetic data and spectral analysis data. I also need to thank Rob Dewdney for technical assistance with foraminifera.

I also need to acknowledge my office mates—Alissa, Jessie, Laura, and Carolyn who put up with my moaning and also offered me advice and support when I needed it, thanks. Thanks to my girlfriend Kat who motivated me to finish this thesis that might have taken an eternity otherwise.

A great deal of thanks goes out to my parents who have been a constant pillar of support with all the decisions I’ve made so far in my life. Thanks Mum and Dad for always being there for me and for not hesitating to offer help. Thank you so much and you’ll always be the best parents a kid could ask for.
# Table of Contents

Frontispiece ......................................................... ii  
Abstract ................................................................ iii  
Acknowledgements ....................................................... iv  
Table of contents ...................................................... v  
List of figures ............................................................ vi  

## Chapter 1 – Introduction

1.1 Cycliclity in the geologic record ................................. 1  
1.1.1 Orbital parameters as a mechanism of sea level change .. 1  
1.1.2 Orbital parameters of the late Oligocene and early Miocene .. 3  
1.1.3 Shackleton et al. (1999, 2000) late Oligocene to early Miocene age calibration. ........................................... 3  
1.1.4 Wilson et al. (2002) late Oligocene to early Miocene age calibration. ...................................................... 3  
1.2 The aim of this thesis .................................................. 5  
1.2.1 Requirements to fulfil the aim of this study ................. 5  
1.2.2 Objectives to achieve the requirements of this study ..... 6  
1.3 Study area location .................................................... 6  
1.4 Regional geological setting ......................................... 7  
1.4.1 Basement rocks – Fiordland complex ....................... 7  
1.4.2 Pioneering work in the Waiau and Te Anau basins ....... 9  
1.4.3 The Waiau Basin .................................................. 9  
1.5 Approach and layout of this thesis ............................... 10  
1.6 Appendix material layout .......................................... 11  

## Chapter 2 – Literature Review

Introduction ............................................................... 12  
2.1 Nature of the Oligocene – Miocene (O-M) boundary ....... 12  
2.1.1 Paleogene - Neogene geochronology ...................... 12  
2.1.2 Oligocene – Miocene Climate ............................... 14  
2.2 Similar studies ...................................................... 16  
2.2.1 Overseas studies ................................................ 16  
2.2.2 Turbidite successions .......................................... 17  
2.2.3 Similar Studies from New Zealand ......................... 20  
2.3 Waiau Basin Geology .............................................. 24  

## Chapter 3 – Lithostratigraphy

Introduction ............................................................... 27  
3.1 Lithostratigraphic nomenclature of Tertiary Sediments of the Waiau Basin ......... 27  
3.1.1 The Blackmount Formation .................................. 29  
3.1.2 Ligar Breccia Member ....................................... 30  
3.1.3 Sunnyside Member ........................................... 30  
3.1.4 Taylors Member .............................................. 30  
3.1.5 McIvor Formation ............................................ 31
Chapter 4 - Biostratigraphy

Introduction

4.1 The Waikakian – Otaian (Lw-Po) Stage boundary background

4.2 Biostratigraphy Methods

4.2.1 Field methods

4.2.2 Lab methods

4.2.3 Mounting foraminifera

4.3 Biostratigraphy – Lw – Po benthic and planktonic faunas

4.3.1 Biostratigraphic analysis of B.L Wood (1940's) and Carter and Norris (1970’s).

4.3.2 Biostratigraphic analysis of this study

4.3.3 Benthic foraminifera of the Lw - Po

4.3.4 Spiroloculina novozealandica (Po – R)

4.4 Planktonic foraminifera of the Lw – Po

4.4.1 Globigerina euapertura (Lwh – mid Lw)

4.4.2 Globigerina brazieri (upper Ld – Po?)
4.4.3 *Globoquadrina dehiscens* (Lw – Ti)  
4.4.4 *Globigerina woodi* woodi (Lw – WN)  
4.4.5 *Globigerina woodi connecta* (Lw – lower PI)  
4.4.6 *Cataspynx dissimilis* (Lw – Po? Pl?)  
4.5 Biostratigraphy of the Waitakian – Otaian boundary  
Summary.  

Chapter 5 – Facies analysis

Introduction 64
5.1 Facies and facies associations 64
Mudstone associations-
5.1.1 Massive mudstone facies (Mm) 64
5.1.2 Banded mud facies (Mb) 66
5.1.3 Mud with sand lenses facies (Ms) 66
Sandstone association-
5.2.1 Siliciclastic sandstone facies (Ss) 67
5.2.2 Bioclastic sandstone facies (Sb) 67
5.2.3 Shelly sand facies (Sl) 68
5.2.4 Sand with sedimentary structures, facies (Sst) 68
5.2.5 Sand with trace fossil, facies (Stf) 69
5.2.6 Sand with fluid escape structure facies (Sfe) 70
5.2.7 Limestone facies (Ls) 71
5.3 Facies Successions and Bouma Sequences 72
5.3.1 Turbidite Bouma divisions 72
5.3.2 Sediment distribution 73
5.3.3 Sedimentation 73
5.3.4 Sedimentary structures 74
5.4 Bouma divisions of this study 74
5.4.1 Taylors Member Bouma sequences 74
5.4.2 Diggers Hill Member Bouma sequences 75
5.5 Sedimentary motifs 78
5.5.1 Thin Section data – Siliciclastic motif (figure 5.32a-f) 79
5.5.2 Thin section data – Bioclastic motif (figure 5.33a-f) 79
5.5.3 Summary of thin section data – Siliciclastic and Bioclastic motifs. 80
5.6 Interpretations of the motif data 80
5.6.1 Deep marine turbidite deposition 87
5.6.2 Paleo-geography of the Waico sub-basin 88
5.6.3 Eocene to Miocene environment of deposition in the Waico sub-basin. 88
5.6.4 Summary of depositional history 92

Chapter 6 – Cyclicity

6.1 Aims and hypothesis of this chapter 95
6.2 Methods 95
6.3 Spectral analysis 99
6.3.1 Spliced data sets 101
6.3.2 Spectral peaks 101
6.4 Interpretations – identifying orbital parameters of cyclicity 101
6.4.1 Orbital parameters of cyclicity from section 1 (0-105.6m) 105
6.4.2 Orbital parameters of cyclicity from section 2 (105.6-211.2m) 105
6.4.3 Orbital parameters of cyclicity from Section 3 (211.2-316.8m) 105
6.4.4 Orbital parameters of cyclicity from Section 4 (316.8-422.4m) 105
6.4.5 Orbital parameters of cyclicity from Section A (52.8-158.4m) 106
6.4.6 Orbital parameters of cyclicity from Section B (158.4-264m) 106
6.4.7 Orbital parameters of cyclicity from Section C (264-316.9m) 106
6.4.8 Orbital parameters of cyclicity from 0-211.2m Section 106
6.4.9 Orbital parameters of cyclicity from 211.2-422.4m Section 108
6.5 Orbital parameters of cyclicity from 0-422.4m section 108
6.6 Potential sources of error identified in this exercise 108
6.7 Evaluation of orbital parameters of cyclicity 110
6.7.1 Evaluation of local climate events and tectonic parameters on turbidite sedimentation. 110

Chapter 7 – Discussion
7.1 Cyclostratigraphic record 113
7.1.1 Reliability of the cyclostratigraphic record 113
7.2 Linking orbital parameters of cyclicity to sedimentation Process. 114
7.3 Correlating the cyclostratigraphic record 114

Chapter 8 – Conclusions
8.1 Lithostratigraphic record 119
8.2 Lithostratigraphic nomenclature 119
8.3 Biostratigraphic record 120
8.3.1 Geographic placement of lithostratigraphic and biostratigraphic boundaries 122
8.4 Facies assessment 122
8.5 Cyclostratigraphy 124
8.6 Future work 125

Appendices
Appendix A1
Appendix A2
Appendix A3
Appendix A4, Stratigraphic Column lift-out 1 and 2
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.01</td>
<td>Primary orbital components of climate change.</td>
<td>2</td>
</tr>
<tr>
<td>1.02</td>
<td>Astronomically calibrated composite record across the O-M boundary.</td>
<td>4</td>
</tr>
<tr>
<td>1.03</td>
<td>The suggested duration of Mi-1.</td>
<td>5</td>
</tr>
<tr>
<td>1.04</td>
<td>Location of the Waiau Basin in New Zealand.</td>
<td>6</td>
</tr>
<tr>
<td>1.05</td>
<td>Four major structural blocks of Fiordland and western Southland.</td>
<td>8</td>
</tr>
<tr>
<td>1.06</td>
<td>Paleogeographic / paleotectonic sketch maps of southwestern New Zealand.</td>
<td>10</td>
</tr>
<tr>
<td>2.07</td>
<td>Age estimates of the O-M boundary.</td>
<td>13</td>
</tr>
<tr>
<td>2.08</td>
<td>Integrated chronology of the O-M boundary.</td>
<td>13</td>
</tr>
<tr>
<td>2.09</td>
<td>Complete Bouma sequence showing Bouma divisions A-E.</td>
<td>18</td>
</tr>
<tr>
<td>2.10</td>
<td>Pie chart showing the percentage of occurrence of complete to partial Bouma sequences.</td>
<td>20</td>
</tr>
<tr>
<td>2.11</td>
<td>The range and correlation of planktonic foraminifera across the Oligocene – Miocene boundary.</td>
<td>21</td>
</tr>
<tr>
<td>2.12</td>
<td>Paleogeography and paleobathymetry of the New Zealand region at 22 Ma.</td>
<td>23</td>
</tr>
<tr>
<td>2.13</td>
<td>Stratigraphic correlation chart for the Waiau and Te Anau basins.</td>
<td>25</td>
</tr>
<tr>
<td>3.14</td>
<td>The lithostratigraphic nomenclature of the Waiau Group.</td>
<td>28</td>
</tr>
<tr>
<td>3.15</td>
<td>Geologic map of the field area of this study.</td>
<td>29</td>
</tr>
<tr>
<td>3.16</td>
<td>Map of measured sections A-G.</td>
<td>34</td>
</tr>
<tr>
<td>3.17</td>
<td>Markers used to mark out measured sections A-G.</td>
<td>35</td>
</tr>
<tr>
<td>3.18</td>
<td>A, B, and C Section measurement methodology.</td>
<td>35</td>
</tr>
<tr>
<td>3.19</td>
<td>Images of Taylor Member beds.</td>
<td>45</td>
</tr>
<tr>
<td>3.20</td>
<td>Images of Diggers Hill and Glendearg member beds.</td>
<td>46</td>
</tr>
<tr>
<td>3.21</td>
<td>Thin section images from Taylors Member beds.</td>
<td>47, 48</td>
</tr>
<tr>
<td>3.22</td>
<td>Thin section images from Diggers Hill Member beds.</td>
<td>48, 50</td>
</tr>
<tr>
<td>3.23</td>
<td>Summary stratigraphic column of the measured section.</td>
<td>51</td>
</tr>
<tr>
<td>4.24</td>
<td>Geographic location of biostratigraphy sample sites of the measured section of this study, and of the studies of B.L Wood (1947), and Carter and Norris (1977a).</td>
<td>56</td>
</tr>
<tr>
<td>4.25</td>
<td>Biostratigraphic age model for the measured section.</td>
<td>63</td>
</tr>
<tr>
<td>4.26</td>
<td>Facies key.</td>
<td>65</td>
</tr>
<tr>
<td>5.27</td>
<td><em>Scolithos</em> images.</td>
<td>70</td>
</tr>
<tr>
<td>5.28</td>
<td>Sketch and images describing fluid escape structure formation.</td>
<td>72</td>
</tr>
<tr>
<td>5.29</td>
<td>Taylors Member Bouma sequences.</td>
<td>76</td>
</tr>
<tr>
<td>5.30</td>
<td>Diggers Hill Member Bouma sequences.</td>
<td>77</td>
</tr>
<tr>
<td>5.31</td>
<td>Pie chart of the occurrence of truncated Bouma sequences identified from the measured section.</td>
<td>78</td>
</tr>
</tbody>
</table>
Chapter 1 - Introduction

"An ice age here, million years of mountain building there. Geology is the study of pressure and time. That's all it takes really, pressure, and time. That, and a big god-damned poster." Morgan Freeman – The Shawshank Redemption (1994).

1.1 Cyclicity in the geologic record

Historically, sedimentologists have looked for explanations for cyclicity in the stratigraphic record. In many early investigations, pattern recognition was centred on the analysis of the observed sequences of lithologies (Weedon, 2003). The study of two alternating lithologies (sand and mud beds) which are described as rhythmic are the focus of this study.

The way in which lithostratigraphic successions were viewed changed when Vail et al. (1977, 1991) employed sequence stratigraphic methods that divided sedimentary sections into genetically related stratigraphic units. Vail et al. (1991) developed a classification scheme based partly on the duration of sea level cycles that was believed to be ultimately responsible for the genetically related stratigraphic units (Weedon, 2003). The classification scheme developed by Vail et al. (1991) identified 'first order' sequences that lasted more than 50 million years to 'sixth order' sequences formed between 10,000 to 30,000 year cycles (Weedon, 2003).

1.1.1 Orbital parameters as a mechanism of sea level change

Through the study of Cenozoic sedimentary rocks it has become apparent that the Earth’s climate system has undergone continuous change, drifting from extremes of expansive warmth with ice free poles, to extremes of cold with massive continental ice sheets and polar ice caps (Zachos et al., 2001b). Climate change is not unexpected, because the primary forces that drive long term climate, (Earth’s orbital geometry and plate tectonics) are constantly in motion [Zachos et al., 2001b]). Much of the higher frequency change in climate ($10^4$ to $10^5$ years) is thought to be generated by periodic oscillations in earth’s orbital parameters of eccentricity, obliquity, and precession. These parameters alter
climate by varying the distribution of solar energy on Earth, (Zachos et al., 2001b). The primary orbital components of climate change are presented in figure 1.01.

Figure 1.01 Primary orbital components of climate change (after Zachos et al., 2001b). Variations in the amplitude of eccentricity, obliquity, and precession are shown by the red coloured graphs in A, B, and C. Eccentricity is also seen as a 95kyr periodicity; and precession can be seen at 24, 22, and 19kyr periodicities but is commonly seen as a 23kyr cycle.

Eccentricity measures the departure of Earth’s orbit from that of a perfect circle (Muller and MacDonald, 2000). The three frequencies (400, 125, and 95kyr) that belong to eccentricity are not independent (Muller and MacDonald, 2000). Eccentricity is not constant and changes slowly with time which is related to the angular momentum of Earth in its orbit (Muller and MacDonald, 2000).

Obliquity is defined as the angle of the tilt of the Earth’s pole towards the Sun (Muller and MacDonald, 2000). The present obliquity of Earth is 23.5° but this value changes through time because the plane of the orbit of Earth is constantly changing (Muller and MacDonald, 2000). The variation in the plane of Earth’s orbit consists, primarily, of a 41kyr cycle that has smaller side peaks at 53 and 29kyr (Muller and MacDonald, 2000).

Precession is the slow change of the direction of the North Pole, as the Earth wobbles under the torque that the moon and the sun exert on its equatorial bulge (Muller and MacDonald, 2000). The precessional orbital parameter corresponds to 24, 22, and 19kyr frequencies. Precession affects climate because it results in the Earth’s closest approach of the sun, perihelion, occurring in different seasons (Muller and MacDonald, 2000). At present, the perihelion is close to the Winter Solstice in the Northern Hemisphere, and in the Milankovitch theory this is related to the fact that we are now in the middle of an interglacial period (Muller and MacDonald, 2000). According to the insolation theory of
Milankovitch (1941), the key driving force of the glacial cycles is the summer insolation at northern latitudes (Muller and MacDonald, 2000). Note that total insolation on the Earth depends only on eccentricity; obliquity and precession, which determine the distribution and not the total amount of insolation (Muller and MacDonald, 2000).

1.1.2 Orbital parameters of the late Oligocene and early Miocene

Historically, the identification, correlation and dating of the Oligocene-Miocene boundary have been recognised as difficult tasks. Recent studies by Shackleton et al. (1999, 2000) and Wilson et al. (2002) using analyses of different data sets attempted to refine the date of the Oligocene-Miocene boundary (23.8 ± 1 Ma; Cande and Kent, 1995).

1.1.3 Shackleton et al. (1999, 2000) late Oligocene to early Miocene age calibration

Shackleton et al. (1999, 2000) used oxygen and carbon isotopes as well as biostratigraphic analysis gathered from the Deep Sea Drilling Project (DSDP) -site 522, correlated with data from the Ocean Drilling Project (ODP) site 929 to calibrate astronomically the Oligocene-Miocene boundary at 22.9 ± 0.1 Ma.

The astronomical calibration used to date the O-M boundary by Shackleton et al. (2000) relies on the correlation of a minima in the amplitude of obliquity with an abrupt increase in δ¹⁸O (recognised as Mi-1 by Miller et al. 1991) at ODP Site 929. Shackleton et al. (2000) then used key biostratigraphic and carbon isotopic data in the vicinity of the O-M boundary to correlate ODP Site 929 and DSDP Site 522. Shackleton et al. (2000) used this correlation to retune Site 522’s magnetostratigraphy to the astronomical time scale of Site 929 and in turn, suggested that the age for the GPTS in the vicinity of the O-M boundary (subchrons C6n.1n-C7n.2n) is 0.9 Ma younger than reported by Cande and Kent (1995).

1.1.4 Wilson et al. (2002) late Oligocene to early Miocene age calibration

Wilson et al. (2002) did not question Shackleton et al’s (2000) correlation of ODP Site 929 to DSDP Site 522, but they have questioned the retuning of Site 522’s magnetostratigraphy to Site 929’s age model.
Wilson et al. (2002) argued that Shackleton et al. (1999, 2000) were three 406 k.y. eccentricity cycles or a 1.2 m.y. modulation of obliquity amplitude too young in their astronomical calibration, and have suggested that the O-M boundary may actually be 0.3 Ma older than the reported in Cande and Kent (1995) and 1.2 Ma older than Shackleton et al’s (2000) date. Wilson et al. (2002) used magnetic polarity analysis calibrated to the Geomagnetic Polarity Time Scale (GPTS), tephra- $^{40}$Ar/$^{39}$Ar dating, and microfossil assemblages to date the boundary at 24.0 ± 0.1Ma gathered from the Cape Roberts Project in Antarctica, (CRP-2A).

Figure 1.02 Astronomically calibrated composite record across the O-M boundary. The boundary is placed using $\delta^{18}$ O changes as well as calibrated orbital eccentricity and obliquity curves. The coincidence of an abrupt increase in $\delta^{18}$ O and an observed minima in the amplitude of obliquity at 22.9 (+/- 0.1) Ma is used as a calibration of the O-M boundary (after Zachos et al., 2001).
Figure 1.03 The suggested duration of Mi-1 expressed as $\delta^{18}O$ changes relative to orbital eccentricity and obliquity amplitudes across the O-M boundary (after Zachos et al., 2001).

1.2 The aim of this thesis

The role of this thesis is to test the role of orbital parameters of cyclicity in relationship to the Oligocene – Miocene boundary (O-M). The O-M boundary is linked to an intensification of the Antarctic Circumpolar Current (ACC) (Flower et al., 1997). Isolation and refrigeration of the Antarctic continent by the ACC fostered the development of significant glacial ice on East Antarctica (Flower et al., 1997). The climatic response associated with polar ice sheet variability in Antarctica near the O-M boundary is thought to have influenced global sea level. This study aims to investigate the role of orbital parameters of cyclicity as mechanisms of sea level change from a section of marine strata that encompasses the O-M boundary.

1.2.1 Requirements to fulfil the aim of this study

The first requirement is to identify an appropriate marine succession that encompasses the O-M boundary. The second requirement to fulfil the aim, requires evaluating the succession to identify orbital parameters of cyclicity and linking them to relative sea level change across the O-M boundary.
1.2.2 Objectives to achieve the requirements of this study
Evaluating cyclicity and sea level controls that are thought to have affected sedimentation of the measured section requires:

- A stratigraphic column of the measured section that acts as a framework for the rest of the data collected in the study.
- A biostratigraphy to build a chronology for the measured section.
- A facies analysis to assess lithostratigraphic and biostratigraphic descriptions of the measured section.
- An evaluation of the measured section on a cyclostratigraphic basis that can be compared with orbital parameters of cyclicity from other well known sections of strata.

1.3 Study area location

Figure 1.04 Location of the Waiau Basin in New Zealand. The location of the field area is modified from Carter and Norris (2005).
The strata studied here are exposed along a 600m outcrop on the banks of the Waiau River, 4km South of Sunnyside Station (NZMS: D44, 929726 – fig.1.04). This location is the only recorded outcrop of this sequence of strata in the Waiau Basin (Carter and Norris, 2005). The measured section forms part of the western limb of the McIvor Syncline.

1.4 Regional geological setting
Western Southland and Fiordland comprise a major block of Paleozoic to Cretaceous continental crust lying immediately to the east of the Australian – Pacific plate boundary and form the basement rock of the region (Turnbull and Uruski, 1993). Tertiary sediments are found in sedimentary basins within the Fiordland block in the Te Anau and Waiau basins (see fig. 1.04). The Te Anau and Waiau basins were created during the late Eocene along a precursor to the Alpine Fault plate boundary, when a zone of extension passed northwards through the southwestern South Island (Carter and Norris, 2005).

1.4.1 Basement rocks – Fiordland complex
The Fiordland complex in the west comprises plutonic and high grade metamorphic rocks of the Tuhua orogen and has an age ranging from Paleozoic to late Mesozoic (Carter et al. 1974, Mortimer et al. 1999, Mortimer 2004). The Fiordland complex is divided into three main structural blocks – western, southwestern, and eastern Fiordland blocks (Turnbull and Uruski, 1993, see figure 1.05). These three structural blocks are separated by fault zones and described briefly below.

The western block consists of a central zone comprising metasediments intruded by foliated granitoids and older granulitic gneiss and a western zone comprised of older granulitic gneiss with some areas overlain by central zones metasediments (Turnbull and Uruski, 1993). Work by Bradshaw (1990) and Mattinson (1986) identified these two zones as being one larger zone – the western block (Turnbull and Uruski, 1993). The western block is Cretaceous in age (Turnbull and Uruski, 1993). A wide range of metasedimentary and plutonic lithotypes are present in the western Fiordland block.
The southwestern block is characterised by low grade metasediments, possibly of Cambrian age with some recognisable sedimentary structures preserved and in the far southwest some Ordovician graptolites. The block is delineated by the Alpine Fault, Dusky Fault, and the southern extension of the Surprise Creek and Howitt Peaks fault zone (Turnbull and Uruski, 1993). In places, the metasediments are intruded by mid-Paleozoic, Jurassic, and Cretaceous granites, granodiorites and diorites, respectively (Turnbull and Uruski, 1993).

The eastern block is characterised by large granitoid intrusions with a layered ultramafic complex at Mount Luxmore being considered significant by Turnbull and Uruski (1993). The intrusives range from mid Paleozoic to Cretaceous in age with Cretaceous ages dominating as older Paleozoic rocks yield uplift ages rather than primary cooling ages, (Turnbull and Uruski, 1993). Eastern Fiordland block units were an important source for Cenozoic sediments particularly in Eocene – Oligocene sequences (Turnbull and Uruski, 1993).

The Takitimu Mountains on the far eastern margins of the Southland region form another structurally significant block that has implications for the formation of the Waiau Basin and comprise the Brook Street Volcanic Group (BS, fig.1.05).
1.4.2 Pioneering work in the Waiau and Te Anau basins

Early observations of Cenozoic strata from the Blackmount area were made by Hector (1863), during a trip from Riverton to Te Anau, and later by Hutton (1872). These observations were followed by a geological map covering strata cropping out in the region by Cox (1878). Later work by Park (1921) provided a more detailed account of the geology of the region and assigned strata of the Blackmount region to the ‘Miocene Oamaruian System’. The work by Park (1921) is important for establishing the fault controlled, graben nature of the Waiau – Te Anau basins and identified Tertiary sediments overlapping the edges of the graben during deposition.

Detailed geological mapping was later undertaken by Wood (1966) as part of the New Zealand Geological Survey 1:250,000 map series. Work in the Waiau and Te Anau basins continued with Turnbull, Carter and Norris (1970’s to present) being key contributors in developing comprehensive lithostratigraphic nomenclature(s) for the Waiau and Te Anau basins and the sub-basins they comprise. They also identified tectonic controls on the Waiau and Te Anau basin, and offshore basin, formation and speculated how this might have affected the accumulation of Tertiary sediments that now fill the basins. Recent work by Zinc and Norris (2004) evaluated the stacking of submarine fan facies. Some of the fan sequences of strata evaluated by Zinc and Norris (2004) comprise the measured section of this study.

1.4.3 The Waiau Basin

The margins of the Waiau Basin are defined by the Hauroko Fault in the west and the Moonlight Fault System in the east (Norris and Carter, 1980, 1982). The structurally significant blocks described above are interpreted to be major influences on basin architecture throughout the Cenozoic as the basin was filled with sediment (Turnbull and Uruski, 1993). The deepest parts of the basin were in the north and west, adjacent to the Hauroko and Blackmount faults and linked to the Blackmount sub-basin, (Turnbull and Uruski, 1993). The eastern margin of the Waiau Basin is inferred to have been the shallowest depositional area within the basin (Turnbull and Uruski, 1993). Sediments that fill the Waiau Basin range from basal Eocene coal measures to Oligocene - Miocene...
submarine fan deposits. Younger, Miocene to Pliocene deposits include massive mudstones/beds. Figure 1.06 below is a paleogeographic / paleotectonic sketch of the western Southland region during the early Oligocene and early Miocene and shows the tectonic rearrangement during the period.

![Paleogeographic / paleotectonic sketch maps of southwestern New Zealand during the early Oligocene (A), and the early Miocene (B) (after Norris and Turnbull, 1993).](image)

**Figure 1.06**

1.5 Approach and layout of this thesis

Chapter two presents summary accounts of work by authors who have investigated the nature of the Oligocene – Miocene boundary and include Berggren (1985, 1995), Cande and Kent (1992, 1995), Miller et al. (1985, 1987, and 1991), Naish et al. (2001), Zachos et al. (1997). Summary accounts of authors who have covered similar topics to this study using similar approaches are also presented and include Gallagher et al. (2000), Prothero et al. (1983), Bouma (1962 - 2004), Stromberg and Bluck (1998), Jenkins (1966), Morgans et al. (1999) and Graham et al. (2000). Chapter two also presents work by previous authors who have worked in the Waiau Basin that include Carter and Norris (1977a, b, 1978, 1980) and Turnbull and Uruski (1993), and Zink and Norris (2004).
Chapter three presents the lithostratigraphy of the section studied here including lithostratigraphic nomenclature, sedimentary descriptions and thin section analysis of the measured section.

Chapter four presents the biostratigraphy of the measured section and identifies the first appearance datums (FAD), and last appearance datums (LAD) of key planktonic and benthonic foraminifera. The FAD and LAD of key species yield an age model for the measured section.

Chapter five presents facies associations and facies successions developed from observations made in the lithostratigraphy and biostratigraphy chapters. These facies analyses are then used to develop sedimentary motifs for the measured section. Chapter five also presents a basin analysis that reviews facies analysis interpretations and places them in context within the Waiau Basin.

Chapter six evaluates cyclicity in the measured section and investigates the repetitive nature of strata using spectral analysis.

Chapter seven evaluates the interpretations made in the cyclicity and facies analysis chapters along with observations made in the lithostratigraphy and biostratigraphy chapters.

Chapter eight presents conclusions of the thesis.

1.6 Appendix material layout
The appendices of this study are laid out in the following order:

- A1, Paleomagnetic evaluation on the measured section of strata.
- A2, Biostratigraphic census data and Scanning electron micrograph (SEM) images.
- A3, Spectral analysis data.
- A4, Stratigraphic column lift out S1 and S2.
Chapter 2 - Literature Review

Introduction –

Literature reviewed here is presented as a summary using the key points and key figures of selected papers. These key points outline the geochronology, astrochronology, biostratigraphy and paleoclimatology of Oligocene to Miocene (O-M) marine strata. Literature reviewed is divided into three parts:

2.1) Nature of the Oligocene – Miocene boundary
2.2) Similar studies
2.3) Waiau Basin geology

2.1 Nature of the Oligocene – Miocene (O-M) boundary

This section is divided into two parts:

1. Geochronological literature
2. O-M climate literature

2.1.1 Paleogene - Neogene geochronology

Berggren et al.; 1985, 1995

Berggren et al. (1985) summarised a magnetobiochronology for the Cenozoic that incorporates available magnetobiostratigraphic correlations for both marine and non-marine rocks. Berggren et al. (1985) reviewed numerous biostratigraphic criteria that have been used to position the O-M boundary, and used the FAD of Globorotalia kugleri and the LAD of Dictyococcites bisectus as definitive criteria.

Berggren et al. (1995) presented a revised (magnetobiochronologic) Cenozoic timescale based on a re-assessment of 150, pre-Pliocene, high latitude planktonic foraminiferal datum events complemented by a (re)assessment of nearly 100 nanofossil datum events as well as $^{40}$Ar/$^{39}$Ar dates from the Cretaceous – Paleogene period and all epochs of the Paleogene and Neogene.
Berggren et al. (1995) identified that major advances had been made in radioisotopic dating (in particular the use of high precision $^{40}$Ar/$^{39}$Ar dating), magnetostratigraphy and biostratigraphy as well as the introduction of astrochronology. These major advances in dating rocks led to the re-evaluation of the Cenozoic timescale of Berggren et al. (1985) and others. Below in Table 2.07 all dates for the O-M boundary to 1995 are presented.

<table>
<thead>
<tr>
<th>Time (Ma)</th>
<th>Chrons</th>
<th>Polarity</th>
<th>Epoch</th>
<th>Age</th>
<th>Planktonic Foraminifera Zones</th>
<th>Calcareous Nannoplankton</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>C6Bn</td>
<td>M1b</td>
<td>Early</td>
<td>African</td>
<td>Gl. rugosi/Rg. delicosa</td>
<td>NN2</td>
</tr>
<tr>
<td>23</td>
<td>C6Cn</td>
<td>M1a</td>
<td>Early</td>
<td>African</td>
<td>Glo. pmorus PK2</td>
<td>NN1, Cn1, A &amp; B</td>
</tr>
<tr>
<td>25</td>
<td>C6Cr</td>
<td></td>
<td>Late</td>
<td>Chinese</td>
<td>Gl. cibicides PK2, PR2</td>
<td>AP16, GP11, C24</td>
</tr>
<tr>
<td>26</td>
<td>C8n</td>
<td></td>
<td>Late</td>
<td>Chinese</td>
<td>G. eschscholtzi PK2</td>
<td>NP25, C19, B</td>
</tr>
</tbody>
</table>

Table 2.07 Age estimates of the O-M boundary after Berggren et al. (1995).

Berggren et al. (1995) adopted the O-M boundary of 23.8 Ma from Cande and Kent (1992) who placed the boundary at the base of Chron C6Cn.2n rather than at the LAD of D. bisectus. Figure 2.08 below presents planktonic foraminifera zones with calcareous nannoplankton zones of different workers correlated to the magnetochronology of the late Oligocene to early Miocene.

Cande and Kent; 1992, 1995

Cande and Kent, (1992) developed a composite geomagnetic polarity sequence based on data from spreading ridges from the north, central and south Atlantic, eastern Pacific, Southern Ocean and the Indian Ocean. The timescale of Cande and Kent (1992) helped date major plate re-organisations using data gathered from these regions. Plate re-organisations around the O-M boundary (Anomaly C6C) are discussed with reference to
erratic spreading rates on all ridge systems except the north Pacific, the timing of which coincides with the break up of the Farallon Plate into the Nazca and Cocos plates, (Cande and Kent, 1992).

A revised calibration of the GPTS for the late Cretaceous and Cenozoic was presented by Cande and Kent in 1995. They reported that new radioisotopic dates and magnetic anomaly spacings had made it necessary for some changes to be made to boundary dates, these changes did not affect the Cande and Kent (1992) O-M boundary age of 23.8 Ma, at the base of Chron C5Cn.2n.

### 2.1.2 Oligocene – Miocene Climate

This section reviews the global climate change across the O-M boundary. Works by Miller et al. (1985, 1987, and 1991), Zachos et al. (1997, 2001), and Naish et al. (2001) are reviewed here.


Miller et al. (1985, 1987) presented an isotope stratigraphy for the late Oligocene – early Miocene using glaciomarine sediments that indicate the presence of continental ice sheets on Antarctica in the early Oligocene. The Oligocene – modern "ice house world" (Fischer, 1984) saw the waxing and waning of these continental ice sheets resulting in glacioeustatic sea level changes of up to 100m (Miller et al., 1987). Miller et al. (1991) used Pleistocene $\delta^{18}$O records to estimate the timing and magnitude of glacioeustatic sea level changes for the Oligocene – Miocene period as well as spliced isotope records from deep sea cores gathered from different locations.

The isotope stratigraphy of Miller et al. (1991) and Wright and Miller (1990) identified eight zones for the Oligocene and Miocene, with the base of each zone defined by a maximum $\delta^{18}$O value and given a corresponding sequenced name, for example the first zone in the Miocene is Mi1 (Miocene Isotope zone 1). The Mi1 event begins in the uppermost Oligocene and peaks in the lowermost Miocene, and, using a Pleistocene $\delta^{18}$O/sea level calibration, Miller et al. (1991) suggested that a 90m glacioeustatic sea level
lowering occurred between 24.5Ma and 23.5Ma. The Mi1 event is interpreted as a 1-m.y. cycle containing a number of smaller “Milankovitch bandwidth” cycles (20kyr - 400kyr, Miller et al., 1991).

**Zachos et al.; 1997**

Zachos et al. (1997) identified orbitally paced climate oscillations across the O-M boundary. This work reviewed the climate indicators (oxygen isotopes etc.) during the Oligocene to the early Miocene with their data and suggested that there was high latitude cooling and continental glaciation, in what was thought to be ice free conditions. Zachos et al. (1997) suggested that there is a strong response in the oxygen isotope record at the 40kyr, obliquity level. The effects of obliquity on insolation is strongest at high latitudes, this suggested that obliquity oscillations controlled high latitude climate change during the late Oligocene – early Miocene (Berger and Loutre, 1991). This finding, as also seen in Plio-Pleistocene records, suggested that obliquity forcing had been a feature of the global climate signal for the past 34Myr.

**Naish et al.; 2001**

Naish et al. (2001) present sediment data from the Ross Sea region that exhibit well dated cyclic variations, which link the extent of the East Antarctic ice sheet directly to orbital cycles during the late Oligocene – early Miocene.

The Cape Roberts Project (CRP), drilled 1500m of offshore strata from the western margin of Victoria Land Basin that contain a laterally extensive, seaward thickening wedge with 46 unconformity bounded Oligocene – Miocene glaciomarine cycles, (Fielding et al., 2000, Cape Roberts Science Team, 1999, 2000). The unconformity bound cycles are viewed as cycles of expansion and contraction of the Eastern Antarctic ice sheet, Naish et al. (2001). Naish et al. (2001) concluded that the cycles recorded by glaciomarine sequences reflect a style of behaviour exhibited by the less stable Northern hemisphere ice sheets of the past 2.5Myr.
2.2 Similar studies

This section of the literature review is broken into three parts:

1) Overseas studies
2) Turbidite successions
3) Studies from New Zealand

2.2.1 Overseas studies

Two studies from overseas are reviewed here, one from the Otway Basin in Australia and the other from the White River Group (WRG), in the U.S.

Gallagher et al. (2000) presented work on the Otway Basin in southeast Australia that contains a thick sequence of late Eocene – Miocene marine neritic siliciclastic and carbonate sediments. These sediments recorded the late Paleogene – mid Neogene history of events surrounding the progressive opening of the Southern Ocean (Gallagher et al., 2000). Prothero et al. (1983) presented a magnetostratigraphy of the White River Group, and review its implications for Oligocene geochronology.

The Otway Basin

The Paleogene – Neogene neritic strata from the Otway Basin in South Australia preserves signals of glaciation in the east Antarctic as initiated by the evolution of the Antarctic Circumpolar Current in the Southern Ocean (Gallager et al., 2000). The evolution of the Antarctic Circumpolar Current and initial glaciation in east Antarctica is indicated by facies changes shown by planktonic and benthic foraminiferal assemblages during the late Oligocene – early Miocene (Gallagher et al., 2000).

The White River Group Magnetostratigraphy

Prothero, et al. (1983) used radiometrically dated magnetostratigraphy in an attempt to calibrate the changes in land faunas during the Oligocene. Major oceanic circulation system re-arrangements identified by Berggren and Hollister (1974, 1977), and Kennett (1977, 1980) as well as climate re-arrangements identified by Van Andel (1975) and Van Andel et al. (1977) are described as lacking a direct correlation with terrestrial events by Prothero et al. (1983).
Prothero et al. (1983) claimed that a correlation between terrestrial and marine sequences for this task is only achievable using magnetostratigraphy. Prothero’s paleomagnetic dating of the WRG calibrates the Oligocene North American mammal ages for the first time to the geomagnetic polarity timescale. The major oceanic circulation changes documented by Prothero are similar changes that this study aims to document.

2.2.2 Turbidite successions

This study evaluates a succession of turbidites that span the Oligocene – Miocene boundary. This section presents work by Bouma (1962 and 2004), and Stromberg and Bluck (1998) on marine turbidite sequences.

**Sedimentology of Some Flysch Deposits; Bouma (1962)**

Bouma (1962) described the depositional motif of turbidity currents using a comprehensive system of graphic logs recording all sediment properties of sequences of rock largely from the French Maritime Alps (FMA). The study detailed current directions, lithology, sedimentary structures, faunal content of a turbidite sequence in the FMA and proposed a genesis for the turbidites (Bouma, 1962).

Early workers working in the Peira-Cava region interpreted the alternating sand and mud units to result from variations in depth of deposition, with sand beds deposited in shallow water and mud beds deposited in deeper water (Bouma, 1962). However, the repetitive nature of the sand and mud beds made this interpretation untenable.

Kuenen (1953a, b) described the main structures and successions in turbidites. Bouma (1962) confirmed the observations of Kuenen, with a restricted number of sedimentary structures observed in the Peira-Cava turbidites, in a fixed characteristic succession, which has become known as the Bouma sequence (see figure 2.09 below).
Terminology of the complete Bouma sequence (Bouma, 1962):

a) *Graded interval*: The bottom part of the layer consists of sand–gravel textures, showing a more distinct graded bedding. If the material is well sorted then bedding will not be apparent.

b) *Lower interval of parallel lamination*: Coarse parallel lamination of sand and clay. Grading is reflected by sorting in lamellae.

c) *Interval of current ripple lamination*: This layer consists of current ripples typically less than 5cm in height, and no longer than 20cm. Ripples are typically convolute. Grading of sediment textures is still apparent in this layer.

d) *Upper interval of parallel lamination*: Indistinct parallel laminations occur here. Textures forming the laminations are typically fine sands to silty pelites.

e) *Pelitic interval*: The upper interval of the layer shows no visible sedimentary structures. Foraminifera may be found in this interval.

**Bouma; 2004**

The key controls of turbidite systems are outlined here, following Bouma’s (2004) discussion of the various interactive natural controls on turbidite systems and their
terminology as developed in other studies. Interactive natural controls outlined by Stow (1985) include:

A) Sediment type and supply
B) Tectonic setting and activity
C) Sea level variations

In addition to Stow’s (1985) controls Bouma (2004) included climate, sedimentary processes, and basin characteristics. Tectonic setting and sea level variation are two different natural controls on turbidite successions that are relevant to this study.

Tectonic controls are the major influence on the growth of sediment yielding mountains as well as controlling the development of a sedimentary basin where sediment can be accommodated. Climate changes regulate the amount of water available for sub-aerial erosion and transport from the source area to the sedimentary basin where turbidites form. Variation in sea level can control the size of sub-aerial land exposure, and thus influences the source area and transport mechanism used in a turbidite system.

Stromberg and Bluck; 1998

This paper describes the Aljibe flysch, which is the largest tectono-sedimentary unit in the Gibraltar Arc. This unit provides a complete record across the O-M boundary. Turbidite facies, fluid escape structures, and mechanisms of emplacement of the Aljibe Flysch are reported here.

The Aljibe Flysch can be subdivided into two sub units, the Benizia Flysch (BF, late Oligocene), and the Aljibe Arenites (AA, early Miocene), which have distinctly different depositional histories. The BF is characterised by laterally continuous siltstones and mudstones which contain complete and partial Bouma sequences. The AA differs from the BF as it comprises thick bedded, quartz rich arenites which are dominated by fluid escape structures. Given the time range (O-M) that the Aljibe Flysch covers and the two distinctive units that comprise it and their different depositional histories makes this study a possible barometer for investigations into turbidites relevant to this study.
Figure 2.10 Pie chart showing the percentage of occurrence of complete to partial Bouma sequences in the Benzia Flysch (from Stromberg and Bluck, 1998).

A lack of outcrop to outcrop correlation in this paper made it difficult to interpret the depositional histories across the basin of the BF and AA units. However, it is apparent that the mode of emplacement between the two units is different. Stromberg and Bluck (1998) also interpreted the boundary of the BF – AA units as a stratigraphic boundary possibly representing a sequence boundary or, alternatively a major tectonic reorganisation of the basin.

2.2.3 Similar Studies from New Zealand

Jenkins (1966) presents a foraminiferal zonal scheme based on the ranges of 103 species and subspecies of planktonic foraminifera divided into 14 zones, defined and described in relation to New Zealand Stages of the late Cretaceous to the early Miocene. The identification and zoning of *Globigerina euapertura* and *Globoquadrina dehiscens* cover the late Oligocene – early Miocene and their zones are displayed in fig. 2.11.

The ancestry of *Gq. dehiscens* is presented by Scott (1978). Finlay (1947) and McGowran (1968) investigated the morphology and ancestry of *Gq. dehiscens* as well as its stratigraphic distribution. A selection of scanning electron micrograph pictures of *Globoquadrina dehiscens* from the Otekaike Limestone, type locality for the Waitakian Stage is presented by Hornibrook (1978), as well as a brief review of early workers on the Waitakian Stage.
Other planktonic foraminifera that have zones (defined by Jenkins, 1966) in the early Miocene (mid-late Waitakian) are *Globigerina woodi woodi* and *Globigerina woodi connecta*. Later work by Morgans et al. (1999) and Graham et al. (2000) review the zonal scheme of Jenkins (1966), redefining some zones, particularly around the O-M boundary.

<table>
<thead>
<tr>
<th>New Zealand Series</th>
<th>Stage</th>
<th>Planktonic Foraminiferal Zones</th>
<th>Correlation with the International Timescale</th>
<th>Planktonic Foraminifera Age Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landon</td>
<td>Waitakian</td>
<td>Lower <em>Globigerina woodi connecta</em></td>
<td>Lower Miocene</td>
<td>Lower Oligocene</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Globigerina woodi woodi</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Glabraquadrina dehiscens</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duntroonian</td>
<td></td>
<td><em>Globigerina euapertura</em></td>
<td>Upper Oligocene</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.11 The range and correlation of planktonic foraminifera across the Oligocene – Miocene boundary, A: *Gl. eupertura*, B: *Gl. woodi woodi*, C: *Gl. woodi connecta*, and D: *Gq. Dehiscens*. (After Jenkins, 1966). The Duntroonian – Waitakian Stage boundary is no longer considered to be the equivalent of the O-M boundary (Morgans et al., 1999).

**Graham et al.; 2000**

Graham et al. (2000) undertook a study to investigate the strontium isotope stratigraphy of a late Oligocene – early Miocene section of the Otekaike Limestone (south Canterbury, New Zealand). The Otekaike Limestone is the type section for the local Waitakian Stage boundary, and contains the Duntroonian – Waitakian Stage boundary, Graham et al. (2000) found correlating the New Zealand stages to international divisions difficult as there was a lack of reliable, biostratigraphically constrained radiometric dates from previous studies in New Zealand.

Analysis of strontium isotopes from the Otekaike Limestone section by Graham et al. (2000) assumed that:

1) At any point in time, the $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio of sea water is homogenous throughout the world’s oceans (Elderfield, 1986; Faure 1986) because the oceanic residence time of Sr is much longer than the mixing time of the oceans.
2) Over geologic time, $^{87}\text{Sr} / ^{86}\text{Sr}$ varies because of changes in the relative fluxes of Sr to the oceans from different sources like large river deltas.

3) Strontium is removed from sea water by co-precipitation of biogenic carbonate.

With these assumptions in mind, it was found that the $^{87}\text{Sr} / ^{86}\text{Sr}$ analyses of bulk samples, macrofossils and foraminifera showed a coherent pattern of slightly increasing Sr ratios with stratigraphic height. Results from the Graham et al. (2000) study indicated that the Duntroonian-Waitakian Stage boundary is not coincidental with the Oligocene–Miocene boundary, and that the Duntroonian – Waitakian boundary is defined by the FAD of *Globoquadrina dehiscens* and the LAD of *Vaginulopsis interruptus*.

**Morgans et al.; 1999**

Morgans et al. (1999) presented an integrated stratigraphy of the Waitakian – Otaian (Lw-Po) Stage (21.7 Ma) boundary from the Po type section at Bluecliffs in South Canterbury using lithostratigraphy, depositional setting, biostratigraphy, correlation and geochronology. Morgans et al. (1999) examined the history of the positioning of the Lw-Po boundary and the bioevent proxies used to achieve this. Benthic foraminiferal events define the Waitakian – Otaian stage boundary, specifically the LO (lowest occurrence) of *Ehrenbergina marwicki*. The poor resolution of benthic foraminiferal events led Morgans et al. (1999) to search and identify suitable bioevents as time proxies to better date the Lw-Po boundary.

Biostratigraphic analysis from Morgans et al. (1999) evaluated the nature, distribution, and utility of selected bioevents in the vicinity of the Lw-Po Stage boundary. These selected bioevents use the FADs of benthic foraminifera *E. marwicki* (FAD – 21.7Ma) and *Spiroloculina novozealandica* (FAD – 21.3Ma), as well as planktonic foraminifera the LADs of *Globigerina brazieri*, *Globigerina euapertura*, and the *Paragloborotalia* spp. The LAD of planktonic foraminifera *Gl. euapertura* and *Gl. brazieri* occur below the Lw-Po boundary, whereas the FAD of *E. marwicki* marks the base of the Po and therefore the Stage boundary.
The LADs of the planktonic foraminifers *Gl. brazieri* and *Gl. euapertura* from the Bluecliffs section do not match those of Berggren et al. (1995). Berggren et al. (1995) placed the LAD of *Gl. euapertura* in Chron C6Cn.2n (23.68-23.80 Ma), at the O-M boundary and before the FAD of *Globoquadrina dehiscens* (Chron C6Br, 23.07-23.35 Ma). Morgans et al. (1999) record of the LAD (22Ma) of *Gl. euapertura* is well above the FAD of *Gq. dehiscens* (25.2Ma), therefore the two bioevents overlap and this is where their record conflicts with the record of Berggren et al. (1995). The discrepancy may be due to the earlier extinction of *Gl. euapertura* in southern high latitudes than at Bluecliffs, or conversely there was an earlier appearance of *Gq. dehiscens* in New Zealand (Morgans et al., 1999).

Independent chronology was obtained for benthic and planktonic foraminiferal shells, from the Bluecliffs section using $^{87}\text{Sr} / ^{86}\text{Sr}$ analysis yielding an age for the Lw-Po boundary at 21.7 Ma.
2.3 Waiau Basin Geology

Work by Norris and Carter (1977a, 1978, and 1980), Norris and Turnbull (1993), and Zink and Norris (2004) is reviewed and synthesised as they each deal with different aspects of Waiau Basin geology.

In south-western New Zealand, a number of small, fault controlled marine basins were initiated in the late Eocene, with thick sedimentary fills accumulating in the surrounding onshore Te Anau and Waiau basins, as well as the offshore Solander and Balleny basins (Norris and Carter, 1980). Norris and Carter (1980) discussed the fault bounded blocks and their role in localising sedimentation adjacent to the Alpine Fault in southern New Zealand. They suggested that the development of these basins was related to the behaviour of the Fiordland microplate, a rigid block of continental crust located between the Moonlight, Hollyford, and Alpine fault systems.

Norris and Turnbull (1993) argued that the development of Cenozoic basins of southwest New Zealand reflected the propagation of the Australian/Pacific plate boundary through the New Zealand region. From late Eocene to early Oligocene times, tectonic activity on the Moonlight and Hollyford fault systems in southwest New Zealand gave rise to rapid subsidence in the Waiau and Te Anau basins. Submarine fans infilled these rapidly subsiding basins with subsidence outpacing sedimentation (Norris and Turnbull, 1993). During early Miocene time, continuing tectonic activity caused further subsidence of the region (Norris and Turnbull, 1993).

Zink and Norris; 2004

The Waiau and Te Anau basins are examples of two small sedimentary basins exhibiting stacked patterns of submarine fan facies in restricted basins. The Eocene to Miocene saw the reorganisation of the Australia – Pacific plate boundary, where the newly formed Te Anau and Waiau basins evolved in close proximity. The original shape of the Waiau Basin was destroyed during basin eversion but can be described as a half-graben, with sedimentary successions thickening and coarsening toward the west – northwest. The sediment fill of the Waiau Basin is of great thickness (single bodies in a succession
>1000m), showing rapid lateral and vertical facies changes with a wide range of depositional environments represented. Depositional environments range from proximal rock fall debris flow deposits – brecciated through to thick sand dominated fluvial and submarine fan deposits and hemi-pelagic mudstones.

The Blackmount Formation from the Waiau Basin is Oligocene – Miocene in age and exhibits rapid lateral and vertical facies changes that are common to fan successions within the basin. The basal succession comprises a westerly derived mass flow breccia of poorly sorted diorite and gneiss clasts derived from the basement Fiordland complex with a variable thickness that ranges from 5-100m. Overlying the breccia are thick packets (5-15m) of amalgamated sandstone beds exhibiting Bouma A and Bouma B divisions. These thick sand packets are interpreted as sand feeder channels in a proximal fan depositional facies. More distal facies of the Blackmount Formation are mudstone dominated turbidite beds with basal sand layers overlain by darker clastic rich mud grading into lighter hemipelagic layers of mud.
The McIvor Formation is interpreted to be of Miocene age sourced from a limestone shelf area rich in bryozoan biosparites accompanied by variable amounts of terrigenous sand. Carter and Norris (1977a). Distal parts of the McIvor Formation are well exposed with sections often comprising well developed flysch successions. Well preserved flute casts indicate an east to west flow for the turbidity currents comprising the Formation. At the contact, westerly derived Blackmount Formation turbidites interfinger with easterly derived McIvor Formation turbidites indicating that these formations may have been laid down in the centre of the basin.
Chapter 3 - Lithostratigraphy

Introduction

The section measured in this study is 465m thick, comprises 802 alternating sand and mud beds, and is capped by a 9m thick limestone. A high resolution stratigraphic log (centimetre scale) records all sedimentary features, sample locations, and the lithostratigraphic boundaries of the measured section (appendix S1 and S2). An obscured portion of the measured section (282-324m) is covered by river levee deposits.

The measured section shows little deformation, with only small fault traces (and jointing) with minor offset recorded. Beds dip between 35-72°, and strike at 20-34°.

The lower portion (0-120m, +/-20m gradational variability) of the measured section comprises sand beds that are predominantly siliciclastic. Siliciclastic beds grade (over 40m) up into sand beds comprised of predominantly bioclastic carbonate material. In this study, the capping limestone at the top of the measured section is the final, albeit abrupt, lithologic change recorded. Limestone beds of variable thickness overlain by calcareous mud beds dominate the material above the top of the measured section and are not measured or described in this study. A summary stratigraphic column is presented in figure 3.23 at the end of this chapter.

3.1 Lithostratigraphic nomenclature of Tertiary Sediments of the Waiau Basin

Waiau Group rocks were defined by Turnbull et al. (1989, 1993) as re-deposited shallow to deep marine sediments overlying the Nightcaps and Annick groups. The Group is over 8km thick in places and contains rocks ranging in age from late Eocene - Pliocene (Turnbull et al., 1989). Turnbull et al. (1989) nominated three sections in the Waiau Basin as reference sections for the Group, although the Waiau Group is also mapped in the Te Anau Basin. The section of strata exposed in the Waiau River, between the Monowai road bridge (D44/927769), and the axis of the McIvor Syncline (near D44/948703), is the type locality for the lower parts of the Group. The upper part of the
Waiau Group is best exposed further South, at Clifden and in the Lillburn Valley (Carter and Norris, 2005).

The lithologies of the Waiau Group are varied, predominantly mudstone but sections are replaced by flysch graded sandstones and muds (Turnbull et al., 1989). Other lithologies present in the Waiau Group are shallow marine (shelf) limestones and sandstones (Turnbull et al., 1989).

<table>
<thead>
<tr>
<th>Ma</th>
<th>Age</th>
<th>Biozones</th>
<th>Formations</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>Pliocene</td>
<td>Tongaporutuan (Tt) to Nukumaruan (Wn)</td>
<td>Prospect</td>
<td>Little Creek</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tanglely</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waisuan (Sw)</td>
<td>Duncraigen</td>
<td>Hydro</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Duncalf</td>
</tr>
<tr>
<td>Miocene</td>
<td></td>
<td>Lillburnian (Sl)</td>
<td>Monowai</td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clifdenian (Sc)</td>
<td>Units 1-8 (Monowai River only)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Altonian (Pl)</td>
<td>Borland</td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Glendearg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ouian (Po)</td>
<td>McIvor</td>
<td>Diggers Hill</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waitakian (Lw)</td>
<td>Waicoe</td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td>24</td>
<td>Miocene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blackmount</td>
<td></td>
<td>Taylors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Duntroonian (Ld)</td>
<td></td>
<td>Sunnyside</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whaingaroan (Lwh)</td>
<td></td>
<td>Ligar</td>
</tr>
<tr>
<td>37</td>
<td>Oligocene</td>
<td></td>
<td>Blackmount</td>
<td>Taylors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nightcaps</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whaingaroan (Lwh)</td>
<td></td>
<td>Jericho</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Runangan (Ar)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.14 The lithostratigraphic nomenclature of the Waiau Group (after Carter and Norris, 2005).

Formations and members in bold and underlined in table 3.14 are the lithostratigraphic units identified and recorded in this study. Sediments recorded in this study identify the Taylors and Diggers Hill members of the Blackmount and McIvor formations (respectively). It is also useful to identify and discuss other lithostratigraphic members that also comprise the Blackmount and McIvor formations that lie above and below...
the Taylors and Diggers Hill members as they have some bearing on facies analysis discussed in Chapter 5.

Field area of this study

![Geologic map of the field area of this study. The field area on the western limb of the McIvor syncline, Waiau Basin, western Southland New Zealand (modified from Carter and Norris, 2005).](image)

Figure 3.15 Geologic map of the field area of this study. The field area on the western limb of the McIvor syncline, Waiau Basin, western Southland New Zealand (modified from Carter and Norris, 2005).

3.1.1 The Blackmount Formation

The Blackmount Formation is a grouped sequence of mass transported breccias, conglomerates, thick bedded sandstones, and alternating beds of sand and mud. The Formation lies on the western side of the Waiau Basin, against the Blackmount Fault, and is a 2500m thick succession of early – middle Oligocene with type sections found on the banks of the Waiau River between the Blackmount Fault intersection with the Waiau River to the Sunnyside Station (D44 926769 to 929723, Carter and Norris, 2005). Within the Waiau Basin, the Blackmount Formation contains three members (oldest to
youngest); the Ligar Breccia Member, the Sunnyside Member, and the Taylors Member. Work by Turnbull et al. (1989) recorded the Taylors Member as being the Waicoe Formation, this study recognises the Taylors Member as belonging to the Blackmount Formation.

3.1.2 Ligar Breccia Member
The Ligar Breccia Member forms the base of the Blackmount Formation, and lies unconformably on basement rocks and is found at the base of the Waiau River section. The Ligar Breccia is massive, structureless, coarse grained, with some clasts being of meter dimensions, and supported by a coarse sandy gravel matrix, crudely graded, and fines upward into a muddier member containing rare macrofossils (Turnbull and Uruski, 1993).

3.1.3 Sunnyside Member
The Sunnyside Member conformably overlies the Ligar Breccia, and is broadly described as a gritty, angular, quartzose sandstone. Bedding in the Sunnyside Member is confined to packets (5-30cm thick) of graded beds with a cumulative thickness of 5-10m (Carter and Norris, 2005). Occasional beds of the Sunnyside Member contain poorly graded conglomeratic layers comprising subangular quartz clasts which eventually grade into beds comprising more well sorted and rounded, imbricated clasts (Carter and Norris, 2005).

3.1.4 Taylors Member
The Taylors Member is restricted to the Waicoe sub-basin and the lower contact of the Member gradationally overlies the Sunnyside Member, (Carter and Norris, 2005). The contact is gradational over a long distance (tens of metres) with the contact being arbitrary, as Sunnyside like graded beds occur within the lower Taylors Member (Carter and Norris, 2005). This study covers the middle and upper sections of the Taylors Member. The Taylors Member comprises alternating grey - green sand and mud beds typically no thicker than 2m. Sand and mud beds all fine upwards with sand beds having sharp lower contacts with underlying mud beds. Sand beds are coarse at their base with
3.1.5 McIvor Formation

Within the Waicoe Sub-basin the McIvor Formation is divided into two members, the Diggers Hill and Glendearg members. The top of the McIvor Formation is not exposed within the type section with only the Glendearg Member sediments mapped east of the Blackmount Fault (Turnbull and Allibone, 2003). The McIvor Formation is described as comprising 350m of meter to decimetre carbonate based sediments (Turnbull and Uruski, 1993). To the south, in the Hindley and Lill burns, the Waicoe Formation is mapped as conformably overlying the McIvor Formation (Carter and Norris, 2005). The base McIvor Formation gradationally overlies the Blackmount Formation. The top of the McIvor Formation is faulted against the overlying Waicoe Formation in the Waiau River, downstream from the measured section of this study.

3.1.6 Diggers Hill Member

The Diggers Hill Member crops out at the base of Diggers Hill, which forms a 320m thick section of strata recorded and described in this study. It is described by Turnbull and Allibone (2003) as a decimetre to metre bedded bioclastic limestone, with interbedded mudstone. Diggers Hill Member beds exhibit a number of sedimentary features that include, scoured bases, cm scale graded bedding, convolute structures, laminar layering, mud lenses, concretions, burrowing, and rare trace fossils. Fluid escape structures are also a common feature of Diggers Hill Member beds. The section studied here represents the only known outcrop of the Diggers Hill Member and the McIvor Formation.

3.1.7 Glendearg Member

The Glendearg Member comprises rhythmically spaced alternating sand and mud beds (30-40cm thick). Sand beds grade up, are well cemented, have multiple bedding features
and are composed of mainly shell fragments. Bedding features include, laminar layering, weakly defined convolute structures, and sorting. Mud layers contain abundant foraminifera and are weakly cemented. The Glendearg Member conformably and gradationally overlies the Diggers Hill Member. The base of the Glendearg Member is interpreted to occur at the top of the measured section of this study (NZMS: 2093280, 5472200).

3.2 Lithostratigraphy methods
Sections were logged and described using the nomenclature of Andrews (1982) with a slight difference; rocks are firstly described as un-weathered with post depositional descriptions like weathering alteration and jointing as secondary descriptive features. Well cemented sand beds often contained easily recognisable sedimentary features, unlike mud beds that are described as massive and show little variability from bed to bed. In this study, lighter coloured mud layers are interpreted as being hemi-pelagic.

3.2.1 Measured section rock descriptions
Sections of rock were described on a bed by bed basis using the following criteria:

A) Rock colour – Sand beds are commonly green/blue grey in the lower (older), to yellow/brown grey in the upper (younger). Mud beds are commonly described as dark to light grey in colour.

B) Texture – Sand beds are typically coarse at the base sometimes containing small clasts (>2mm in diameter, typically not larger than 3mm) supported by a medium - coarse grained sand. Sand beds fine up and are better sorted and medium grained at their tops.

C) Sorting and cementation – Sorting of sediments tends to be reflected by bedding features, for example convolute layers reflect poorly sorted layers, whereas well defined laminar layers reflect better sorted sediments. Sorting is more easily recognised in sand beds than mud beds. Some mud beds exhibit lighter layers that are interpreted to be hemi-pelagic. Cementation of sand beds is variable
throughout the section, however un-weathered mud layers are typically well cemented.

D) Lower contact – Sand beds have sharp lower contacts with some variability regarding the extent of scouring. Mud beds have gradational lower contacts that are variable in thickness.

E) Fossil content – The presence of fossils described the shape/size of the fossil material, fossil state (preservation – well/poorly preserved), orientation and the supporting sediment texture. Fossils identifiable in hand specimen commonly include reworked bivalves that are 2-4mm in size, angular and supported by a medium grained sand. Fossil layers are commonly found at the base of sand beds.

F) Sedimentary structures – Mud beds lack sedimentary features, and are therefore described as massive. Sand beds contained easily recognisable sedimentary structures including fluid escape structures, rip up clasts, and shell layers.

G) Weathering – post-depositional alteration of sediments due to weathering required describing the colour and state of weathered surfaces, for example iron oxide staining is common in mud layers and is reflected by conchoidal cracks, which is another weathering feature common in mud layers.

H) Dewatering features – Fluid escape structures indicated by offset bedding.

I) Tectonic features – Faulted surfaces are described by amount of offset where important and direction of offset.

3.2.2 Section measurement
The base of the measured section of this study is located at: NZMS: 2092850, 5472660. Well exposed parts of the section were logged first. Less accessible and less well exposed parts of the section were logged last. These logged sections were marked out using reference markers (see fig.3.16 and 3.17).

3.2.3 Reference / marker points
Markers (Fig. 3.17) used to position measured sections and samples of this study were also mapped, initially, using a handheld GPS. The results from this exercise were unreliable, given the high resolution centimetre scale of this study. Therefore, tape
measure and compass directions were then used to map in the markers on the outcrop. This relied on a known, reference point (2092940, 5472790).

A marker comprises an 8” reinforcing nail driven into the outcrop. A 50 x 50mm spacer washer is then attached with no. 2 wire to the embedded nail. The location (bed number and marker number) are then scribed onto the spacer. The markers were able to withstand the flood waters of the Waiau River, and therefore were good, reliable reference points for section logging.

3.2.4 Sampling
Samples were collected for paleomagnetic, biostratigraphic and lithostratigraphic analysis and the methodology for each is outlined in their respective sections. All sample sites
required a similar level of site preparation. Site preparation involved clearing a surface using a spade or crow bar to enable sample collection from the least weathered sediment.

Figure 3.17 Above is one of 31 markers used in this study to mark out sections to be logged and sampled. Marker points were commonly placed on sand units as they were less weathered and were more easily identified in the field.

Figure 3.18 A, B. Proposed measured section of rock is firstly marked out using reference points that commonly placed a line perpendicular to the strike of bedding between two marker points. The measured section was then logged. Strike and dip readings were also recorded as these vary along the section. Fig. 3.18C displays the uncorrected thickness (143m) of E section. All stratigraphic logs of this study (A-H [see fig. 3.16]) are divided into these measured sections. The X is the location of marker 18 shown in fig. 3.18A.

3.2.5 Graphic logging of measured sections

In this study Corel Draw® was used to create a graphic log of the measured sections (see appendix A4s1 and A4s2 - stratigraphic logs). Graphic logs were compiled following the method of Andrews (1982). Measured sections were corrected for bedding thicknesses, keeping in mind the changes in apparent dip. Graphic logs include a sampling log that records the type of sample (paleomagnetic, biostratigraphic and lithostratigraphic), see - appendices A4s1 and A4s2.
3.2.6 Thin section sampling

Rock samples for thin section analysis were taken using a paleomagnetic coring drill. This method allowed for easy drilling of sand and mud beds where bedding features would be well preserved. A total of 23 cores were taken for thin section analysis. Two lithologically different parts of the section (one predominantly siliciclastic, one predominantly bioclastic) were sampled, with each set of samples representing a turbidite set (sand bed grading into silty sand, to a silty mud, to a lighter finer grained mud).

3.3 Sedimentology

Siliciclastic sediments in this study are interpreted to comprise the Taylors Member of the upper Blackmount Formation. These siliciclastic sediments grade into the Diggers Hill Member of the McIvor Formation that contain sandy bioclastic sediments. This section of the Lithostratigraphy Chapter outlines the criteria that define the upper Blackmount and lower McIvor formations based upon the field observations of this study.

3.3.1 Visual characteristics of the Taylors Member of the upper Blackmount Formation:

a) Grey in colour. Basal sand beds of a turbidite package are a darker grey. Mud beds are a lighter grey colour that grades into a very light grey colour near the top of the bed. Sand bed colour reflects water content of the bed, which in turn reflects the poor cementation of sand beds.

b) Medium to coarse grained. Basal sections of sand beds typically contain reworked shell fragments and rare whole valves (1-10mm in size) in layers 2-5mm thick. Overlying these shell layers are typically moderately well sorted medium grained sand. Sand beds grade (over 0.1-1m) into mud beds. Mud beds are fine grained with rare foraminifera observed in hand specimen.

c) Sediment sorting is variable. Basal sand beds are moderately well sorted but often support shell beds that are coarse grained. Rarely, small (<3mm in diameter), rounded clasts are found at the base of sand beds. Sorting of mud beds can not be determined from field observations.
d) Cementation of Taylors Member beds. Sand beds tend to be moderately well cemented, and mud beds are well cemented.

e) Fossil content is sparse. Although shell fragments are common at the base of sand beds, they often contain poorly preserved, and reworked specimens that can only be identified as bivalves. Rare lenses and coal streaks are recorded. Lenses are typically no longer than 100mm and only 3-4mm in thickness. Mud beds contain foraminifera.

f) Graded bedding and weakly defined laminar bedding in sand layers can be used to define bedding. Bedding in mud layers is indicated by the transition of darker pelagic mud to lighter coloured hemi-pelagic mud. Banding of mud layers is also recorded in the lowermost part of the section (0m). Banding is indicated by alternating dark and light layers of mud. Concretions and concretionary horizons are common sedimentary structures observed. Calcite jointing is apparent and interpreted to be a post-depositional feature. Large (up to 8cm across and 30cm in length) veins of calcite trace bed offsets by minor faulting, or fluid escape structures.

g) Weathered surfaces are indicated by iron oxide staining and conchoidal fracturing of mud beds and some finer grained sand beds.

3.3.2 Visual characteristics of the Diggers Hill Member of the lower McIvor Formation:

a) Weathered sand beds display a grey – brown – yellow colour. Unweathered, these sand beds are grey in colour. Mud beds are dark grey at the base and grade into a lighter grey colour in hemi-pelagic layers.

b) Textures of sediment vary but all show normal grading. Basal layers of sand beds are typically coarse grained and commonly comprise well-sorted, well-rounded quartz clasts (2-3mm in size) supported by a medium grained sand matrix. Coarse basal layers grade into well defined laminar layers (1-5mm thick) containing fossil fragments of bryozoan, sponges and bivalves. Mud layers are fine grained. Sand sediments are moderately well sorted. Some poor sorting is apparent in basal
sections of sand layers where finer grained sand often supports coarser material. Sorting within mud beds can not be determined from field observations.

c) Sand beds are well cemented with calcite as cement. Mud beds are also moderately well cemented but not to the same degree of sand beds.

d) Sand beds are rich in fossil content, although whole specimens of fossils occur only rarely fossil fragments are more common. Mud beds also contain foraminifera. One bed is rich in trace fossil specimens (bed D163). These trace fossils are interpreted to be from *Scolicia*.

e) Where gradin. is apparent, all beds exhibit normal graded bedding. Sand beds contain the majority of sedimentary structures. Sand beds typically have a scoured basal contact with the underlying mud. Shell layers 2-10mm thick, comprising reworked shells and shell fragments comprise basal sections of most sand beds. Other shelly layers are coarse and sometimes crudely defined, but some shelly layers comprise well defined laminar layers (1-15mm in thickness). Convolute structures are commonly found immediately above laminar layers. Laminar layers rarely occur immediately above convolute structures. Other bedding features include – rare rip up clasts, sand and mud lenses, burrowing, fluid escape structures, and coal lenses/streaks. Sand beds grade into mud beds typically over 0.3-1m. Calcite jointing is apparent and interpreted to be a post-depositional feature. Large (up to 8cm across and 30cm in length) veins of calcite trace bed offsets from minor faulting.

f) Distinctive weathering features are confined to sand beds. Jointing of well cemented sand beds are common. Karst weathering is also identified in the limestone at the top of the measured section. Weathering of mud beds is restricted to conchoidal fracturing.

### 3.4 Thin section analysis

A total of 10 slides were prepared and used to further investigate the sediments of the measured section by examining subtle bedding features, grain size / grain texture, grain sorting, and grain mineralogy. Thin section images are presented in figures 3.21 and 3.22.
3.4.1 Taylors Member thin section analysis

3.4.2 Thin section S1; 42m, bed C35

Texture: Grains are angular to sub-angular, including some rare rounded grains (glaucony, opaques). S1 comprises grains that are 50% grain, 50% matrix supported.

Sorting: Mostly well sorted sand. Larger grains of glaucony and opaque grains as well as rock fragments of quartz and feldspar partially supported by a fine grained matrix. Matrix comprises a microcrystalline calcite cement and rock fragments of quartz.

Bedding: No alignment of grain long axes. Bedding appears massive.

Mineralogy: Quartz, opaques, glaucony, calcite cement, rare foraminifera, and rare plagioclase.

3.4.3 Thin section S2; 47m, bed C47

Texture: Grains are sub-angular to sub-rounded. Some larger opaques and glaucony grains are well rounded. Large (>200 microns) foraminifera and foraminifera fragments are common. 50% grain, 50% matrix supported.

Sorting: Moderately well sorted sand. Larger grains are supported by a fine grained, microcrystalline matrix of quartz and plagioclase rock fragments. Larger moderately well preserved foraminifera are present too.

Bedding: In hand view of the thin section crude layering can be seen. In thin section a weak alignment of grain long axes is observed. Bedding is faintly indicated by grain sorting. Foraminifera show no preferential bedding orientation.

Minerals: Quartz, calcite cement, plagioclase, opaques, foraminifera (whole and fragments), glaucony.

3.4.4 Thin section S3; 55m, bed C61

Texture: Grains are sub-angular to sub-rounded. 25% grain, 75% microcrystalline calcite/rock fragments matrix supported. Glaucony and opaque grains are rounded to well-rounded in shape. Quartz grains are angular to sub-angular in shape.

Sorting: Well sorted sand. Larger rounded opaque and glaucony grains are common as are foraminifera and fragments of foraminifera. Larger quartz grains and rounded opaque
and glaucony grains are supported by a microcrystalline matrix. Matrix comprises a mix of calcite and microcrystalline rock fragments.

Bedding: Strong alignment of grain long axes of quartz grains indicate the bedding direction.

Minerals: Quartz, calcite (cement and foraminifera), plagioclase, opaques, glaucony.

3.4.5 Thin section S4; 63m, bed C75

Texture: Grains are sub-angular to rounded but predominantly sub-angular, supported by a 40% grain, 60% calcite/rock fragment matrix. Large opaque grains and shell fragments form the majority of coarse grains of S4. Opaque grains are well rounded and larger than sub-angular quartz grains. Glaucony grains are smaller than opaque grains but are also well rounded in shape.

Sorting: Moderately well sorted sand comprising a microcrystalline calcite matrix. Coarse (opaques and foraminifera) to fine grains are largely supported by a microcrystalline matrix.

Bedding: Weak alignment of opaque grain long axes indicates bedding direction. Bedding direction is also indicated by microcrystalline calcite matrix layering that is parallel to the bedding direction indicated by the alignment of opaque grains.

Minerals: Quartz, calcite (cement and foraminifera), plagioclase, opaques, glaucony.

3.4.6 Thin section S5; 83m, bed C111

Texture: Grains are angular to sub-rounded in shape. Grains are supported by a 50% grain, 50% microcrystalline calcite matrix. Larger foraminifera (>200 microns) and foraminifera fragments are common.

Sorting: Well sorted sand, indicated by grains that largely comprise sub-angular to sub-rounded quartz grains that are consistent in grain size.

Bedding: In hand view of the thin section bedding is well defined with dark, parallel layers observed that are thought to indicate a bedding direction. Calcite veining is parallel to inferred bedding. A weak alignment of grain long axes is observed.

Minerals: Quartz, calcite (cement and foraminifera), plagioclase, opaques, glaucony.
3.5 Diggers Hill Member thin section analysis

3.5.1 Thin section C6; 158m, bed D01
Texture: Large quartz clasts / grains (>500 microns) are well rounded, smaller grains are less well rounded. Large shell fragments are common. Grains are 100% microcrystalline calcite matrix supported. Large shell fragments (>500 microns) are angular to rounded in shape.
Sorting: Poorly sorted sandy gravel with shells and shell fragments. Smaller fragments comprise smaller quartz and shell fragment grains.
Bedding: In hand view crude bedding of larger grains is apparent. No alignment of grain long axes is apparent in thin section. Shell fragments show no preferential orientation.
Minerals: Calcite (matrix and shell fragments), quartz, plagioclase, glaucony, opaques.

3.5.2 Thin section C7; 189m, bed D83
Texture: Grains are angular to sub-rounded and are supported by a 100% microcrystalline calcite matrix. Quartz and less common glaucony grains are predominantly well rounded in shape. Large (<200 microns) foraminifera and shell fragments are common and are angular to rounded in shape.
Sorting: Moderately well sorted shelly gravel supported by a microcrystalline calcite matrix.
Bedding: Bedding is crudely indicated the weak alignment of quartz and glaucony grain long axes. Foraminifera and shell fragments also show a weak preferential orientation that matches the direction of grain axes.
Minerals: Calcite (shell fragments/foraminifera and microcrystalline cement), quartz, glaucony, plagioclase, opaques, and rare sercite.

3.5.3 Thin section C8; 227m, bed D155
Texture: Clasts are typically large (<500 microns), quartz grains that are well rounded in shape, smaller grains are sub-angular-rounded in shape. Grains are 100% supported by a fine grained, microcrystalline calcite matrix. Whole shells, shell fragments, and foraminifera are angular to rounded in shape. Glaucuny grains are also rounded in shape but smaller than most other grains of the thin section.
Sorting: Poorly sorted sandy, shelly gravel that is supported by a microcrystalline matrix.
Bedding: Crudely bedded observed in hand view of the thin section. A weak alignment of foraminifera indicates a bedding direction.
Minerals: Calcite (shells and fragments, foraminifera, microcrystalline cement), quartz, glaucony, plagioclase, opaques. A foraminifera resembling *S. novozealandica* is seen in C8. Its diagnostic features can not be fully observed but it is highlighted in the thin section images of figure 3.22.

3.5.4 Thin section C9; 235m, bed D173

Texture: Grains are sub-angular to well-rounded with common small shell fragments (<100 microns), which is supported by a 60% quartz grain, and 40% microcrystalline calcite matrix.

Sorting: Moderately well sorted sand comprising larger grains of glaucony (<200 microns) but dominated by smaller (<100 microns), angular quartz grains.

Bedding: In hand view of the thin section, layering of darker minerals is apparent. In thin section view, the basal section appears more chaotically bedded. Fining up of grain textures is observed and there is an alignment of grain long axes that also indicates bedding.

Minerals: Calcite (shells and fragments, foraminifera, microcrystalline cement), quartz, glaucony, plagioclase, opaques.

3.5.5 Thin section C10; 244m, bed D193

Texture: Grains are sub-rounded to rounded supported by a 60% quartz grain, 40% microcrystalline calcite matrix. Textural layering of calcite cement observed. Large (>200 microns) shells and shell fragments angular to rounded in shape are observed.

Sorting: Grain sorting is variable. Well sorted layers are observed as well as poorly sorted layers that comprise a range of grain sizes.

Bedding: In hand view of the thin section, layering of grains is apparent. In thin section bedding is observed with a strong alignment of grains, foraminifera, and shells that also indicate bedding direction.
Minerals: Calcite (shells and fragments, foraminifera, microcrystalline cement), quartz, glaucony, plagioclase, opaques.

3.6 Conclusions from thin section analysis
Thin section analysis of sand beds from the Taylors and Diggers Hill members has shown that Taylors Member beds typically comprise a more consistent grain size than Diggers Hill Member beds. Taylors Member beds typically comprise beds that are more clast supported, whereas Diggers Hill Member beds typically comprise matrix supported beds. Taylors and Diggers Hill member beds are interpreted to both contain microcrystalline calcite as a matrix. Both members also comprise opaque and glaucony grains.

3.7 Chapter Summary
Lithostratigraphic nomenclature of the measured section and sediments above and below the measured section has been outlined in the lithostratigraphy chapter. The Taylors and Diggers Hill members of the Blackmount and McIvor formations, respectively, have been measured and described. A summary stratigraphic column presents the findings in figure 3.23. Thin section descriptions of the two members validate the lithostratigraphic nomenclature identified in this study using high resolution stratigraphic logs.

Stratigraphic logs (appendices A4 [S1 and S2]) are an accurate record of the lithologies of the measured section and provide key texture data that is used later in this study in the cyclicity chapter (Chapter 6). A summary account of the Taylors and Digger Hill members is presented below.

Taylor Member beds are predominantly siliciclastic, finer grained than Diggers Hill beds sediments and contain fewer shells and shell fragments but do contain a surprising number of foraminifera. They are typically well-sorted and show clearer examples of graded bedding.

Digger Hill Member beds are predominantly bioclastic and coarser grained showing a greater variety in grain size and grain texture. Coarser grained sediments typically
comprise graded shell layers, shell fragments and opaques and foraminifera, as well as large, rounded, clastic quartz clasts / grains that are restricted to the base of sand layers of Diggers Hill Member beds. Diggers Hill Member beds are commonly weakly graded, poorly sorted, and have crude bedding features with rare exceptions (C9), and are well cemented with microcrystalline calcite that also forms the matrix of many beds.

Both Taylors and Diggers Hill sediments share similar mineral contents but in different proportions. Paleoenvironmental interpretations can be made from thin section data, and this is undertaken in the Facies Analysis chapter (Chapter 5).
Figure 3.19 Images of Taylors Member beds

a. Lower A section (0-30m), looking down the direction of dip. Spade is 1.5m in length.

b. Upper A section (30-35m). Tape measure drawn along strike is 6.5m in length.

c. Mid C section (40-70m), looking obliquely across strike direction. People shown are 1.7m in height. Source: Carter and Norris, (2005).

d. Upper C section (70-80m) looking up the direction of dip. People are approximately 1.5m in height.

e. Upper most C section (approx 100m), looking obliquely down the plane of dip. Book is 20cm across.
Figure 3.20 Images of Diggers Hill and Glendearg members

a. Lower D section (160m), looking across the plane of strike. Book is 20cm in length.

b. Mid D section (160 - 250m), looking down the direction of dip. Hammer is 1m in length, Source: Carter and Norris, (2005).

c. Lower E section (350-390m), looking down the direction of dip. Person is 1.7m in height.

d. Upper E section (460-360m) looking at the plane of dip. Book is 20cm in height.

e. The contact between the Diggers Hill and Glendearg members looking across the plane of strike. Book is 20cm in height.

f. Lower Glendearg Member beds immediately overlying the capping limestone at the top of the measured section. Book is 15cm across.
Figure 3.21 Thin section images from Taylors Member beds

Plain polarised

10 X objective

Cross polarised

**S1; 42m, bed C35**
- No alignment of grain long axes
- Grain supported bed
- Angular to sub-rounded grain shape
- Opaque grains
- Quartz
- Microcrystalline matrix
- Glaucony

**S2; 47m, bed C47**
- Very weak alignment of grain long axes
- Grain supported bed
- Sub-angular to sub-rounded grain shape
- Glaucony
- Rounded quartz
- Rounded opaque grains
- Microcrystalline matrix

**S3; 55m, bed C61**
- Alignment of grain long axes
- Matrix supported bed
- Sub-angular to sub-rounded grain shape
- Glaucony
- Quartz
- Rounded opaque grains
- Microcrystalline matrix
Figure 3.21 continued

Plain polarised

10 X objective

Cross polarised

S4: 63m bed C75

Alignment of
grain long axes
Matrix supported bed

Sub-angular to rounded
grain shape
Quartz
Shell fragments
Well rounded opaque grains
Microcrystalline matrix

S5: 83m, bed C111

Matrix and grain supported
bed

Sub-angular to sub-rounded
grain shape
Well rounded quartz
Rounded opaque grains
Microcrystalline matrix
Figure 3.22 Thin section images from Diggers Hill Member beds

Plain polarised

C6; 158m, bed D01

No alignment of grain long axes
Glaucony
Shell fragments
Matrix supported bed
Well rounded quartz
Angular to well-rounded grain shape
Microcrystalline matrix

C7; 189m, bed D83

Matrix and grain supported bed
Sub-angular to sub-rounded grain shape
Foraminifera
Angular quartz
Shell fragments
Glaucony
Microcrystalline matrix
Weak alignment of grain long axes

C8; 227m, bed D155

No alignment of grain long axes
Glaucony
Angular to well rounded grain shape
Matrix supported bed
Shell fragments
Well rounded quartz
Foraminifera
Microcrystalline matrix

Cross polarised

4 X objective
figure 3.22 continued

Plain polarised

4 X objective

Cross polarised

C9: 235m, bed D173

Matrix and grain supported bed
Glaucoby
No alignment of grain long axes
Foraminifera
Angular quartz
Sub-angular to sub-rounded grain shape
Microcrystalline matrix

C10: 244m, bed D193

Bedding apparent
Microcrystalline matrix
Matrix and grain supported bed
Sub-angular to well rounded grain shape
Rounded quartz grains
Shell fragments
Glaucoby
Rounded opaque grains
Alignment of grain long axes
**Figure 3.23 Summary Stratigraphic column of the measured section**

**Glendearg Member (9m)**
The Glendearg Member comprises rhythmically spaced alternating sand and mud beds (30-40cm thick). Sand beds grade up, are well cemented, have multiple bedding features and are composed of shell fragment material. Bedding features include, laminar layering, weakly defined convolute structures. Mud layers contain abundant foraminifera and are weakly cemented. The Glendearg Member conformably overlies the Diggers Hill Member. This study identifies 9m of the base of the Glendearg Member and is interpreted to occur (NZMS 209, 336, 572200), at the top of the measured section of this study. Weathered surfaces of the Glendearg Member identified in this study are indicated by karst surfaces and jointing.

**Diggers Hill Member (320m)**
The Diggers Hill Member comprises beds of bioclastic sand/gravels, with interbedded mudstone. Diggers Hill Member beds exhibit a number of sedimentary features that include, scoured bases, cm scale graded bedding, convolute structures, laminar layering, mud lenses, concretions, burrowing, and rare trace fossils. Fluid escape structures are also a feature of Diggers Hill Member beds.

**Taylors Member (146m recorded in this study)**
The Taylors Member comprises alternating grey-green sand and mud beds typically no thicker than 25cm. Sand and mud beds all fine upwards up and graded bedding is poorly preserved. All sand beds have sharp lower contacts with underlying mud beds. Sand beds comprise coarse based sands with small (<5mm in diameter) shells and shell fragments as well as common glauconite pellets. Sand beds grade into finer more well sorted layers with some laminar layers recorded. Sand beds grade into muddier pelagic hemi-pelagic mudstones. Taylors Member sediments contain calcite cement.

* Glendearg Member and the section of it recorded in this study
S, C = thin section samples
Chapter 4 - Biostratigraphy

Introduction
The key aim of biostratigraphic analysis undertaken in this study was to locate the Waitakian (Lw) - Otaian (Po) Stage boundary in the measured sections of the Blackmount and McIvor formations. Biostratigraphy in this study used benthic and planktonic foraminiferal age-range zones from Homibrook et al. (1989), and The New Zealand Geological Timescale (2004). The presence of Scolithos trace fossils did yield some information into the depositional environment but does not aid in building a biostratigraphy for the measured section given the age range of Scolithos.

Previous unpublished biostratigraphic work has been undertaken on sediments of the measured section. B.L Wood collected samples for biostratigraphic analysis in the 1940's. This was then followed up by Carter and Norris in the early 1970’s. Their data is presented in part 4.3 of this chapter.

4.1 The Waitakian - Otaian (Lw-Po) Stage boundary background
The Waitakian (Lw) Stage was initially proposed by J. Park (1918) as being the glauconitic calcareous sandstone that forms the Waitaki stone (later Otekaike Limestone of Gage, 1957) as the upper substage of the Hutchinsonian Stage (Homibrook et al., 1989). This interpretation of the Lw Stage proved to be wrong, as Park confused the Kokoamu and Gee Greensands. Allan (1933) later proposed that the Lw should refer to... "the period of time represented by the deposition of the Waitaki Limestone and the Otekaike beds of the Waitaki Valley". The base of the Lw is defined by the FAD of Globoquadrina dehiscens (Jenkins, 1960, 1964, 1973). The LAD (Last Appearance Datum) of Globigerina euapertura is used to mark the middle of the Lw, and Globigerina woodi connecta is used to mark the upper limits of the Lw. There are no LADs of planktic or benthic foraminifera identified at the Lw-Po boundary.

The lower Hutchinsonian was divided establishing the Otaian (Po) Stage (Finlay and Marwick, 1947), with its stratotype designated in the Bluecliffs Siltstone and Southburn
Sands at Bluecliffs, in south Canterbury. The Po is defined by the FAD (First Appearance Datum) of primarily *Ehrenbergina marwicki*, and secondly *Spiroloculina novozealandica* (Morgans et al., 1999). Both species are benthic foraminifera. The FAD of *S. novozealandica* is identified in this study and used to help mark the base of the Po.

**4.2 Biostratigraphy Methods**

Sampling for biostratigraphy was undertaken in two parts. Firstly, six samples were collected for a pilot study that broadly sampled the section and determined a mid Waitakian – mid Otaian – Lw-Po (24-20Ma) approximate age for the measured section. The pilot study indicated that a high resolution sample regime needed to be implemented to constrain the relative position of the boundaries. A further 64 samples were collected at approximately 7m intervals, utilising material from paleomagnetic core sites, which are spaced approximately seven meters apart. All samples collected adjacent to paleomagnetic sample sites were collected from the overlying mud bed if the paleomagnetic core was collected from a sand bed. FAD and LAD ages of benthic and planktonic foraminifera identified in this study are correlated to the New Zealand Geological Timescale, Cooper et al. (2004) that used the GPTS (geomagnetic polarity timescale) of Berggren et al. (1995).

**4.2.1 Field methods**

All samples in this exercise were collected from light grey coloured mud beds. These mud beds were interpreted to be hemi-pelagic rain out material, and therefore the most reliable strata for *insitu* foraminifer specimens. Samples were gathered 15cm below the overlying sand bed of a turbidite set to ensure sampling in the hemi-pelagic layer. Prior to the collection of the sample, the area to be sampled was cleared of weathered material. This typically involved removing 5cm of weathered overburden rock. A rock hammer was used to chip 200-300g samples into a sample bag.

**4.2.2 Lab methods**

The kerosene method is used here to process mud samples for foraminifera. All equipment used in the lab was cleaned before use to reduce contamination and gloves
were worn at all times, and where necessary a visor was worn. This follows the lab guide of R.E Fordyce (2004). The procedure is outlined here:

a) Firstly, raw samples were placed in between layered paper (changed between each sample) upon a wooden crushing block, where samples were crushed into chunks less than 1cm in diameter using a rock hammer. Samples were then weighed giving an approximate wet weight of 160g, placed in a metal dish and dried in a sample oven at 90°C for 24 hours to remove all bound water from the sample. This typically yielded a dry weight of 140-150g. Completely dry samples were essential to the kerosene method, as bound water inhibits the effectiveness of the kerosene in sample processing. Samples were processed in batches of four as this typically equated to one day of lab work. Wet and dry weights were recorded as well as the final dry weight of the sieved sample fraction.

b) Samples were then placed into 250ml beakers below a funnel in a fume cupboard. Filter paper was placed into the funnel, and 100ml kerosene passed through the filter paper. The filter paper was necessary as the kerosene was ‘recycled kerosene’ having being used in the processing of samples for other studies. Care was taken to ensure no contamination of samples.

c) The sample was then degassed by placing the sample beaker into a vacuum chamber for 1-2 minutes. The de-gassing drew kerosene into the sample as air was drawn out of pore spaces within the mud.

d) After de-gassing, the sample was then drained of kerosene with filter paper.

e) The sample was then added to a pot of boiling water that contained 30-35g of sodium hexametaphosphate (NaPO₃)₆ in solution, within a fume cupboard. After 10 minutes of the sample boiling, 20ml of hydrogen peroxide (H₂O₂) was added. Use of hydrogen peroxide required the use of a visor, an apron and especially gloves, as it is extremely harmful to exposed skin. A sample was boiled for 45-50 minutes and then filtered.

f) Filtering used a 63micron wet sieve (4phi). Firstly, the wet sieve was soaked / saturated in methylene blue for a minute, rinsed and then washed with dish washing detergent. The sample was then passed through the wet sieve.
g) All samples needed steps e) and f) repeated at least 3 times to ensure all bound mud was removed.

h) After final filtering and rinsing, samples were then ready to be dried. Drying involved placing samples in metal dishes in the sample oven at 90°C, or below heating lamps.

i) After samples were completely dry they were then split into two sets, a working set that was used in this study, and an archive set. The archive set was necessary as it was a back up working set that could be drawn upon if contamination of the working set was suspected.

4.2.3 Mounting foraminifera
The identification of specimens required the working set samples to be sieved into smaller working sets. This was done to reduce the sample to a more manageable volume so that species were more easily identifiable. Individual specimens from spilt samples were mounted on slides.

4.3 Biostratigraphy – Lw – Po benthic and planktonic faunas
Data is presented here is two parts. The first section briefly summarises biostratigraphic data collected in two previous unpublished studies. The second part lists and describes key benthic and planktonic species recorded from the section as well as their biostratigraphic utility.

4.3.1 Biostratigraphic analysis of B.L Wood (1940’s) and Carter and Norris (1970’s)
Unpublished work by B.L Wood, and Carter and Norris sampled several sites within the measured section of this study. Their work is unpublished but their biostratigraphic census data is available online at http://data.gns.cri.nz/fred. The approximate sample sites of their study that lie within the area of this study are outlined in figure 4.24. Biostratigraphic samples gathered by Wood, and Carter and Norris indicated a Whaingaroan (Lwh) to Otaian (Po) age.
Biostratigraphic Sample sites of the Measured section

Figure 4.24 Geographic location of biostratigraphic samples of the measured section from this study, and of the studies of B.L. Wood (1947), and Carter and Norris (1977a). Sixty-four samples were collected in the exercise but only the 19 samples shown by black and green squares were finally used.

The age/census data from Wood, Carter and Norris are not used for biostratigraphic analysis in this study, but their results are used as a guide. Biostratigraphic analysis undertaken by Wood, Carter and Norris in the Waiau Basin did not match the FAD and LAD data of recent work by Morgans et al. (1999), and Graham et al. (2000) of key taxa across the Lw-Po. Ages of these samples are relatively ambiguous as they only indicate a (Whaingaroan) Lwh-Po age for the section.
4.3.2 Biostratigraphic analysis of this study

The recognition, distribution and utility of species from the measured section are evaluated here using 19 samples analysed in the laboratory. The number of samples analysed is only a third of that collected and processed. Samples were collected on the basis that some collected and subsequently processed may not yield adequate populations for biostratigraphic / paleoenvironmental analysis. This method worked well as the samples eventually used for these analyses are samples with better populations than those that were initially looked at in some instances. Recognition of key species in this study use similar criteria as Morgans et al. (1999), Jenkins (1966), and Hornibrook et al. (1989). The recognition of species of foraminifera used descriptive criteria outlined in Hornibrook et al. (1989) as a guide for recognising species in this study. A plate of scanning electron micrograph (SEM) pictures of key planktonic and benthonic taxa recovered from the section is presented in appendix A2_{vij}.

4.3.3 Benthic foraminifera of the Lw - Po

The FAD of *Ehrenbergina marwicki* is used as a key benthic species to mark the base of the Po (Morgans et al., 1999). *E. mariwcki* was not identified in any samples of this study. Morgans et al. (1999) also used the FAD of *Spiroloculina novozealandica* as a secondary species in placing the Lw-Po boundary. One sample (OU 76378) containing specimens of *S. novozealandica* were identified in this study.

4.3.4 *Spiroloculina novozealandica* (Po - R)

Recognition – *S. novozealandica* is recognised as elliptical, spiralled, flattened benthic foraminifera with tabular chambers and a stout apertural neck. Poorly preserved specimens of *S. novozealandica* can be confused with *S. canaliculata* (Ab-Tt). Specimens of *S. novozealandica* identified in this study were well preserved and easily identifiable.

Distribution – In this study *S. novozealandica* was identified with its FAD occurring at 355m (sample OU 76378). Populations of *S. novozealandica* are recorded by Morgans et al. (1999) as small. It is possible that samples collected stratigraphically higher than OU
76378 contained highly altered specimens of *S. novozealandica* as some reprecipitated calcite flakes resembled an *S. novozealandica* morphology.

Biostratigraphic utility – Although the FAD of *S. novozealandica* is not exactly coincidental with the Lw-Po boundary (Morgans et al., 1999, identified it above the lowest occurrence [LO] of *E. mariwcki* which they used as the base of the Po in the Bluecliffs section), *S. novozealandica* is however a useful proxy and one of the most reliable bioevents this study can use in building a biostratigraphic age model for the measured section.

4.4 Planktonic foraminifera of the Lw – Po

4.4.1 *Globigerina euapertura* (Lwh – mid Lw)

Recognition – *Gl. euapertura* is distinguished by a broad, low arched umbilically situated aperture, bound by strongly embracing chambers (Hornibrook et al., 1989). *Gl. euapertura* is easily misidentified from the similarly structured *Gl. woodi*. The common features that *Gl. euapertura* and *Gl. woodi* share include the calcellate (‘honeycomb’) wall topography as well as low arched chambers that are similar in appearance for both species. Features of *Gl. euapertura* that distinguish it from *Gl. woodi* include an inconspicuous rim, which is often narrow and concealed. Post-depositional reprecipitated calcite has formed overgrowths on specimens of *Gl. euapertura* and made identification of its distinguishing features difficult.

Distribution – *Gl. euapertura* is recognised in the lowermost sample (OU 76375, 30m) and its highest record is at 83m (OU 76376). Populations of *Gl. euapertura* from analysed samples vary. However, a decline in the number of specimens up section is apparent.

Biostratigraphic utility – Morgans et al. (1999) recorded the LAD of *Gl. euapertura* 15m below the FAD of *Ehrenbergina marwicki*, and regard it as an inferior maker of the Lw-Po boundary. This study also utilises the LAD of *Gl. euapertura* as a marker near to the Lw-Po boundary. The LAD *Gl. euapertura* is a good indicator for the mid Lw, and aids
in placing the boundary when taking into account the relative stratigraphic position FAD of *S. novozealandica* in this study.

### 4.4.2 *Gobigerina brazieri* (upper Ld – Po?)

**Recognition** — *Gl. brazieri* is recognised as having a low trochospiral, sinistrally coiled globular chambers, with perforated and pitted walls (Hornibrook et al., 1989). The aperture of *Gl. brazieri* is high, rounded and circular shaped with a thick rim. Other studies have outlined problems in identifying *Gl. brazieri*, as it is easily confused with *Gl. woodi woodi*. *Gl. brazieri* is distinguished from *Gl. woodi woodi* as possessing a higher arched, more rounded and nearly circular shaped aperture with a smoother rim (Jenkins, 1966).

**Distribution** — The FAD of *Gl. brazieri* is at 229m (OU 76408), it occurs again at 245m (OU 76411). *Gl. brazieri* is only recorded at these two heights.

**Biostratigraphic utility** — Although the LAD of *Gl. brazieri* is not well defined it can be assumed that it occurs in the middle of the Lw and can be used to help further constrain the relative placement of the Lw – Po boundary. Morgans et al. (1999) recorded *Gl. brazieri* as being rare and impersistent before its extinction near to the LAD of *Gl. euapertura*.

### 4.4.3 *Globoquadrina dehiscens* (Lw – Tt)

**Recognition** — *Gq. dehiscens* is subquadrate (block like) foraminifera with four chambers that have flattened inner faces. The surface of *Gq. dehiscens* is distinctively subhexagonal. Specimens of *Gq. dehiscens* identified in this displayed some variability in morphology. This was manly due to post-depositional reprecipitation of calcite.

**Distribution** — *Gq. dehiscens* is found at the base and at the top of the measured section and in most samples, indicating an age of at least Lw or younger for the entire section. Variability of population size and preservation of *Gq. dehiscens* is apparent through the section.
Biostratigraphic utility – The FAD of *Gq. dehiscens* is a key species form marking the base of the Lw. The FAD of *Gq. dehiscens* is recorded by Scott (1976) as being late Oligocene – early Miocene (base of the Lw). Morgans et al. (1999) also recorded a similar FAD for *Gq. dehiscens*. Hornibrook et al. (1989) placed the FAD of *Gq. dehiscens* at the base of the Miocene, which is mid Lw.

**4.4.4 Globigerina woodi woodi (Lw – WN)**

Recognition – *Gl. woodi woodi* is identified as having, four chambers in the final whorl that are deeply sutured; a rough, porous surface, and a high apertural arch with a thick lip. *Gl. woodi woodi* is similar in morphology to *Gl. bulloides* and the two can be easily confused. *Gl. woodi woodi* does however have a higher arched apertural lip and a coarser wall structure (Jenkins and Murray, 1981).

Distribution – The FAD of *Gl. woodi woodi* is recorded in the mid to upper Lw from the Bluecliffs section in south Canterbury (Morgans et al., 1999). In this study *Gl. woodi woodi* first appears at the base of the section (OU 76375, 0m).

Biostratigraphic utility – The FAD of *Gl. woodi woodi* does overlap with the upper limits of *Gl. euapertura* (LAD – mid Lw). This overlap of the two species matches that of other studies. In this study, the occurrence of *Gl. woodi woodi* is used to place a mid Lw age on the base of the measured section.

**4.4.5 Globigerina woodi connecta (Lw – lower PI)**

Recognition – *Gl. woodi connecta* is distinguished from *Gl. woodi woodi* by its lower arched aperture, however morphologically transitional forms linking these two species do exist (Kennett and Srinivasan, 1983).

Distribution - *Gl. woodi connecta* is found at the base of the measured section, and at the top of the measured section. Hornibrook et al. (1989) do not record the FAD of *Gl. woodi connecta* as overlapping with the LAD of *Gl. euapertura*.
Biostratigraphic utility – The presence of *G. woodi connecta* at the base of the section with *G. euapertura* either indicates an earlier FAD of *G. woodi connecta* in southern latitudes during the Lw, or indicates a later LAD of *G. euapertura* in southern latitudes. Jenkins (1966) used the FAD of *G. woodi connecta* to mark the base of the *Globigerina woodi connecta* zone in the upper Lw.

4.4.6 *Cataspydrax dissimilis* (Lwh – Po? Pl?)

Recognition – *Cs. dissimilis* is distinguished as having a compact low spire, having four chambers in the final whorl. The surface of *Cs. dissimilis* is a distinctly cancellate, being coarse, porous and rough. The apertural opening is covered by a single umbilical bulla (Kennett and Srinivasan, 1983).

Distribution - *Cs. dissimilis* is recognised in sample OU 76391 at 94m, and also occurs at the top of the section in OU 76379 (455m). Populations of *Cs. dissimilis* are small and confined to only a few samples of this study.

Biostratigraphic utility – Hornibrook et al. (1989) recorded *Cs. dissimilis* as being common in the Lw-Po, with some populations remnant in the early Altonian (Pl). Kennett and Srinivasan (1983) used the LAD of *Cs. dissimilis* as an important marker for the early Miocene. Although the LAD of *Cs. dissimilis* is not recorded in samples from the measured section (and therefore not used in the age model, fig. 4.25), it is a useful species for paleoenvironmental analysis which will be elaborated on in Chapter 5, Facies analysis.

4.5 Biostratigraphy of the Waitakian – Otaian boundary Summary

Figure 4.25 presents a biochronology of the Lw – Po. This figure presents microfossil zonations from Jenkins (1966), Hornibrook et al. (1989), The New Zealand Geological Timescale (2004), and the microfossil zonations using the biostratigraphy of this study. Key species that this study used to define the boundary are LAD of *G. euapertura* (83m) and FAD of *S. novozealandica* (368m). Other species mentioned above are used to aid in locating the Lw-Po boundary and are also used for paleoenvironmental analysis.
The biostratigraphy of this section is far from ideal, given the poor preservation of specimens, the absence of *E. marwicki*, and the lack of good populations of key species. As a result a biostratigraphy has been developed using the available data albeit less than ideal.

The FAD and LADs of key taxa identified and described above are not synchronous with the occurrence in the type section (Bluecliffs, South Canterbury) where ages for the Lw-Po were established by Morgans et al. (1999).

The section is dated as follows:

1) the Mid Waitakian (0-168m +/- 35m)
2) the Mid-Upper Waitakian (200-345m +/- 25m)
3) the Otaian (368 – 429 +/- 15m)
4) the Upper Otaian (465m+) to lowermost Altonian (Pl)

A more accurate placement of the boundaries of these subdivisions is difficult to infer given the circumstances mentioned above. Although the biostratigraphic utility of specimens is not ideal it does not exclude paleo-ecological interpretations, Paleo-ecological data for the measured section is presented in the Facies analysis chapter (Chapter 5).

Note – All foraminiferal census data is presented in data tables in appendix A2 with SEM pictures of key taxa.
Figure 4.25 Biostratigraphic age model for the measured section.

- **Jenkins (1966)**
- **WRV Stratigraphy (simplified)**
- **Microfossil zonations (from this study)**

1. Gl. woodi connecta
2. Gl. woodi woodi
3. Gq. dehiscens
4. Gl. euspertura
5. S. novaezeelandica
6. Gl. brazieri
Chapter 5 - Facies analysis

Introduction

Stratigraphic descriptions and measurements and biostratigraphic data are qualitatively assessed as facies and facies associations. Facies and facies associations are then used to build facies successions interpreted from the measured section. Sediments of the measured section are dominated by sand and mud beds with a minor limestone recorded at the top of the measured section. Facies assessment of the sand, mud, and limestone beds recognise mudstone and sandstone lithofacies associations. Lithofacies associations present facies groups that are closely related to one another. A lithofacies assessment is then used to characterise facies successions of the upper Blackmount (Taylors Member), and McIvor formations (Diggers Hill and Glendearg members). Facies successions are then used to develop sedimentary motifs for the sediments of this study.

5.1 Facies and facies associations

Figure 5.26 summarises all the facies and facies associations identified in this study.

Mudstone associations-

5.1.1 Massive mudstone facies (Mm)

Description: Blue grey, crudely graded silty mudstone. Mudstone beds have a silty base that commonly grades into a lighter coloured, finer grained mudstone bed. The beds are well cemented and have a gradational lower contact that varies from 2-3cm to 20-30cm in thickness. Planktonic foraminiferal assemblages of mudstone layers include Globigerina brazieri, Gl. woodi woodi, Gl. woodi connecta, Gl. euapertura, and Globoquadrina dehiscens. Benthic foraminiferal assemblages of mudstone beds include Spiroloculina novozealandica, Karreriella novozealandica, Tritaxilina zealandica, and Vulvulina pennatula. Preservation of foraminiferal assemblages is variable with the lower 100m of the measured section containing poorly preserved specimens. Weathered surfaces of mudstone beds are indicated by iron oxide staining and conchoidal fractures. Minor faulting and less commonly fluid escape structures offset mudstone layers.
<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Symbol</th>
<th>Sediment source</th>
<th>Facies picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mm</td>
<td>Massive mud</td>
<td></td>
<td>Lower shelf slope - rain out</td>
<td></td>
</tr>
<tr>
<td>Mb</td>
<td>Banded mud</td>
<td></td>
<td>Lower shelf slope - rain out</td>
<td></td>
</tr>
<tr>
<td>Ms</td>
<td>Mud with Sand lens</td>
<td></td>
<td>Shelf, shelf slope - rain out</td>
<td></td>
</tr>
<tr>
<td>Ss</td>
<td>Siliciclastic sand</td>
<td></td>
<td>Shelf, shelf slope</td>
<td></td>
</tr>
<tr>
<td>Sb</td>
<td>Bioclastic sand</td>
<td></td>
<td>Shelf, shelf slope</td>
<td></td>
</tr>
<tr>
<td>Sl</td>
<td>Shelly sand layer</td>
<td></td>
<td>Shelf</td>
<td></td>
</tr>
<tr>
<td>Sst</td>
<td>Sand with multiple sedimentary structures</td>
<td></td>
<td>Shelf, shelf slope</td>
<td></td>
</tr>
<tr>
<td>Stf</td>
<td>Sand with trace fossil</td>
<td></td>
<td>Shelf, shelf slope</td>
<td></td>
</tr>
<tr>
<td>Sfe</td>
<td>Fluid escape structure</td>
<td></td>
<td>Shelf, shelf slope - rain out</td>
<td></td>
</tr>
<tr>
<td>Ls</td>
<td>Limestone</td>
<td></td>
<td>Shelf, shelf slope</td>
<td></td>
</tr>
</tbody>
</table>
Interpretation: Facies Mm represents the lowest energy conditions of the Blackmount and McIvor formations. A meso-pelagic to bathy-pelagic marine depositional environment is indicated by benthic foraminiferal assemblages. A 1200 – 1600m depth of deposition is inferred by the assemblages. Facies Mm sediments are inferred to be sourced from the shelf, shelf slope, and from fine sediment rain out.

5.1.2 Banded mud facies (Mb)

Description: Blue to grey, fine-grained, well-cemented mud. Facies Mb occurs only once at the base of the measured section (0-10m). Fossil content is restricted to planktonic and benthic foraminiferal assemblages that are typically poorly preserved. Facies Mb comprises banded layers of alternating dark and light beds of mud 20-30cm thick which grade into each other over 1-2cm. Banded intervals of Mb do not reflect obvious textural changes, contain no sedimentary structures, and are only indicated by colour. Weathered surfaces are indicated by conchoidal fractures and iron oxide staining.

Interpretation: Benthic foraminiferal assemblages that include *V. pennatula* indicate a deep marine depositional environment of at least 800m. Limited paleoenvironmental interpretations can be made regarding the banded layers of Mb. Lighter layers may reflect a higher concentration of rain out fine grained sediment in a quiet depositional environment. Darker layers may represent a more shelf slope derived sediment source. Darker layers, if being sourced from the shelf slope, indicate mass transport of fine grained sediment down the slope and represent a slightly higher energy depositional environment.

5.1.3 Mud with sand lenses facies (Ms)

Description: Blue to grey, fine grained, well cemented mud. Lower contacts are gradational over 5-40cm. Sand lenses comprise a blue grey, moderately well cemented and well sorted sand. Sand lenses have sharp lower contacts and grade into muddy beds over 1-2cm. Lateral continuity of sand lens’ are variable but they can be traced over tens of meters. Weathered surfaces of facies Ms is the same as Mm.
Interpretation: Mud beds are inferred to represent a quiet marine depositional environment with the main sources of sediment from rain out and from the shelf slope. Benthic foraminiferal assemblages of the Ms facies indicate deep marine depositional environments of at least 1200m. Sand lenses are inferred to be from the same deep depositional environment but are inferred to be sediment sourced from higher on the shelf slope.

Sandstone associations-

5.2.1 Siliciclastic sandstone facies (Ss)
Description: Blue, grey, green to yellow grey, coarse to medium grained sandstone. Ss beds are moderately well cemented and sorted. Ss beds comprise siliciclastic material with rare glaucony grains. Ss beds display vertical graded bedding over tens of millimetres to tens of centimetres and have sharp lower contacts that commonly show evidence of scouring. Weathered surfaces of Ss beds are indicated by iron oxide staining, jointing and rare conchoidal fracturing.

Interpretation: Basal sections of the Ss facies indicate a high energy depositional environment that is implied by coarse grained sand overlying a scoured, sharp contact. Graded bedding indicates decreasing depositional energy. Rare, reworked glaucony grains imply that the sediment source for part of the Ss facies is from a quiet depositional environment (that may originate from a sheltered, shallow marine depositional system).

5.2.2 Bioclastic sandstone facies (Sb)
Description: Grey, yellow to brown, coarse to fine grained sandstone, moderately well sorted and well cemented. Sb beds comprise reworked and angular bioclastic fragments with less common grains of quartz and siliciclastic material. Bioclastic deposits comprise largely reworked shell fragments, rarer whole shells and bryozoan fragments. Sb beds display graded bedding over the same scale as beds of the Ss facies. Sb facies have sharp, scoured lower contacts. Weathered surfaces of Sb are the same as Ss facies except jointed surfaces are more common largely due to the well cemented nature of Sb beds.
Interpretation: Facies Sb represents a high energy depositional environment indicated by coarse grained sand and shell fragments that overlie a sharp, scoured lower contact. Benthic foraminiferal data indicates a deep marine depositional environment. Desiccated and reworked bioclastic material indicates a shelf origin and the reworking of this material is due to transport down the shelf slope to a deep marine depositional environment as a high energy deposit.

5.2.3 Shelly sand facies (SI)

Description: Grey – blue to yellow – brown, coarse to medium grained, variably sorted and cemented sand. Lower contacts of SI are sharp and scoured and underlie basal shell layers. Basal shell layers comprise 1-10mm thick layers of largely reworked shelly material with less common whole shells ranging in size from 1-5mm. Shell layers comprise either flat oriented or randomly oriented shelly material and are supported by a minor siliciclastic sandy matrix. Preservation of shelly material is variable. Basal shelly layers typically grade into overlying homogenous sand layers over 1-5mm. Weathered surfaces of facies SI are the same as facies Ss.

Interpretation: Shelly layers of facies SI indicates a shelf origin, like that of facies Sb and overlie a sharp scoured lower contact indicating a high energy depositional environment. Shelly material is, however, restricted to the lower most part of facies SI indicating that supply was limited and possibly became diluted by the more homogenous sand that the shell layers grade into, which indicates a near shelf slope or shelf slope origin. Benthic foraminiferal assemblages indicate a minimum 1200m depth of deposition. Facies SI can be interpreted to represent a transition in sediment source from the shelf to shelf slope environments.

5.2.4 Sand with sedimentary structures facies (Sst)

Description: Grey – blue to yellow – brown, coarse to medium grained, variably cemented and sorted sand. Sst beds have sharp, scoured lower contacts that are overlain by graded sand intervals. Graded sand intervals of the Sst facies are then succeeded by sedimentary structures that can include planar bedded laminations (a), concretions and
concretionary horizons (b), rip-up clasts (c), and convolute structures (d). Laminar bedding typically comprises thin bedded layers (1-5mm) of fine sand. Convolute structures are typically confined to finer grained textures and from structures no larger than 25cm in height. Weathered surfaces of Sst are the same as Ss facies.

Interpretation: Basal sections of facies Sst are interpreted to be high energy deposits indicated by the sharp and scoured lower contact overlain by graded beds. Graded beds are commonly succeeded by planar bedded laminations, which in turn can be succeeded by convolute structures. This succession is inferred to represent a further waning in depositional energy where finer grained sediments are able to form sedimentary structures. Planar bedded laminations that commonly overlie graded intervals indicate a flow regime containing enough depositional energy to form laminar structures.

Convolute structures that commonly overlie laminated intervals indicate a still lower energy flow regime. Basal graded layers of the Sst facies are inferred to be sourced from near the slope edge or the slope itself. Sand beds comprising planar bedded laminations and convolute structures are inferred to have been sourced from the shelf slope as they are fine grained and are usually better sorted. Concretionary deposits indicate the presence of carbonate deposition, possibly as small fragments from which concretions nucleate.

5.2.5 Sand with trace fossil facies (Stf)
Description: Facies Stf is observed only once in this study. The bed in which facies Stf is recorded is described as a yellow to brown, moderately well sorted and cemented sand with a sharp, scoured lower contact, and a basal shell layer overlain by graded laminar bedding. The basal shell layer comprises Sl facies. The laminar layer comprises Sst facies. The trace fossil is restricted to the fine sandy interval at the top of the sand bed. Weathered surfaces are the same as Ss facies. Pictures of the trace fossil from the field and lab are presented below in figure 5.27.
Interpretation: Trace fossil taxa are indicative of the *Scolithos* ichnofacies. The *Scolithos* ichnofacies of facies Stf indicates that high energy sedimentation had ceased and sedimentation was likely to have been dominated by fine grained shelf slope sourced sediments transported by a low energy flow regime. Benthic foraminiferal data indicates that facies Stf is a deep marine deposit. The *Scolithos* ichnofacies also indicates that the Stf facies was well enough oxygenated for organisms like *Scolithos* to thrive.

![Image of Scolithos traces](image1.png)

*Figure 5.27, fig. 5.27a is a field shot (cigarette lighter for scale) of *Scolithos*, no patterns of the trace fossil are observed. Figures 5.27b and 5.27c are lab shots of *Scolithos* traces taken from a section of rock containing facies Stf.*

**5.2.6 Sand with fluid escape structure facies (Sfe)**

Description: Offset sand beds belonging to the Sfe facies are described as blue – grey to yellow brown, moderately well sorted and cemented sand beds. The lower contact is sharp. Initially, the structure resembles slip offset on a steeply dipping fault plane (90° dip). However, closer observation shows the underlying mud (bed D14, see appendix stratigraphic log) ‘wedging out’ into the rupture zone (see figure 5.28a, b, and c). Calcite veining is apparent within the rupture zone. The calcite vein contained by bed D15 is up to 8cm across. Further investigation of beds overlying bed D15 show no offset, indicating that this feature is localised to this bed at this location. The displacement of the bed is 1.12m. The thickness of bed D15 is 0.88m. Either side of the rupture zone the edges of bed D15 are splayed upwards in the direction of dip, (see fig. 5.28).

Interpretation: Offset bedding of the facies Sfe are interpreted as fluid escape structures. Fluid escape structures are restricted to sand beds and imply soft sediment deformation. Owen (1996) discussed the anatomy of a water escape cusp in the upper Proterozoic
Torridon Group sandstones, Scotland. These water escape cusps are interpreted to have formed during a fluidised state. In Owen’s (1996) study, un lithified layered sediments trapped water in small pockets that offset overlying bedding, forming a cusp. In some instances, these water-filled cusps penetrated the overlying offset beds but never ‘burst out’. The dewatering structures recorded and interpreted by Owen (1996), are similar in structure to the ones recorded in this study and offer some explanation as to how they formed.

Interpretation of the D15 fluid-escape structure

Figure 5.28 (below) is an interpretation of how the D15 fluid escape structure formed. In Fig. 5.28a an un-deformed sand layer is subjected to overburden pressure (Fig. 5.28a and b) from overlying sediments in a fluidised state. Below the sand bed, finer grained sediments also in a fluidised state add to the stress on the sand bed. A breach (Fig. 5.28b) of the sand bed is inferred to nucleate from the underlying layers as the lipped edge (Fig. 5.28b and c) shows a paleo-direction of the fluid escape. The presence of calcite veining (Fig. 5.28c) indicates that fluid escaping from the underlying structure was rich in calcite, which is interpreted to have been re-precipitated from the dissolution of carbonate material in underlying beds.

The interpretation of fluid escape structures, using bed D15 as an example, indicates that sand layers de-watered more quickly than finer grained sediments which is a function of sorting and grain size of the sediments. Better sorted, coarser grained sediments lithified more quickly than more poorly sorted mud layers.

5.2.7 Limestone facies (Ls)

Description: Facies Ls is recorded only once, at the top of the measured section. Grey, coarse - fine grained, well cemented and poorly sorted limestone. Facies Ls lower contact is sharp, scoured, wavy and contains lenses of the underlying mud of bed E186. The dip of bed E187 varies from 51-58° and the thickness varies between 7-9m. Convolute structures overlie the basal contact and develop into large scale mud lens structures (1m in length, 30cm in width). Rounded pebbles comprise part of the lower
4.5m of E187, with pebbles being rounded, 2-3mm in size and having no preferred orientation and supported by a fine grained sand with carbonate cement. Bedding in E187 is crudely defined, typically graded over several meters. The upper 3m of E187 grades into a finer grained limestone with fewer pebbles present. Shells and shell fragments are present in E187. Shells and shell fragments are well preserved and are randomly oriented. Weathered surfaces of E187 are indicated by flute casts and iron oxide staining. Karst weathering is more apparent nearer the top contact with the overlying mud.

Figure 5.28 Fluid escape structure, bed D15 (167m)

Interpretation: Crudely graded and poorly sorted lithofacies Ls indicates a grain flow deposit. Large scale mud lenses and a sharp wavy lower contact indicate that at the base (lower 4.5m) Ls was transported and deposited under high energy depositional conditions sourced from the shelf given the macrofossil and coarse sediment content. Convolute structures in the lower part of Ls indicate a waning in depositional energy and the upper, finer grained 3m indicates an even lower energy depositional environment. Benthic foraminiferal data collected from the bed below the Ls lithofacies indicate a 1500-2000m depth of deposition.
5.3 Facies Successions and Bouma Sequences

Facies successions identified in this study are interpreted to be Bouma sequences. Bouma sequence terminology is firstly presented, which is then followed by examples of Bouma sequences from the measured section of this study. The term sequence is used in this study to describe sediments that are genetically-related unconformity bounded packages of strata.

5.3.1 Turbidite Bouma divisions

The italicised text below is extracted directly from Bouma (1962), and offers hypothetical interpretations for the origin, transport, and deposition of turbidites in some detail. Bouma’s interpretations use observations from the Peïra-Cava area in the French Maritime Alps (See chapter 2, Literature Review) and hypotheses from other studies of Kuenen (1951-1960). Sequences identified from the measured section that lack finer sediment intervals are still interpreted to be turbidite sequences as they are interpreted to have been transported in a fluidised state that has allowed some sediment sorting (graded bedding). The fluidised transportation mechanism in coarser deposits is interpreted to have been lacking finer material that is accounted for by Bouma $T_{c,e}$ divisions.

5.3.2 Sediment distribution

'The coarsest material will be concentrated in the front part of the current and a few finer grains will be carried along in the wake of the coarsest grains. The bulk of the finer material and some fine sand grains will tend to be concentrated in the tail of the current. The density of the sandy part at the front will be very high and will decrease upwards and towards the tail of the current. The specific weight of the front part will thus be higher than that of the back part resulting in a faster velocity in the sandy part rather than the pelitic part.'

5.3.3 Sedimentation

'During the sedimentation the current still flows past with the result that the subsequent grains of the turbidite to be deposited do not come from a higher position in the current but from a place farther behind. The result is a decrease of grain size in the upward sense
in the layer, and thus graded bedding. As the coarsest material of the nose falls out, the maximum grain size of the suspended material decreases downstream causing horizontal grading in the turbidite in the direction of the current.’

5.3.4 Sedimentary structures
‘Experiments have indicated that, with increasing current velocity over a sand bed, different stages of sand transport can be distinguished. In the case of a low velocity of the water no movement of the grains occurs. By increasing the velocity a slight transport starts, depending on the grain size of the sand. At a certain higher speed current ripples are formed. At a still greater velocity the ripples disappear and erosion starts (Menard, 1950). The various stages happen in the reverse order in a turbidity current. The current velocity decreases and the turbidity current is overloaded, so that sedimentation takes place instead of erosion. Only the front of the turbidity current may have an erosional influence on the underlying layer and may leave its marks in the clay causing them to fill up as casts... Gradually the velocity of the current decreases so far that the turbulences lose a great deal of their power and traction exerts more influence on the grains.’

Bouma’s (1962) hypothetical explanations for the origin, transport and deposition of turbidites are used in this study for paleo-environmental interpretations. This study assumes that similar conditions outlined above were operating when sediments of the Taylors and Diggers Hill members were deposited.

5.4 Bouma divisions of this study
Ten examples of Bouma sequences are presented here. No complete Bouma sequences ($T_1 = T_{a-e}$ divisions) are recorded from the measured section. All $T_e$ divisions are truncated (the top is eroded).

5.4.1 Taylors Member Bouma sequences (fig. 5.29)
Sediments of the Taylors Member crudely show some of the features of truncated Bouma divisions, (typically $T_{a-b}$ and $T_e$ divisions and rarely $T_{a-c}$ and $T_e$ divisions). Four examples of Taylors Member turbidite sequences are shown in figure 5.29a-d. Fig. 5.29a and 5.29d
are good examples of a $T_{a-c}$, $T_e$ divisions. These are relatively rare in the Taylors Member, as few sequences contain readily identifiable sedimentary structures.

Taylors Member beds also have a more consistent grain size that tends to reflect fewer sedimentary structures, as opposed to Diggers Hill Member sediments that show a greater range in sediment texture. Figures 5.29b and 5.29c are more typical of examples of Taylors Member Bouma sequences. Their sedimentary features are simple and, within the Bouma classification scheme, are confined to graded ($T_a$), and laminar ($T_b$) sand beds overlain by ($T_e$) mud beds. Sedimentary features that do not fit within Bouma’s classification are restricted to burrowing, concretionary horizons, and calcite veining. These are interpreted to be largely post-depositional features. A sedimentary feature commonly shared by most beds of the Taylors Member is that they contain a basal shell bed of 3-5mm reworked, abraded, disarticulated shells (of variable preservation). This basal shell layer is included as a constituent texture in the graded interval ($T_a$) of the classification scheme.

5.4.2 Diggers Hill Member Bouma sequences (fig. 5.30)

Sediments of the Diggers Hill Member show clear examples of truncated Bouma sequences. Sequences are a mix of $T_{a-c}$, $T_e$ and $T_{a-b}$, $T_e$ divisions. Graded bedding is clearly visible, as are laminations that show normal grading. Sedimentary structures are also readily visible and are usually represented by convolute bedding.

Six examples of Bouma sequences are shown in figure 5.30e-j. Fig. 5.30e and 5.30f are examples of $T_{a-c}$, $T_e$ sequences and are common. Fig. 5.30g-i are also typical divisions seen in the Member. Fig. 5.30j is a stacked sequence showing $T_{a-b}$, $T_e$ divisions. The repetitive stacking (thin bedded turbidites, typically less than 5cm) seen is limited to the upper 150m of the Member. Fig. 5.30j also shows the relatively short stratigraphic interval in which Bouma sequences can be stacked and repeated. Diggers Hill Member sediments are predominantly bioclastic. Bioclastic sediments are restricted to the sand beds of turbidite sequences.
Figure 5.29 Taylors Member Bouma sequences

Figures 5.29a-d. Bouma sequences from the Taylors Member. $T_{a-b}$, $T_b$ sequences are typical but $T_{a-c}$, $T_a$ sequences are also found but are less common. All sequences of the Taylors Member have a $T_a$ sequence that gradationally overlies $T_{a-c}$ and $T_{a-b}$ sequences. Figure 5.29d is the one of the uppermost sequences from the Taylors Member and is a good example of a $T_{a-c}$, $T_a$ sequence. All heights are in cm.
Figure 5.30 Diggers Hill Member Bouma sequences

<table>
<thead>
<tr>
<th>Figure</th>
<th>Lithology</th>
<th>Graphic Log</th>
</tr>
</thead>
<tbody>
<tr>
<td>e.</td>
<td>F85 &amp; F86 (137m) $T_{e1} T_{a}$</td>
<td><img src="image1" alt="Lithology Graphic Log" /></td>
</tr>
<tr>
<td>f.</td>
<td>D83 &amp; D84 (137m) $T_{e1} T_{a}$</td>
<td><img src="image2" alt="Lithology Graphic Log" /></td>
</tr>
<tr>
<td>g.</td>
<td>D107 &amp; D108 (202m) $T_{e1} T_{a}$</td>
<td><img src="image3" alt="Lithology Graphic Log" /></td>
</tr>
<tr>
<td>h.</td>
<td>G09 &amp; G10 (250m) $T_{e1} T_{a}$</td>
<td><img src="image4" alt="Lithology Graphic Log" /></td>
</tr>
<tr>
<td>i.</td>
<td>E43 &amp; E44 (385m) $T_{e1} T_{a}$</td>
<td><img src="image5" alt="Lithology Graphic Log" /></td>
</tr>
</tbody>
</table>

Figures 5.30e-j. Bouma sequences from the Diggers Hill Member. $T_{e1} T_{a}$ sequences are as common as $T_{a1b} T_{a}$ sequences. Fig. 5.30j is a suite of Bouma sequences and shows the repetitive stacked nature of Diggers Hill Member turbidites that occur over a relatively short distance. All heights are in cm.
Sand beds comprising shelly material are graded, laminated and sometimes contain convolute structures. Shelly material is supported by a fine siliciclastic sand matrix in most instances.

Other features observed in these beds include rip up clasts of mud, presumably from the underlying mud layer, which is the underlying $T_e$ division (fig. 5.30g). Rip up clasts are rare, but are lensed in the bedding direction. Rip up clasts are easily observed in Diggers Hill sediments as the grey mud colour contrasts brown, grey, yellow colours of the $T_b$, $T_c$ sequences. Burrowing is also observed in sediments of the Diggers Hill Member. The energy required to rip up clasts of mud contrasts with the lack of energy necessary for burrowing (fig. 5.30g). This indicates a rapid decrease in energy over a relatively small stratigraphic height, indicating that the transition from erosion to sedimentation is rapid.

**Percentage of truncated Bouma sequences from the measured section**

![Pie chart showing the occurrence of truncated Bouma sequences](image)

* $T_{ab}, T_o$ 45% of all sequences
* $T_{ac}, T_o$ 30% of all sequences
* $T_o, T_o$ 20% of all sequences
* $T_{ac}, T_o$ 5% of all sequences

Figure 5.31 Pie chart of the occurrence of truncated Bouma sequences identified from the measured section.

**5.5 Sedimentary motifs**

Two main types of sequence are recognised and are presented as idealised motifs (facies models). The idealised motifs include all turbidite sequences of the Taylors (siliciclastic sand beds) and Diggers Hill (bioclastic sand beds) members. Motifs are largely based on lithostratigraphic criteria and interpretations made using those criteria. Thin section data is used to augment observations made in the field. All sequences observed in this study are bounded by erosional contacts.
5.5.1 Thin Section data – Siliciclastic motif (figure 5.32a-f)

Basal Sil. A thin section belongs to the lower $T_a$ Bouma division and is coarse grained, contains angular, clast supported rock fragments with a minor microcrystalline / carbonate matrix. Rock fragments are quartzose, glauconitic and have minor carbonate fragments and opaques. No bedding or grain orientation is observed in the thin sections of basal Sil. A.

Thin sections Sil. B, C, and D are inferred to represent the $T_b$ Bouma division and are finer grained and better sorted than Sil. A. Crude layering is inferred from the weak alignment of grain long axes in thin section Sil. C and D. The mineralogy of Sil. B, C, and D is consistent with Sil. A.

Thin sections Sil. E and F are inferred to represent the $T_e$ division. These two thin sections are fine grained and have a microcrystalline matrix. Bedding is inferred from the alignment of grain long axes. The mineralogy of Sil. E and F is the same as Sil. A. Sil. F includes large coal lens that may indicate a terrestrial origin for some sediments of this deposit.

5.5.2 Thin section data – Bioclastic motif (figure 5.33a-f)

Thin sections Carb. A, B, and C are interpreted to represent the $T_{a-e}$ Bouma divisions. The basal Carb. A thin section shows a chaotically bedded, poorly sorted, coarse grained deposit with sub-angular to sub-rounded quartz rock fragments and grains of glaucony supported by a fine grained (microcrystalline) calcite matrix. Thin sections Carb. B and C show a finer grained, better sorted sand layer, with a weak alignment of grain long axes supported by a fine grained (microcrystalline) calcite matrix. All three thin sections share the same mineralogy.

Thin section Carb. D is interpreted to represent the lower $T_e$ Bouma sub division. Carb. D shows moderately well sorted sand with some rounded rock fragments. Rock fragments are composed of predominantly quartz with minor glaucony and opaque grains and supported by a microcrystalline quartz matrix. Weakly graded beds can also be seen in
Carbo D and show some alignment of grain long axes. Rounded opaque grains may be coal grains that would indicate a terrestrial source of for some of the sediment.

Thin sections Carbo E and F are from the upper $T_e$ Bouma divisions and show a well sorted muddy silt containing larger grains with aligned long axes that show a bedding direction. Thin section Carbo E clearly shows graded bedding with a fining up sequence inferred. Carbo F shows what is interpreted to be aligned coal lenses that also show a bedding direction and may be derived from terrestrial material. Both Carbo E and F are fine grained and mostly micro-crystalline and are inferred to have the same mineralogy as mentioned in Carbo A-D.

5.5.3 Summary of thin section data – Siliciclastic and Bioclastic motifs
Thin sections have been collected through turbidite sequences of the Taylors and Diggers Hill members. The following points summarise the findings from thin section analysis:

- Basal $T_{a-c}$ divisions have chaotic-graded bedding. Graded bedding is more apparent in better sorted layers, typically as the $T_s$ division fines upwards.
- Basal $T_{a-c}$ divisions record a transition from clast supported bedding to a matrix supported bedding, which is further evidence of fining up.
- Matrix supported beds comprise a microcrystalline calcite matrix that may have resulted from the dissolution of carbonate material.
- The $T_s$ Bouma division is poorly sorted and the $T_{b-c}$ Bouma divisions are better sorted.
- Thin section analysis of Taylors and Diggers Hill member Bouma divisions show sediments fining up from basal $T_{a-c}$ divisions which is also reflected by the alignment of grain long axes.
- Finer $T_e$ Bouma divisions contain coal lenses indicating a possible terrestrial origin for some of the sediments.

5.6 Interpretations of the motif data
Basal, graded sand layers of Siliciclastic and bioclastic motifs are interpreted to be $T_s$ Bouma divisions and are inferred to have had a sediment source on the shelf or the shelf
break of the Waicoe sub-basin. $T_{bc}$ divisions of the motifs are interpreted to have sourced sediment on the shelf slope of the sub-basin. $T_e$ divisions of the motifs are interpreted to have sourced sediment from the rain out of fine grained material and in some instances at the base of coarser $T_e$ division sediments are interpreted to have sourced sediment from lower parts of the shelf slope. Light grey coloured muds of the $T_e$ Bouma division are inferred to be the quietest depositional environment.
Figure 5.32a-f. Taylors Member type motif. Thin sections are presented in plain polarised light (PP), and cross polarised light (XP). A 10x magnification is used. See text for descriptions.
Figure 5.32 continued

**Sil. C**
- Crudely graded bedding
- Microcrystalline matrix
- Rock fragment, quartz.

**Sil. D**
- Crudely graded bedding
- Rock fragment, quartz.
- Microcrystalline matrix
- Moderately well sorted

**Sil. E**
- Alignment of grain long axes
- Graded bedding
- Rounded opaque clasts
- Microcrystalline matrix

**Sil. F**
- Alignment of grain long axes
- Microcrystalline matrix
- Coal streak / lens
- Fine grained
- Rock fragment, quartz.
Figure 5.33 a-f. Diggers Hill Member type motif. All thin section images use a 10x objective except Carb. A. See text for descriptions.
Carb. C
Rounded RF, Qz, RF, Gl.
Moderately well sorted
Microcrystalline matrix
RF, Qz

Carb. D
Graded bedding
Rounded opaque clasts
Moderately well sorted
Microcrystalline matrix
Rounded RF, Qz, RF, Gl.

Carb. E
Well sorted
Alignment of grain long axes
Microcrystalline matrix
Graded bedding

Carb. F
Microcrystalline matrix
Alignment of grain long axes
Coal streak / lens
The Waicoe Sub-basin

The distribution of sediment is affected by basin morphology (Bouma, 2001). In figure 5.34 numbers 1-3 show the key basin morphological features that influence sedimentation in sedimentary basins. Bouma's (1962) sketch is inferred to have a well developed coastal plain (1), a relatively wide continental shelf (2), and a more gently sloping continental slope than that is interpreted from the Waicoe sub-basin.

The Waicoe sub-basin is interpreted as having a narrow, steep coastal plain (1), a continental shelf that is wider in the east (2), and a steep continental slope (3). This sketch illustrates a suitable high-energy depositional environment for Taylors and Diggers Hill sediments deposited off the continental shelf. In this study it is suggested that there is a condensed zone of the source areas for the Ta to Tc Bouma divisions.

Carter and Norris (1977a) used slope and current indicators (based upon the sole markings at the base of turbidite sequences) to infer that the Taylors Member sediments originated from the west, and Diggers Hill Member sediments originated from the east. This study uses their interpretation to help explain the sedimentologic differences between the Taylors and Diggers Hill members.

The arrow labelled RSL in figure 5.34 is used to show the change in relative sea level within the Waicoe sub-basin. Bouma (2004) identified that a lowering of sea level within
a basin would result in the coastline being shifted in a basinward direction and this would result in more sediment being deposited on or near the shelf break. Bouma (2004) identified global climate change and tectonic factors as important mechanisms influencing relative sea level. In this study, the shelf area of the Waicoe sub-basin and its exposure during a sea level lowering is thought to have been critical to turbidite formation beginning on the shelf break. The siliciclastic and bioclastic motifs of the Taylors and Diggers Hill members although being deep marine deposits, are thought to reflect relative sea level change experienced on shelf margins of the Waicoe sub-basin, which in turn are the triggering mechanism for slope failure on the shelf break.

5.6.1 Deep marine turbidite deposition

The depth of deposition of turbidites is identified here from paleo-ecological data of benthic foraminifera gathered from the measured section. Benthic foraminiferal assemblages indicate deepwater depositional environments for both siliciclastic and bioclastic motifs. The chart listed in figure 5.35 shows the paleo-depth changes inferred from benthic foraminifera plotted against stratigraphic height of the measured section. The red line shows the minimum inferred paleo-depth of deposition. The shallowest depth of deposition has used the shallowest level at which benthic foraminifera are thought to exist at to help establish a depth for the depositional environment of the Waicoe sub-basin.

The blue line of figure 5.35 shows the inferred paleo-depth of deposition and is a more reliable indication of the depth of deposition through the mid Lw to the lower PI? of the Waicoe sub-basin. The average depth of deposition indicated is approximately 1300m. Deeper depths of deposition beyond 1300m are indicated by Tritaxalina zealandida that indicates a 1500-2000m depth of deposition. T. zealandida appears four times in samples from the measured section grouped into two clusters. These two clusters indicate periods of basin deepening episodes at approximately 23 and 20Ma. These episodes are attributed to tectonic movement in the Waiau Basin or adjacent to it.
5.6.2 Paleogeography of the Waicoe sub-basin
Sedimentology, biostratigraphy, and paleo-ecology are used in this study to help make an accurate paleogeographic history for part of the Waiau Basin, the Waicoe sub-basin. The sub-basin is used by Carter and Norris (2005) and refers to a small basin occupying an area within the larger Waiau Basin. This study identifies the Waicoe sub-basin as occupying the northern reaches of its larger parent basin (see fig. 5.36 and 5.37). Paleogeographical interpretations of the Waicoe sub-basin integrates interpretations of Turnbull and Allibone (1993), Carter and Norris (1977a & 2005) and paleo-depth data (Morgans, pers comm. 2005) inferred from benthic foraminifera.

Figures 5.36 and 5.37 utilise the paleo-depth interpretations of the chart presented in figure 5.35 and help build a basin profile of the Waiau Basin by indicating that the basin was deep (1300m+). The morphology of the two basins shows the larger Waiau Basin as being as deep as the Waicoe sub-basin but considerably wider with a broad base that can account for the distribution of sediments like the Waicoe Formation. Understanding the morphology of the basins involves depositional history interpretations of Lw-Pl strata. Figure 5.38 is a cross section from Carter and Norris (1977a) and show the lithostratigraphy of the late Eocene through to the Miocene incorporating the Taylors and Diggers Hill members.

5.6.3 Eocene to Miocene environment of deposition in the Waicoe sub-basin
The inferred depositional environment of the Ligar Breccia Member is a marginal marine (at the base) - marine (upper contact), mass flow deposited, debris flow and infers a proximal fan deposit (Carter and Norris, 2005). The Sunnyside Conglomerate Member overlies the Ligar Breccia Member and is fully marine (Carter and Norris, 2005), and comprises well rounded clasts that form clast supported beds. The Sunnyside Conglomerate Member is described as a fining up sequence that infers a deepening depositional environment (Carter and Norris, 2005).
Figure 5.35 Interpreted paleo-depths of the measured section

<table>
<thead>
<tr>
<th>Strat. height</th>
<th>Species</th>
<th>Age</th>
<th>Inferred Paleo-depth zone</th>
<th>Depth</th>
<th>Minimum inferred depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 m</td>
<td>Valvulina penumata</td>
<td>Mid Lw</td>
<td>Bathypelagic</td>
<td>800-1000 m</td>
<td></td>
</tr>
<tr>
<td>59 m</td>
<td>Plumula revi</td>
<td>Mid Lw</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>59 m</td>
<td>Gyrinoides nesoldani</td>
<td>Mid Lw</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>64 m</td>
<td>Pleurostomella sp.</td>
<td>Mid Lw</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>64 m</td>
<td>Eggerella bradyi</td>
<td>Mid Lw</td>
<td>Meso-Bathypelagic</td>
<td>600-800 m</td>
<td></td>
</tr>
<tr>
<td>64 m</td>
<td>K. novozelandica</td>
<td>Mid Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>144 m</td>
<td>Karrievia bradyi</td>
<td>Mid Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>164 m</td>
<td>(no deepwater taxa recovered)</td>
<td>Mid Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>200 m</td>
<td>G. nesoldani</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>200 m</td>
<td>K. novozelandica</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>229 m</td>
<td>T. zelandica</td>
<td>Mid up Lw</td>
<td>Bathypelagic</td>
<td>1500-2000 m</td>
<td></td>
</tr>
<tr>
<td>229 m</td>
<td>Chlaronella rosslea</td>
<td>Mid up Lw</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>229 m</td>
<td>G. nesoldani</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>600-800 m</td>
<td></td>
</tr>
<tr>
<td>229 m</td>
<td>K. novozelandica</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>229 m</td>
<td>K. chlostoma</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>245 m</td>
<td>G. nesoldani</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>T. zelandica</td>
<td>Mid up Lw</td>
<td>Bathypelagic</td>
<td>1500-2000 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>V. penumata</td>
<td>Mid up Lw</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>Pleurostomella sp.</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>G. nesoldani</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>K. bradyi</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>Rotala mariae</td>
<td>Mid up Lw</td>
<td>Epiphanes†</td>
<td>70-100 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>Ceratoneula novicosta</td>
<td>Mid up Lw</td>
<td>Epiphanes†</td>
<td>0.5 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>Distontella tenacissima</td>
<td>Mid up Lw</td>
<td>Epiphanes†</td>
<td>0.5-10 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>Epiphyllum charlingense</td>
<td>Mid up Lw</td>
<td>Epiphanes†</td>
<td>0.5 m</td>
<td></td>
</tr>
<tr>
<td>250 m</td>
<td>Bryozoa</td>
<td>Mid up Lw</td>
<td>Epiphanes†</td>
<td>7shelf</td>
<td></td>
</tr>
<tr>
<td>251 m</td>
<td>(no deepwater taxa recovered)</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>264 m</td>
<td>Chlaronella rosslea</td>
<td>Mid up Lw</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>264 m</td>
<td>Pleurostomella sp.</td>
<td>Mid up Lw</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>264 m</td>
<td>Eggerella bradyi</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>800-1000 m</td>
<td></td>
</tr>
<tr>
<td>264 m</td>
<td>G. nesoldani</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>264 m</td>
<td>K. novozelandica</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>345 m</td>
<td>Pleurostomella sp.</td>
<td>Mid up Lw</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>345 m</td>
<td>G. nesoldani</td>
<td>Mid up Lw</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>368 m</td>
<td>Obéclides rossetanius</td>
<td>Po</td>
<td>Bathypelagic</td>
<td>1000 m</td>
<td></td>
</tr>
<tr>
<td>368 m</td>
<td>V. penumata</td>
<td>Po</td>
<td>Bathypelagic</td>
<td>800-1000 m</td>
<td></td>
</tr>
<tr>
<td>368 m</td>
<td>Pleurostomella sp.</td>
<td>Po</td>
<td>Bathypelagic</td>
<td>800 m</td>
<td></td>
</tr>
<tr>
<td>368 m</td>
<td>G. nesoldani</td>
<td>Po</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>368 m</td>
<td>K. bradyi</td>
<td>Po</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>368 m</td>
<td>K. novozelandica</td>
<td>Po</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>371 m</td>
<td>Bryozoa</td>
<td>Po</td>
<td>Epiphanes†</td>
<td>7shelf</td>
<td></td>
</tr>
<tr>
<td>371 m</td>
<td>(no deepwater taxa recovered)</td>
<td>Po</td>
<td>Meso-Bathypelagic</td>
<td>400-600 m</td>
<td></td>
</tr>
<tr>
<td>399 m</td>
<td>T. zelandica</td>
<td>Po</td>
<td>Bathypelagic</td>
<td>1500-2000 m</td>
<td></td>
</tr>
<tr>
<td>399 m</td>
<td>Cribrotritulus ornatus</td>
<td>Po</td>
<td>Epiphanes†</td>
<td>6-100 m</td>
<td></td>
</tr>
<tr>
<td>429 m</td>
<td>G. nesoldani</td>
<td>Po</td>
<td>Meso-Bathypelagic</td>
<td>600 m</td>
<td></td>
</tr>
<tr>
<td>470 m</td>
<td>T. zelandica</td>
<td>Po</td>
<td>Bathypelagic</td>
<td>1500-2000 m</td>
<td></td>
</tr>
</tbody>
</table>

Minimum inferred paleo-depth
Inferred Paleo-depth
Inferred species depth range
Paleogeography of the Waiau Basin and the Waicoe Sub-basin during the late Oligocene to early Miocene.
The Ligar Breccia and Sunnyside Conglomerate members are derived from the Fiordland Complex Mountains that lie on the Western side of the sub-basin, indicated by their petrography and paleo-current indicators (Carter and Norris, 2005). This study suggests that the Taylors Member is a transitional body of sediment that has recorded the change from a deep water fan siliciclastic sequence of turbidites to a deep water fan carbonate sequence. The mechanism of deposition (turbidity current) and depositional environment remain the same but the origin of the sediment shifts from the west to the eastern margins of the basin (as also suggested by Carter and Norris, 2005).

The inferred small geometry of the sub-basin allows for a relatively rapid shift (1-2Ma) in sediment source to occur as the biostratigraphic and lithostratigraphic data of this study indicate. The small shelf area of the sub-basin would also be affected dramatically by changes in relative sea level. A change in relative sea level would sub-aerially expose or drown a large area of shelf.

The Waicoe sub-basin contains the only known occurrences of the Taylors and Diggers Hill members of the Blackmount and McIvor formations, respectively. The two members are interpreted to be fan deposits, specifically turbidite deposits. Bouma (2001) identified two major types of fan deposits, with deposits being either coarse grained or fine grained. The Waicoe sub-basin lies between two good sources of sediment - the mountains of the south-eastern Fiordland Complex and the Takitimu Mountains that lie farther east (see fig. 5.37), which are a part of an active tectonic margin. Coarse grained submarine fans are related to sediment sources relatively close to the shoreline, occupying a poorly developed coastal plain that also contains small deltas (Bouma, 2001). The offshore basin associated with coarse grained fan deposits is typically smaller in size when compared to the basins in which fine grained fan deposits are found (Bouma, 2001).

The Waicoe Formation comprises fine grained silts and laminated muds that have been interpreted as being basin fill deposits, deposited in quiescent, deep waters (Carter and Norris, 2005). The Waicoe Formation is interpreted to be the dominant, basin fill material during the Lw-Pl in the Waiau Basin (Carter and Norris, 2005). The Taylors Member of
the Blackmount Formation is interpreted in this study as being a lateral equivalent of the Waicoe Formation (similar age and composition) but being found only in the Waicoe sub-basin.

The Taylors Member is only found in the Waicoe sub-basin and is interpreted to occupy a different depositional environment compared to its lateral equivalent (the Waicoe Formation) in the larger Waiau Basin. Taylors Member sediments are interpreted as being turbidite fan deposits requiring a higher energy of deposition. This high energy of deposition is inferred to come from steep shelf slopes that lie adjacent to a relatively narrow continental shelf that had little accommodation space for sediment. Poorly developed river deltas are also thought to occupy part of the continental shelf. River deltas are poorly developed in the Waicoe sub-basin due to the narrow continental shelf and the relatively steep coastal plain (see figures 5.36 to 5.38).

The Diggers Hill Member is also only found in the Waicoe sub-basin and its distribution can be explained in the same way as the Taylors Member, as being high energy fan deposits.

5.6.4 Summary of depositional history

A summary chart (fig. 5.39) presents a basin evolution summary of the Waicoe sub-basin. The evolution of the sub-basin is based on data collected and analysed in this study and data from Carter and Norris (1977a and 2005). Basin deepening is inferred to have taken place during a constant phase of relative sea level rise that progressively drowned the sub-basin. The sub-basin interpreted as occupying the northern reaches of its larger parent, the Waiau Basin would have been drowned last. The complete drowning of the sub-basin is inferred to have taken 1-2Ma (Sunnyside – Taylors member transition), in which a rapid rise in relative sea level would have occurred. The apparent rapidity of the relative sea level rise is due in part to the narrow and steep geometry of the sub-basin. The shift in sediment source (from west to east) within the Waicoe sub-basin recorded by the Taylors Member and suggests that siliciclastic sediments may have occupied a narrow continental shelf that allowed for sorting of sediments aided by what Bouma (2001)
describes as longshore drift. This carbonate material is inferred to be sourced from a larger shelf area able to produce and supply a source of bioclastic material that became the dominant basin fill during the early Miocene in the Waicoe sub-basin.

Petrographic data presented in this study suggests that sediments continued to be sourced from the West but its siliciclastic lithology was diluted with the more abundant bioclastic material sourced from the eastern margins of the Waicoe sub-basin that formed the Diggers Hill Member.
Figure 5.39 Evolution of the Waicoe sub-basin

<table>
<thead>
<tr>
<th>Age</th>
<th>Lithostratigraphic nomenclature, Waicoe Sub-basin</th>
<th>Biostratigraphy (this study)</th>
<th>Sedimentation rate (m/kyr)</th>
<th>Origin</th>
<th>Basin Geometry</th>
<th>Inferred paleo depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligocene</td>
<td>Blackmount</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Whangaroaian (LwL)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duricocoonian (LtL)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waikatanian (Lt)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Otaian (Ppe)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Altonian (P)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miocene</td>
<td>McIvor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sunnyside Conglomerate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Taylors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Doggers Hill</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gondearg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sunnyside Conglomerate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S. novozelandica</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gl. biwaan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gl. waiwaiui</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The sequence of strata this study covers

* Sediment source direction, W vs E

Deep marine, distal fan deposit

Deep marine, distal fan deposit

Deep marine, distal fan deposit

Marine, mass flow deposit inferred to be a turbidity current deposit

Debris flow that is inferred to be a proximal fan deposit
Chapter 6 - Cyclicity

6.1 Aims and hypothesis of this chapter

This chapter evaluates the cyclostratigraphy of the measured section in order to establish whether orbital parameters of cyclicity described in chapter 1 (Introduction) are represented as sedimentary cycles within the measured section. Biostratigraphic data indicate that the sedimentation rate at the bottom of the measured section was more than twice the rate at the top of the measured section and data used in the cyclostratigraphic evaluation of the measured section might be able to refine the biostratigraphic sedimentation rates. Spectra are analysed using a program called Sigview (http://www.sigview.com).

Shanmugman et al. (1985) hypothesised that sedimentation on most modern submarine fans has been controlled by Plio-Pleistocene glacio-eustatic sea level fluctuations. In this study, a similar interpretation is used as the growth and decay of ice sheets during the Oligocene to modern 'ice house world' also resulted in glacio-eustatic sea level change (Miller et al., 1991). Sea level change is thought to be an influence on destabilisation of the shelf break which is where turbidites are interpreted to nucleate from. Thus changes in global sea level during the late Oligocene – early Miocene may be represented in the Blackmount and McIvor formation turbidite sequences.

6.2 Methods

A. Data collection: A centimetre scale digital stratigraphic log of the measured section was made using Corel Draw (appendix A3). The digital stratigraphic log was used to estimate mean sediment grain size from the measured section. 4224 mean grain size estimates were taken at 10cm intervals, in phi units using a grain size ruler (figure 6.40). The grain size ruler is a log scale of gravel – sand – mud grain sizes. Grain size measurements in this study use a visual mean that assumes sand beds having grain sizes ranging from -2 to -2.5 phi and light grey mud beds that overlie sand beds have a grain size close to 7 to 8 phi. The visual estimate was confirmed from thin section analysis.
Gradational contacts were recorded in the field and plotted on the log of the measured section and the grain size ruler was used to estimate mean grain size across the gradational contact. Mean grain size estimates were entered into an Excel spreadsheet against stratigraphic height. The Excel spreadsheet was converted to a tab delimited text file and imported into Sigview.

B. Spectral analysis: The Sigview program works best with evenly spaced data, like the data set of this study (see fig. 6.41). The data set was evenly divided into: 0-105.6, 105.6-211.2, 211.2-316.8, and 316.8 - 422.4m (excluding the un-logged section 280-320m) sections (again excluding the un-logged section 280-320m). Overlapping data sets were then compiled at: 52.8-158.4, 158.4-264, and 264-369.6m sections. Spectral analyses of the overlapping data sets were used to validate the spectral analysis results. Spectral analysis was also undertaken on the lower half (0-211.2m), and the upper half (211.2-422.4m) of the measured section, and finally on the whole measured section (0-422.4m).

D. Tapering data: The effect of tapering data can be described as reducing the presence of high frequencies, (Muller and MacDonald, 2000). A Hanning Window is used in this study to taper or smooth data, and, with Sigview, the user can set the length of the Hanning Window. Adjustment of the Hanning Window length results in smoother data plots that lack higher frequencies. Figure 6.42 shows two examples (Hanning Window length of 50 and 150) of the Hanning Window taper applied to the grain size data from the whole measured section. The Hanning Window taper was applied to the data sets described in section B, above, after spectral analysis had been undertaken using a Hanning Window length of 20.

E. Spectral peaks: The Sigview program graphs data with spectral power (y axis) plotted against cycle frequency (x axis, see figure 6.43 below), and the program also allows the user to copy the spectral data of the graph to an Excel file.
Figure 6.40 The sediment grain size ruler

A. B.

- Mud
- Sand
- Gravel
- Silt
- Very clay
- Coarse sand
- Pink pebble
- Medium sand
- Fine sand
- Very coarse sand
- Granule
- Pebble

Figure 6.41 The division of the measured section for spectral analysis

1. Spectral analysis of section 1 (0-105.6m)
2. Spectral analysis of section 2 (105.6-211.2m)
3. Spectral analysis of section 3 (211.2-316.8m)
4. Spectral analysis of section 4 (316.8-422.4m)
Figure 6.42 Smoothed sediment texture plotted against stratigraphic height of the measured section.
Figure 6.43 Spectral analysis plot of section 1 (0-105.6m) identifying 14.49, 11.11, 4.81, 2.8, 2.54, 2.22m cycle frequencies.

F. Sedimentation rate calibration: Spectral peaks were identified as cycles per metre for each section of data analysed (see figure 6.43). Ratios of spectral peaks with cycle frequencies were matched to ratios of orbital parameters of cyclicity, for example using the spectral analysis of section 1 (0-105.6m), a cycle frequency ratio of 14.49:11.11:4.81:2.8:2.54:2.22m cycles matched a 1:1.31:3.04:5.2:5.6:6.5 ratio or a 125:95:41:24:22:19 ratio of orbital parameters of cyclicity.

Cycles per metre were multiplied by an approximated sedimentation rate based on biostratigraphy, which gave a cycle frequency in years. Spectral peaks that had high spectral power were considered more reliable or valid cycle frequencies. Spectral analysis data is presented in figure 6.50.

6.3 Spectral analysis

Muller and MacDonald (2000) recognised that spectral analysis has been absolutely key in establishing the importance of astronomical forcing in climate studies but they also recognised that spectral analyses entail assumptions, and that the differences in these
Figure 6.44 Overlapping plots of spectral analysis from the measured section showing the distribution of high and low frequencies.
assumptions often account for different results. If the assumptions are known by the analyst then reasonable conclusions can be made (Muller and MacDonald, 2000).

Figure 6.44 presents spectral analyses of all sections that have been outlined in figure 6.41. Visual authentication of coincident spectral peaks in overlapping data sets using figure 6.44 is difficult given the number of data points present from the sections of data.

6.3.1 Spliced data sets
Spectral analysis of sections 3 (211.2-316.8m), C (264-369.6m), 211.2-422.4m, and the 0-422.4m section comprise a spliced section of data, as the un-logged section of this study cannot be used for analysis. This gap in the record is shown in figure 6.42 and the spectral analysis of the sections above may contain spectral peaks resulting as an artefact of this splicing.

6.3.2 Spectral peaks
The spectral peaks between narrow and split, single and narrow, and broad range in shape (figure 6.45). Single narrow peaks indicate a single cycle frequency; split narrow peaks suggest that there may be some cycle frequency overlap. Narrow peaks (split and single) typically have more spectral power than broad peaks which are usually lower frequency cycles and are less likely to represent orbital parameters of cycllicity.

![Figure 6.45 Spectral peak shapes of grain size data from the measured section.](image)

6.4 Interpretations – identifying orbital parameters of cycllicity
Orbital parameters of cycllicity that have been identified from measured sections of data are presented in a set of tables shown in figure 6.46. The data in figure 6.46 present calibrated sedimentation rates and cycle frequencies that match orbital parameters of cycllicity. The orbital parameters that are highlighted have high spectral power suggesting
that they were potential influences on sedimentation recorded in that part of the measured section. Spectral analysis data used in this chapter is presented in appendix A3 of this study.

Spectral peaks with orbital cycle frequencies identified in figures 6.47, 6.48, and 6.49 were used to calibrate sedimentation rates for the measured section by using the ratio system that divided the orbital parameter by the cycle frequency, for example in section 1 (0-105.6m) - 125 thousand year (kyr) eccentricity cycle is divided by a 14.49m cycle, resulting in a sedimentation rate of 1 metre of sediment / 8600 kyr. Sedimentation rates derived from spectral analysis are similar to those derived from biostratigraphic analysis (at the base approximately 1m / 7000 kyr, and at the top 1m / 22000 kyr). Figure 6.49 presents the calibrated sedimentation rates from sections 1-4, and for sections 0-211.2m; 211.2-422.4m of the measured section. Spectral analysis of sections of data has yielded spectral peaks that imply orbital parameters of cyclicity.

Figure 6.46 Tables of orbital parameters identified using spectral analysis and the ratio system described in the methods section of this chapter. Calibrated sedimentation rates are also presented. Bold lettering identifies orbital parameters with relatively high spectral power thought to be recorded by sediments.

In sections 6.4.1-6.4.9, below, cycle frequencies and their spectral power (in brackets) are presented. The ratio of cycle frequencies matches a ratio of orbital parameters of cyclicity in most instances. High spectral power of orbital parameters of cyclicity suggests that
Figure 6.47 Spectral analysis of sections 1-4
Figure 6.48 Spectral analysis of sections A-C
they were recorded by sediments of the measured section. Conversely, low spectral power of orbital parameters of cyclicity suggests that they were not recorded by sediments of the measured section. Interpretations presented below identify orbital parameters thought to be recorded in the sedimentary record of the measured section.

6.4.1 Orbital parameters of cyclicity from section 1 (0-105.6m)
Six spectral peaks that correspond to orbital parameters of cyclicity are identified from section 1 and they are at 14.49m (0.56), 11.11m (0.824), 4.81m (0.354), 2.8m (0.157), 2.54m (0.158), and 2.22m (0.198), with orbital periodicities of 125, 95, 41, 24, 22, and 19 kyr cycles, respectively. The relatively high spectral power of the 125, 95, 41, and 19 kyr cycles suggests that they were potential influences on sedimentation processes in the 0-105.6m part of the measured section at the time of deposition.

6.4.2 Orbital parameters of cyclicity from section 2 (105.6-211.2m)
Three spectral peaks with orbital periodicities are identified from section 2 and are at 9.62m (0.655), 7.19m (0.638), and 3.13m (0.27). The peaks correspond to 125, 95, and 41 kyr cycles (or close to them), respectively. The relatively high spectral power of the 125 and 95 kyr cycles suggests that they were a potential influence on sedimentation processes in the 105.6-211.2m part of the measured section at the time of deposition.

6.4.3 Orbital parameters of cyclicity from Section 3 (211.2-316.8m)
Three spectral peaks with orbital periodicities are identified from section 3, and are at: 9.09m (0.627), 6.8m (0.354), and 3m (0.092), and correspond to 125, 95, and 41 kyr cycles (or close to them), respectively. The relatively high spectral power of the 125 and 95 kyr cycles suggests that they were a potential influence on sedimentation processes in the 211.2-316.8m part of the measured section at the time of deposition.

6.4.4 Orbital parameters of cyclicity from Section 4 (316.8-422.4m)
Two spectral peaks are identified from section 4 with periodicities of 18.18m (0.588) and 5.78m (0.261) correspond to orbital periodicities of 400 and 125 kyr, respectively. The presence of a 400 kyr cycle indicates a major shift toward lower frequency orbital
parameters of cyclicity. The high spectral power of the 400kyr cycle suggests that it was a potential influence on sedimentation processes in the 316.8-422.4m part of the measured section. The spectral power of the 125kry cycle is relatively high when compared to orbital parameters of cyclicity identified in sections 1, 2, and 3 and it can still be considered a potential influence on sedimentation processes in the 316.8-422.4m section but it is not as significant as the 400kyr cycle.

6.4.5 Orbital parameters of cyclicity from Section A (52.8-158.4m)
Three spectral peaks are identified from section A with periodicities of 13.33m (0.588), 4.41m (0.196), and 2.62m (0.144). These periodicities correspond to 125, 41, and 24kyr cycles, respectively. The relatively high spectral power of the 125 and 41kyr cycles suggests that they were potential influences on sedimentation processes in the 52.8-158.4m part of the measured section at the time of deposition.

6.4.6 Orbital parameters of cyclicity from Section B (158.4-264m)
One spectral peak with a periodicity of 9.43m (0.343) matches an orbital periodicity of 125kyr cycle (or close to it). The spectral power of the 125kyr cycle is relatively moderate when compared to the spectral power of other orbital parameters of cyclicity identified in the above text. The potential influence of the 125kry cycle from the 158.4-264m part of the measured section on sedimentation processes is unresolved.

6.4.7 Orbital parameters of cyclicity from Section C (264-316.9m)
Three spectral peaks are identified from section C and are at periodicities of 6.71m (0.454), 5.08m (0.136), and 2.21m (0.128). These peaks correspond to 125, 95, and 41kyr cycles, respectively. The high spectral power of the 125kyr cycle suggests that it was a potential influence on sedimentation processes in the 264-316.8m part of the measured section at the time of deposition.

6.4.8 Orbital parameters of cyclicity from 0-211.2m Section
Six spectral peaks are identified from the 0-211.2m part of the measured section with periodicities of 125m (0.48), 41.67m (0.49), 13.16m (0.518), 4.37m (0.152), 2.54m
Figure 6.49 Spectral analysis of sections 0-211.2, 211.2-422.4m and the whole measured section.
(0.126), and 2.04m (0.117). These peaks correspond to a 1.2myr cycle, 400, 125, 41, 24, and 19kyr orbital parameters of cyclicity, respectively.

The high spectral power of the 400 and 125kyr cycles suggests that they were potential influences on sedimentation processes in the 0-211.2m part of the measured section at the time of deposition. The 1.2myr cycle is not suggested as a potential influence on sedimentation processes in the 0-211.2m part of the measured section at the time of deposition as it would have a 125m cycle thickness that would only be recorded once in the interval analysed.

6.4.9 Orbital parameters of cyclicity from 211.2-422.4m Section
Four spectral peaks are identified from the 211.2-422.4m part of the measured section and have periodicities of 22.73m (0.396), 7.14m (0.258), 5.43m (0.241), 2.33m (0.091) and these peaks correspond to 400, 125, 95 and 41kyr orbital parameters of cyclicity, respectively. The high spectral power of the 400, 125 and 95kyr cycles suggests that they were potential influences on sedimentation processes in the 211.2-422.4m part of the measured section at the time of deposition.

6.5 Orbital parameters of cyclicity from 0-422.4m section
An accurate sedimentation rate can not be derived from spectral analysis of the entire measured section as the sedimentation rate is indicated to be two and a half times lower at the top of the section than at the bottom. Therefore spectral peaks from the entire section can not be calibrated to orbital parameters of cyclicity.

6.6 Potential sources of error identified in this exercise
- The accuracy of some of the data is limited given that spectral peaks are identified by hand (in Sigview) which may be a source of minor errors especially for higher frequency signals.
- Spectral analysis of sections 3, C and the 211.2-422.4m section uses spliced data sets which may be a potential source of error resulting in artefact power spectra.
Figure 6.50 Calibrated sedimentation rates of the measured section based on spectral analysis

New Zealand Geological Timescale Cooper et al. (2004)

- Sedimentation rate sections 1-4
- Sedimentation rate sections 0-211.2, 211.2-422.4m

Legend:
- a. *G. euapertura*
- b. *G. brazeri*
- c. *S. novozealandica*
• Sedimentation rates indicated by the biostratigraphy are approximated and are slightly different from the rates calibrated by spectral analysis of the sections.
• Orbital parameters of cyclicity may be blurred / overprinted by tectonic parameters and climate events not related to orbital parameters of cyclicity.
• Variable sedimentation rates are interpreted to be a potential source of error.

### 6.7 Evaluation of orbital parameters of cyclicity

Figure 6.51 presents spectral analysis of the measured section that identifies orbital parameters as spectral peaks and is a summary of the data presented in 6.4.1-6.4.9 of this chapter. Figure 6.51 shows that low frequency (400, 125, 95 kyr) cycles contain more spectral power than mid (41 kyr) and high frequency (24, 22, 19 kyr) cycles. High spectral power of low frequency cycles suggests that they influenced sedimentation processes of the measured section to a greater extent than mid or high frequency cycles at the time of deposition.

Spectral analysis of the measured section identifies the 125 and 95 kyr cycles to be high in spectral power in most sections analysed and they are interpreted to be the main orbital influence on sedimentation in the Waicoe sub-basin during the deposition of the measured section. The 400 kyr cycle is identified to have a high spectral power in the 316.8-422.4 m, 0-211.2 m and the 211.2-422.4 m sections and is interpreted to be well represented in the sedimentary record of the measured section as an orbital parameter of cyclicity. The 400 kyr cycle is a low wavelength cycle and this study suggests that its low wavelength was better preserved in the sedimentary record of the measured section where the sedimentation rate was variable. Mid to high frequency orbital parameters of cyclicity are not well represented by sediments from the measured section, which is possibly due to the variable sedimentation rate.

### 6.7.1 Evaluation of local climate events and tectonic parameters on turbidite sedimentation

Bouma (2004) identified tectonics, local climate, sedimentary characteristics and processes, and sea level fluctuations as key interactive controls that can influence
Figure 6.51 Orbital frequencies and spectral peaks

Section 1 (0-105.6 m) sediment rate: 1 m/8600 kyr
Section A (52.8-158.4 m) sediment rate: 1 m/9400 kyr
Section 2 (105.6-211.2 m) sediment rate: 1 m/13000 kyr
Section B (158.4-264 m) sediment rate: 1 m/13300 kyr
Section 3 (211.2-316.8 m) sediment rate: 1 m/13600 kyr
Section C (264-369.6 m) sediment rate: 1 m/18600 kyr
Section 4 (316.8-422.4 m) sediment rate: 1 m/22000 kyr
turbidite sedimentation. Spectral analysis of sediment data from the measured section has shown cycle periodicities that are not matched to orbital parameters of cyclicity can be accounted for by some of the local climate controls outlined by Bouma (2004). Climate controls are dependant on latitude and height of mountains that produce sediment and major wind currents that direct and control the distribution of moisture (Bouma, 2004).

This study suggests that local climate events are represented by spectral peaks with high spectral power that have unresolved periodicities. Local climate events include floods, droughts, and periods of more intense storms. Local climate events are interpreted to have influenced all sub-aerial processes of sediment supply and transport within the Waicoe sub-basin, thus affecting deposition on the shelf and shelf break areas of the sub-basin. Turbidite genesis in this study is linked to the destabilisation of the shelf break due to a lack of accommodation space on the shelf (see figure 6.52).

Tectonic parameters are considered another factor affecting sedimentation during the deposition of the measured section. Tectonic parameters are identified by Bouma (2004) as controlling basin geometry, mountain size, and the transport distance between mountains and the sea. In this study tectonic parameters are thought to be represented by some spectral peaks with high spectral power too.

Unresolved spectral peaks that are not accounted for by local climate events, tectonic parameters, or orbital parameters of cyclicity have low spectral power and are interpreted to increase the noise and decrease the coherency of spectral plots.
Chapter 7 - Discussion

7.1 Cyclostratigraphic record

Spectral analysis used in the cyclostratigraphic evaluation of the measured section visually estimated mean grain size of sediments. Spectral analysis was also used to calibrate sedimentation rates for the measured section that used biostratigraphy of the measured section as a guide. This may account for some irregularity observed in spectral analysis used to also determine orbital parameters of cyclicity. Spectral analysis identified spectral peaks that were interpreted to represent local climate events and tectonic parameters and this may have affected the spectral signal of orbital parameters of cyclicity.

7.1.1 Reliability of the cyclostratigraphic record

The method of estimating grain size of sand and mud beds from stratigraphic logs proved to be a reliable method of gathering consistent grain size measurements as the grain size of sand beds was consistently the same as was the grain size of mud beds.

Ratios of spectral peaks were matched to ratios of orbital parameters and these orbital parameters were multiplied by a sedimentation rate indicated by biostratigraphy. Spectral peaks that matched the ratio of orbital parameters were used to calibrate a sedimentation rate that was interpreted to be an accurate record of the changing sedimentation patterns within the basin. The calibrated rates of sedimentation indicated that rates slowed up section, which was validated by biostratigraphic data. Data presented in figure 6.50 is an accurate representation of the actual sedimentation rates of the measured section and matches a general biostratigraphic sedimentation rate presented in figure 5.39.

High spectral power and the ratio matching of cycle peaks to orbital parameter ratios indicated that low frequency, 400, 125, and 95 kyr cycles were recorded by sediments of the measured section. Low frequency orbital parameters with high spectral power were recorded in all analysed sections of data.
7.2 Linking orbital parameters of cyclicity to sedimentation process

Flower et al. (1997a) documented Milankovitch scale climate variability across the Oligocene – Miocene boundary using the spectral analysis of stable isotopes and sand percentages recovered from sediment cores of the equatorial Atlantic. Flower et al. (1997a) suggested that climate variability across the boundary could be linked to variability in the volume of the East Antarctic ice sheet. Spectral analysis of stable isotopes and percent sand records used by Flower et al. (1997a) identified 400kyr cycles that may account for variability of the East Antarctic ice sheet in the late Oligocene – early Miocene.

In this study, the variability in volume of Antarctic ice sheets across the Oligocene – Miocene boundary is inferred to resulted in variability in global sea level. Relative sea level lowering in the Waicoe sub-basin is interpreted to have sub-aerially exposed the shelf, and this is interpreted to have reduced the ability of the shelf to accommodate sediment loads arriving there from fluvial depositional systems.

Figure 7.52 is used to show that during a lower sea level there is greater exposure of the shelf and a reduced accommodation space for sediment resulting in sediment deposition closer to the shelf break. Oversupply of sediment to the shelf and shelf break during a lower relative sea level is thought to have destabilised the shelf break, which is interpreted to have generated turbidity currents. Turbidity currents are thought to have been a naturally occurring component of sedimentation in the Waicoe sub-basin. This study suggests that orbital parameters of cyclicity may have enhanced the natural occurrence of turbidity currents by affecting relative sea level that in turn influenced the available accommodation space for sediment on the shelf. The signal is therefore a stochastic one with a Milankovitch overprint and this study enabled the identification of this component.

7.3 Correlating the cyclostratigraphic record

Smoothed grain size estimates were plotted against stratigraphic height and age model data of the measured section in figure 7.53b. Smoothing of grain size estimates in figure
7.53b used a Hanning Window taper of 150 (shown by the blue line) and 50 (shown by the red line). Smoothed grain size estimates shown by the blue and red lines of figure 7.53b is used to show grain size trends in the measured section. Grain size trends shown in figure 7.53b indicated that there are intervals of the measured section that are dominated by a greater proportion of coarse grained sediments and other intervals that are dominated by a greater proportion of fine grained sediments. This is validated by visual inspection of the stratigraphic logs used in this study (appendix A4 S1 and S2).

With respect to interpretations made in the facies analysis and cyclicity chapters (Chapters 5 and 6) intervals of the measured section dominated by coarse grained sediments indicate that there was an enhanced phase of destabilisation at the shelf break area (nucleation point of turbidites). This suggested enhanced phase of shelf break destabilisation is shown between the black lines on figure 7.53b.

Extended periods of lower relative sea levels in the Waicoe Sub-basin are interpreted to account for enhancing natural destabilisation of the shelf break within the sub-basin as fluvial deposits would have been deposited sediment closer to the shelf break. Likewise the intervals of the measured section dominated by a greater proportion of fine grain sediments can be interpreted to account for a greater stability of the shelf break area due to higher relative sea levels.

The grain size trends shown in figure 7.53b are interpreted to have significant implications for the cyclostratigraphy of the measured section. Smoothed grain size estimates between the black lines of figure 7.53b is linked to Zachos et al. (2001) identification of Mi-1 shown in figure 7.53a. The timescale of Zachos et al. (2001) used the GPTS of Berggren et al. (1995). This age model of this study used the New Zealand Geological Timescale, Cooper et al. (2004) that correlated New Zealand Stage to the GPTS of Berggren et al. (1995).
Figure 7.52 A sketch interpreting the effects of a change in relative sea level in the Waicoe sub-basin.

A lowering of relative sea level in the Waicoe sub-basin (1-2) is thought to have exposed more of the shelf (A). Exposure of the shelf is interpreted to have limited the accommodation space available for sediments arriving on the shelf. During a lower relative sea level, sediment loads that cannot be accommodated on the shelf are interpreted to have been deposited closer to the shelf break (B), which destabilises due to the oversupply of sediment forming turbidity currents that travel down what is interpreted to be a steep shelf slope (C) and depositing sediments on the basin floor (E).
Zachos et al. (2001) interpreted Mi-1 as coinciding with a period of low eccentricity associated with the 400 kyr cycle shown as the blue lines in figure 7.53a. Zachos et al. (2001) also identified an extended period of low amplitude variability in obliquity at the same time shown as the red lines in figure 7.53a. Zachos et al. (2001) suggested that the Mi-1 event was a rare climatic anomaly near a major epoch boundary and that Mi-1 may be able to account for a full scale ice sheet on east Antarctica. A full scale ice sheet on east Antarctica would account for a lowering of global sea level which would result in a lower relative sea level in the Waicoe sub-basin.

A lower relative sea level suggests that there may have been an extended period of enhanced destabilization of the shelf break area that may be represented by a greater proportion of sand deposition in the portion of the measured section shown between the black lines of figure 7.53b. Thus the data presented in figure 7.53a, b are interpreted to identify the Mi-1 glaciation of Antarctica from grain size data of the measured section.

The suggested influence of the Mi-1 glaciation on sedimentation processes in the Waicoe sub-basin during the deposition of the measured section might be reflected by the lithostratigraphy of the measured section. The Mi-1 may account for the interpreted west to east switch in sediment source that facies analysis in this study interpreted to be recorded by the Taylors and Diggers Hill members.

The age model of this study does lack key bioevents making it less robust in its usage for correlation to Zachos et al. (2001) identification of Mi-1. However identification of Mi-1 from this study can offer some insight into the effects of relative sea level during the late Oligocene to early Miocene in the Waiau Basin / Waicoe sub-basin and may account for the lithostratigraphy of the Taylors and Diggers Hill members.
Figure 7.53 Correlating smoothed sediment texture data to orbital parameters of cyclicity

A.

Obliquity

Eccentricity

26 25 24 23 22 21 20 Age (Ma)

Source: Zachos et al. (2001)

δ¹⁸O

B.

Phi

Age (Ma), Using the age model of this study.

Height (m)

Taylors Member

Diggers Hill Member

Glendearg Member

Blackmount Formation

Mclvor Formation

No data used here = Trend inferred

Hanning taper length of 150

Hanning taper length of 50

No data gathered here
Chapter 8 - Conclusions

8.1 Lithostratigraphic record

Lithostratigraphy of the measured section recorded a 470m section of the Taylors and Diggers Hill members of the Blackmount and McIvor formations, respectively. Thickness of the members may vary at a different exposure, for example sediments that comprise the lithostratigraphic record of this study have a known lateral continuity over tens of metres, however over hundreds of meters this may vary which would have implications for analyses undertaken in the Cyclicity chapter (Chapter 6). Lithostratigraphy in this study also recorded a 42m portion of un-logged strata of the measured section. The un-logged portion of the measured section is a gap in the sedimentary record and may have had implications for analyses undertaken in the Cyclicity chapter (Chapter 6).

Evaluation of the measured section of marine strata identified the Waitakian (Lw) to Otaian (Po) Stage boundary and sediments in the vicinity of the Oligocene to Miocene (O-M) boundary. The base (0-140m) of the section is identified as the Taylors Member of the upper Blackmount Formation and is comprised of siliciclastic sediments. The mid to upper (140-470m) portion of the measured section is identified as the Diggers Hill Member of the McIvor Formation and is comprised of bioclastic sediments. Thin section analysis validated observations made in the field and were used in placement of the Blackmount – McIvor formation (Taylors – Diggers Hill member) lithostratigraphic boundary.

8.2 Lithostratigraphic nomenclature

A revised lithostratigraphic nomenclature is presented in figure 8.54 that has modified the placement of the Blackmount and McIvor formations that Carter and Norris (2005). The age model developed in this study is used to revise the lithostratigraphic nomenclature of the Taylors and Diggers Hill members of the Blackmount and McIvor formations, respectively. Figure 8.54 is used to show that the Lw is represented by the Taylors Member and most of the Diggers Hill Member with the upper part of the Diggers Hill Member comprising the Po.
8.3 Biostratigraphic record

Biostratigraphic analysis of the measured section indicated that the record lacked some of the key taxa used in other studies (Morgans et al., 1999; Graham et al., 2000) that investigated the Lw-Po Stage boundary. Morgans et al. (1999) biostratigraphic analysis of the Bluecliffs section used the FAD of *E. marwicki* as the nearest bioevent to mark the base of the Po. Biostratigraphic analysis in this study did not identify *E. marwicki* in any samples. Morgans et al. (1999) identified the FAD of *S. novozealandica* as a secondary marker for the base of the Po which was stratigraphically above the FAD of *E. marwicki*. *S. novozealandica* is identified from the measured section and has a FAD at 368m.

<table>
<thead>
<tr>
<th>Age</th>
<th>New Zealand Stage</th>
<th>Formations</th>
<th>Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>Pliocene</td>
<td>Prospect</td>
<td>Little Creek</td>
</tr>
<tr>
<td></td>
<td>Tongaporutuan (Tt) to Nukumaruan (Wn)</td>
<td>Undifferentiated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waiauan (Sw)</td>
<td>Duncraigian</td>
<td>Tangle</td>
</tr>
<tr>
<td></td>
<td>Lillburnian (Sl)</td>
<td></td>
<td>Hydro</td>
</tr>
<tr>
<td></td>
<td>Clifdenian (Sc)</td>
<td></td>
<td>Duncalf</td>
</tr>
<tr>
<td>24</td>
<td>Miocene</td>
<td>Monowai</td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td></td>
<td>Altonian (Pi)</td>
<td>Borland</td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td></td>
<td>Otaian (Po)</td>
<td>McIvor</td>
<td>Glendearg</td>
</tr>
<tr>
<td></td>
<td>Waitakian (Lw)</td>
<td>Waloe</td>
<td>(undifferentiated)</td>
</tr>
<tr>
<td>37</td>
<td>Oligocene</td>
<td>Blackmount</td>
<td>Tawyers</td>
</tr>
<tr>
<td></td>
<td>Dunroonian (Ld)</td>
<td></td>
<td>Sunnyside</td>
</tr>
<tr>
<td></td>
<td>Whaingaroan (Lwh)</td>
<td></td>
<td>Ligar</td>
</tr>
<tr>
<td></td>
<td>Whaingaroan (Lwh)</td>
<td>Nightcaps</td>
<td>Jericho</td>
</tr>
<tr>
<td></td>
<td>Runangaen (Ar)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8.54 Revised lithostratigraphic nomenclature of the Waiau Basin (modified from Carter and Norris, 2005). The revision is focused on new biostratigraphic ages of the Taylors and Diggers Hill members of the Blackmount and McIvor formations (respectively) developed in this study.

The placement of the Lw-Po Stage boundary in this study is interpreted to be placed near to the boundary due to the absence of *E. marwicki* as a useful bioevent. Morgans (pers comm., 2005) identified that bioevents identified from the measured section may not be isochronous with events in the Canterbury Basin where the present timescale for the late Oligocene to early Miocene has been developed (Trig Z and Bluecliffs).
The base of the measured section is considered to be mid Lw and used the FAD of *G. dehiscens*, *Gl. woodi woodi*, and *Gl. woodi connecta*. The FAD of *G. dehiscens* used by Morgans et al. (1999) in the Bluecliffs section marked the base of the Lw, *Gl. woodi woodi* and *Gl. woodi connecta* are identified as mid Lw from the Bluecliffs section. The mid Lw age for the base of the measured section of this study lacked an accurate bioevent to accurately constrain its age. The most useful bioevent of the Lw in this study is the LAD of *Gl. euapertura* (83m) which has been used to mark the Oligocene – Miocene boundary by Berggren et al. (1995). However, Berggren et al. (1995) LAD of *Gl. euapertura* may not be isochronous with the LAD of *Gl. euapertura* in this study and remnant populations of *Gl. euapertura* may have persisted into the lower Miocene during the deposition of the measured section, giving a later LAD for *Gl. euapertura* in this study.

Morgans (pers. comm., 2005) identified that the LAD of *Gl. euapertura* in New Zealand had not been well dated and was cautious with the LAD Berggren et al. (1995) used for *Gl. euapertura*. Morgans (pers. comm., 2005) also identified that there was no single good section where the relative positions of the FAD of *Gl. woodi woodi* and *Gl. woodi connecta* with the LAD of *Gl. euapertura* can be well documented.

Berggren et al. (1995) placed the LAD of *Gl. euapertura* at the O-M boundary. However, there is a lack of data regarding the LAD of *Gl. euapertura* in New Zealand, which makes its utility as a marker for the boundary in New Zealand unresolved. Placement of the O-M boundary at the base of the measured section used the FAD of *Gl. euapertura*, *Gl. woodi woodi*, and *Gl. woodi connecta*. The LAD of *Gl. euapertura* at 83m is also used in placement of the O-M boundary. The mid to upper Lw is identified by the FAD of *Gl. brazieri* at 229m and its LAD at 245m.

Placement of the Lw-Po boundary used the FAD of *S. novozealandica* which Morgans et al. (1999) identified from Bluecliffs (Lw-Po Stage boundary stratotype section) to be a key marker occurring just above the Lw-Po boundary.
8.3.1 Geographic placement of lithostratigraphic and biostratigraphic boundaries

Placement of the Oligocene – Miocene and the Waitakian – Otaian (Lw-Po) boundaries are geographically shown in figure 8.55 that also shows the geographic boundaries of the Taylors, Diggers Hill, and Glendearg members of the Blackmount and McIvor formations, respectively. Placement of lithostratigraphic and biostratigraphic boundaries used criteria outlined in the lithostratigraphy and biostratigraphy chapters.

Figure 8.55 Geographic placement of lithostratigraphic and biostratigraphic boundaries identified in this study.

8.4 Facies assessment

Facies, facies associations, and facies successions were identified from the measured section. Facies analysis of the measured section identified 10 facies belonging to two facies associations. Facies successions were used to establish siliciclastic and bioclastic
motifs that characterised sediments from the Taylors and Diggers Hill members of the measured section. Facies analysis of the measured section identified turbidite sequences that fit the Bouma classification scheme (1962).

Turbidite generation resulted from destabilisation of the shelf break in the Waicoe sub-basin. Destabilisation of the shelf break was partly due to sub-aerial exposure of the shelf caused by a drop in relative sea level resulting in a lack of accommodation space for sediments arriving to the shelf from fluvial systems. The net result was that sediment loads arriving on the sub-aerially exposed shelf were deposited closer to the shelf break enhancing its destabilisation.

The Waicoe sub-basin occupied the northern reaches of its larger parent basin – the Waiau Basin. Waicoe sub-basin paleo-geography was an ideal generator for turbidite sequences for the following reasons:

- The sub-basin had a narrow shelf that had a limited ability to accommodate sediment.
- The shelf slope was steep and terminated in a deep, and narrow depositional basin floor. Paleo-ecological interpretations of benthic foraminifera analysed in this study that indicated an average basin depth of 1300m.
- The southeastern Fiordland and Takitimu mountains ensured a supply of sediment for the shelf region.
- The shelf margins of the basin are interpreted to have been asymmetric, with the western side interpreted as having a narrower shelf than that of the eastern side of the basin. The eastern side of the Waicoe sub-basin is interpreted to have had a larger shelf that was able to generate bioclastic material of the Diggers Hill Member.

Facies analysis in this study and from Carter and Norris (1977a,b, and 2005) indicated that sediments that comprise the Taylors Member sourced sediment from western margins of the Waicoe sub-basin, and sediments that comprise the Diggers Hill Member sourced sediment from eastern margins of the basin. Thin section analysis in this study
indicated that the two members comprised different mineral assemblages, however thin section analysis was not able to accurately account for a western or eastern provenance of the sediments that comprise the two members. This study agrees with the interpretation of Carter and Norris (1977a, b, and 2005) but goes on to interpret the upper Taylors Member as the transitional member of sediment that recorded the west to east sediment source transition. The Diggers Hill and Glendearg members are interpreted to have sourced sediment solely from the eastern margins of the sub-basin.

Facies analysis also indicated that sediments that comprise the measured section were deposited in a deep marine depositional environment (approximately 1300m), however key benthic foraminiferal taxa *Tritaxalina zealandica*, 1500-200m used in the facies analysis of this study can only infer a range in depth of deposition.

### 8.5 Cyclostratigraphy

Cyclostratigraphic evaluation of the measured section used spectral analysis of grain size data to identify orbital parameters of cyclicity. Grain size data was measured from the stratigraphic logs of this study (see appendix A4s1 and s2). Spectral analysis in this study used Sigview which proved to be a reliable method that identified cycle periodicities using grain size data. Lateral continuity of beds in this study can be traced over tens of meters but not over hundreds of meters. Spectral analysis of a lateral equivalent of the measured section would identify the same cycle periodicities but with marginal spectra power differences.

Ratios of spectral peaks were matched to ratios of orbital parameters of cyclicity and this was used to identify orbital parameters of cyclicity and to calibrate sedimentation rates for the measured section. Calibrated sedimentation rates used biostratigraphy of the measured section as a guide and indicated that sedimentation rates varied during the deposition of the measured section. Spectral peaks also identified cycle periodicities that were not linked to orbital parameters of cyclicity. These parameters were restricted to local climate events and regional tectonics. Turbidite sedimentation is not solely attributed to orbital parameters of cyclicity but identified as factor that can enhance
turbidite generation. Natural destabilisation of the shelf break is attributed to local climate factors like floods, droughts, and periods of wind current change.

Unresolved spectral peaks with low spectral power that were not linked to orbital parameters of cyclicity or local climate events or tectonics had low spectral power and were identified as noise in the analysis and had little bearing on the analysis undertaken that identified orbital parameters of cyclicity.

Spectral analysis identified 400, 125, and 95 kyr signals as the main orbital parameters recorded in sediments of the measured section. The 400 kyr cycle was identified by Zachos et al. (2001) as coinciding with Mi-1 and a period of low amplitude variability in obliquity. Zachos et al. (2001) suggested that the decline in amplitude of 400 kyr cycle and obliquity resulting in cooler polar summers that may account for an east Antarctic ice sheet. This study identified an interval of the measured section that contained a predominantly greater amount of coarse grained sediments that may reflect an enhanced phase of shelf break destabilisation due to lower relative sea levels. Lower relative sea level in the Waicoe sub-basin during the deposition of the coarse grained interval identified by the black lines of 7.53b may reflect the establishment of an ice on east Antarctica during the late Oligocene to early Miocene.

The enhanced phase of shelf destabilisation may also account for the switch in sediment source that is interpreted to be shown by the siliciclastic sediments of the Taylors Member to the bioclastic sediments of the Diggers Hill Member. The age model of this study links the phase of enhanced shelf break destabilisation to the Mi-1 event Zachos et al. (2001) identified.

8.6 Future work
Evaluation of the measured section has indicated that the establishment of an age model incorporating magnetostratigraphy and an isotope stratigraphy would allow for greater correlation to other studies that investigated the Oligocene to Miocene boundary and the Waitakian to Otaian Stage boundary. However, paleomagnetism in this study identified
pervasive overprints in 70 percent of samples (see appendix A1) and foraminifera used in biostratigraphy indicated calcite overgrowths on many specimens that would make isotope analysis unsuitable. Future evaluation of sections like the one in this study may look to undertake a more comprehensive pilot study to establish the limitations of paleomagnetism and biostratigraphy.
References

Allan, R. S., (1933). On the system and stage names applied to sub-divisions of the Tertiary strata in New Zealand. Transactions of the New Zealand Institute Vol. 63, pp. 81-108.


Appendix A1 - Paleomagnetic evaluation of the measured section

Introduction –
Paleomagnetic investigations evaluated the magnetic behaviour and intensity of sediments of the measured section. The aim was to establish a chronostratigraphy for the measured section in order to determine an accurate age for the measured section of strata. Thermal demagnetisation was used in this study and is the selective removal of secondary NRM through progressive heating steps.

A1.0 Paleomagnetic methods
Sampling for paleomagnetism was carried out in two parts. The pilot study collected 32 cores from eight sites. This study was used to investigate the intensity and magnetic behaviour of samples from the measured section it also indicated that mud beds (preferable lithology to core for paleomagnetic analysis as it is fine grained, and a better carrier of a paleomagnetic signal) would be difficult to core as they were heavily fractured and weathered. The main sampling exercise followed, collecting 230 cores from 62 sites, which took 10 days in the field.

A1.1 Sampling - planning
Sampling was undertaken at intervals calculated to resolve the polarity intervals of the Global Polarity Time Scale (GPTS) across the Oligocene – Miocene (23.8Ma), and Lw-Po boundaries (21.7Ma). Biostratigraphic age constraints of the measured sections base are approximately 24Ma, and the top of the section is approximately 18-19Ma that indicated a 1m/ 10500 years sedimentation rate for measured section, although sedimentation rates are interpreted to have varied during the deposition of the measured section.

The shortest polarity interval of the GPTS thought to be represented in the measured section is C6AAr.2n, age: 22.459 – 22.493Ma; which is 34,000 years in duration. To identify C6AAr.2n would require sampling every 3.9m, and this was beyond the scope of
the field sampling exercise. The polarity interval C6Bn.1r, duration 22.804 – 22.750Ma (54,000 years) was then used as the shortest duration polarity interval that indicated sampling every 6.5-7m. If the bounding polarity intervals of C6AAr.2n (C6AAr.3r and C6AAr.2r) could be identified then further sampling in between would hopefully identify C6AAr.2n, therefore almost halving the necessary samples to be collected.

Evaluation of the pilot study demagnetisation behaviours suggested that sediments of the measured section carried a magnetic signal that was interpreted to be ChRM, which led to the main paleomagnetic sampling and analysis program.

A1.2 Sample collection
Ideally, sampling was undertaken on the least weathered rock cropping out within the river in 5-10cm of water; however this was not the case with samples collected in this study. Samples for paleomagnetism were collected from beds cropping out on the banks of the Waiau River (see fig. 1.4, Introduction Chapter). Samples were collected in this way due to the river being too deep and too swift to core. Fracture planes were also hard to identify in rock cropping out in the river.

The pre-calculated sampling intervals required sampling of a variety of textures both fine grained (mud) and coarser grained (sand) sediments. Fine grained sediments were preferentially cored as they are more effectively aligned by the geomagnetic field and are less likely to acquire viscous components of magnetisation. However in this study coarser grained sand beds were more well cemented and had fewer fracture planes and therefore were more reliable textures to core. Collecting a paleomagnetic core involved:

a) Clearing a fresh drilling surface on which to core from. This involved using a 1.8m long pinch bar to remove weathered overburden rock from heavily fractured mud beds. Sand beds being typically less fractured had fewer fracture planes.

b) At a given site, four 25mm diameter cores were drilled using a battery operated 18V Makita water lubricated hand drill, using a diamond tipped drill bit with an ideal length being at least 100mm. Cores were drilled in different configurations
at successive sample sites so that they could be more readily recognised in the field (see appendix stratigraphic log).

c) Once each core was drilled, the z-azimuth (the angle of declination of the core makes with the present magnetic field), and core plunge (the dip angle of the core axis with respect to a horizontal plane) were recorded using a Brunton compass. Cores were then scribed with a brass scribe marking the downward direction of the core, see fig. A1.

d) Cores were then removed from the outcrop using a stainless steel spoon and labelled according to site and core number. Cores were then wrapped in newspaper to slow their drying.

e) After a day of drilling and extraction all cores were then placed for storage in a Mu metal shielded container that ensured samples would not acquire any viscous components of magnetisation during the field exercise.

Note: all compass measurements in the field are to magnetic North and corrected to geographic North in the lab.

Figure A1 Core orientation scheme. a) orientation of core in outcrop, b) orientation of a single core where a line is scribed down the long axis of the core marking the downward direction, c) After sample preparation (see below) cores are divided into specimens 1 to 4. Specimens are labelled with the batch (D), the site number of the batch (07) and the core number (24) and the specimen number (.1). The horizontal line orients the down dip direction of the core when oriented flat as shown.

A1.3 Sample preparation

Prior to measurement samples needed to be prepared for the magnetometer, this involved:

a) Cutting scribed cores into 25mm sections with a volume of 10cm³ with a brass bladed core cutter.

b) Painting core orientations and specimen numbers using non-magnetic white Indian ink.
A1.4 Sample analysis

Samples in this study were analysed for:

a) Characteristic Natural Remnant magnetism, ChRM.

b) Magnetic Susceptibility

All measurements were undertaken in the Paleomagnetism laboratory in the Geology Department of Otago University. The laboratory houses a 2G Enterprises horizontal, 3 axis cryogenic magnetometer in a magnetically shielded room with a resultant internal field of 150 nanotesla, and was used for measuring discrete thermally demagnetised specimens (592 in total). Alternating Field (AF) demagnetisation was used to measure 8 specimens in the pilot study.

A1.5 Alternating Field (AF) demagnetisation

Alternating field demagnetisation procedure exposes a sample to an alternating magnetic field that erases NRM (natural remnant magnetism) carried by grains with coercivities less than the peak demagnetising field (Butler, 1992). This was the first procedure undertaken in the pilot study. AF demagnetisation can be used to effectively remove secondary NRM and isolate ChRM in a sample (Butler, 1992).

In this study a single specimen from each pilot study site was run through the cryogenic magnetometer using AF demagnetisation. Initially magnetic moment and magnetic susceptibility were measured. Samples were then exposed to an incrementally increasing alternating field demagnetisation in steps beginning with 5 millitesla (mT), with increments of 5mT to 40mT, and then followed by 10mT increments to 100mT where samples were fully demagnetised. AF demagnetisation yielded no identifiable components of magnetisation due to the presence of iron oxyhydroxide minerals, which did not respond to AF treatment.

A1.6 Thermal demagnetisation

Thermal demagnetisation was then undertaken and proved a more reliable method for gathering demagnetisation data. Thermal demagnetisation involves heating specimens to an elevated temperature ($T_{demag}$) below the Curie temperature of constituent
ferromagnetic minerals (Butler, 1992). This was done using the oven in a magnetic field free room, where samples were heated for 50 minutes. A sample was initially measured at 20°C and then at 30°C increments to 300-400°C. Between each heating step samples were measured for magnetic moment and magnetic susceptibility.

A1.7 Magnetic susceptibility (MS)
Magnetic susceptibility was measured using a Bartington single specimen susceptibility bridge. MS results indicate the concentration and composition of ferro and ferri magnetic minerals in specimens from the measured section.

A2.0 Paleomagnetic behaviour of the measured section sediments
Figures (A2-S) are samples of the types of magnetic behaviour encountered using thermal demagnetisation of specimens collected from the measured section. Specimens exhibited a variety of behaviours with the majority interpreted to have pervasive overprints that masked the ChRM. Identification of a ChRM component of magnetisation was problematic as it could be easily be mistaken for a single overprint component of magnetisation.

The behaviour shown in figure A2 is interpreted to be a well behaved single overprint component of magnetisation with good magnetic intensity. This behaviour type was the most common overprint behaviour type shown by samples from the measured section. Figure A3 shows a cluster plot of magnetic components that has a very weak magnetic intensity and poorly behaved components of magnetisation. Figure A4 is an example of multiple components of magnetisation that are poorly behaved with a variable magnetic intensity. Figure A5 is an example of a well behaved specimen that is interpreted to not be an overprinted component and has good magnetic intensity and possibly shows a ChRM component of magnetisation. Components of magnetisation of figure A5 trace toward an offset origin that may be accounted for by magnetic components that have high blocking temperature spectra.
A3.0 Conclusions

Paleomagnetic evaluation of the measured section identified that there are pervasive overprints in 70 percent of the 600 specimens analysed. Pervasive overprints made the identification of a ChRM component of magnetisation difficult as they were not removed effectively using thermal demagnetisation and lacked adequate magnetic intensity to be processed using AF demagnetisation. Further paleomagnetic work that samples less weathered sediments of the measured section may yield data that can show primary components of magnetisation that can be used to establish a chronostratigraphy. The sample planning exercise may be a suitable guide for similar exercises in the future.
## Appendix A2i Biostratigraphic census data

<table>
<thead>
<tr>
<th>OU Sample number</th>
<th>76375</th>
<th>76383</th>
<th>76386</th>
<th>76376</th>
<th>76395</th>
<th>76399</th>
<th>76404</th>
<th>76408</th>
<th>76411</th>
<th>76412</th>
<th>76377</th>
<th>76414</th>
<th>76419</th>
<th>76378</th>
<th>76422</th>
<th>76425</th>
<th>76429</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratigraphic height</td>
<td>0m</td>
<td>25m</td>
<td>25m</td>
<td>83m</td>
<td>146m</td>
<td>164m</td>
<td>168m</td>
<td>200m</td>
<td>229m</td>
<td>245m</td>
<td>250m</td>
<td>251m</td>
<td>264m</td>
<td>345m</td>
<td>368m</td>
<td>371m</td>
<td>396m</td>
</tr>
<tr>
<td>New Zealand Stage</td>
<td>mid Waitakian (mid Lw: ca. 23.8 Ma)</td>
<td>Mid-Upper Waitakian (mid-upp Lw: ca. 23.8-21.7 Ma)</td>
<td>Lwian (Po: 21.7-19.0 Ma)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agglutinated taxa</td>
<td>*</td>
<td>*</td>
<td>58</td>
<td>59</td>
<td>52</td>
<td>59</td>
<td>52</td>
<td>51a</td>
<td>2b</td>
<td>38</td>
<td>40a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>misc. agglutinated form</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Ammodiscus archimedes</td>
<td>4a</td>
<td>40</td>
<td>51b</td>
<td>40</td>
<td>49.50</td>
<td>*</td>
<td>52</td>
<td>51a</td>
<td>*</td>
<td>2b</td>
<td>*</td>
<td>38</td>
<td>40a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>19</td>
</tr>
<tr>
<td>Ammodiscus finitius</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Ammodiscus sp.</td>
<td>4b</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Arenodiscus antipoda</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Bathysiphon eocenicus</td>
<td>1</td>
<td>*</td>
<td>49</td>
<td>*</td>
<td>40</td>
<td>1a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Bathysiphon sp.</td>
<td>16a</td>
<td>*</td>
<td>54</td>
<td>57</td>
<td>*</td>
<td>42</td>
<td>1b,15a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Bolivinopsis cubensis</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>41</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Cyclammina incisa</td>
<td>18</td>
<td>35</td>
<td>54</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Cyclammina rotundata</td>
<td>49</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Cyclammina sp.</td>
<td>*</td>
<td>42</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Dorothia sp.</td>
<td>*</td>
<td>55b</td>
<td>*</td>
<td>43a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Eggereilla bradyi</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Gaudryina sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1b</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Glomospira charoides</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>4b</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Hauserella hectori</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Hauserella cf. textilliformis</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>13c</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Haplophragmoides sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>44</td>
<td>19</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>53</td>
<td>58,59</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Hyperammina sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>53</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Karreriuella bradyi</td>
<td>*</td>
<td>*</td>
<td>45</td>
<td>15b</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>14a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>1a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Karreriella chiostoma</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Karreriuella novozelandica</td>
<td>*</td>
<td>*</td>
<td>44</td>
<td>*</td>
<td>*</td>
<td>57</td>
<td>42ower</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>51</td>
<td>*</td>
<td>1b</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Karreriuella sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Karreriuina obscura</td>
<td>15b</td>
<td>*</td>
<td>*</td>
<td>25</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Liluotuba sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Martinottiella communis</td>
<td>13b</td>
<td>*</td>
<td>45</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>14a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Martinottiella sp.</td>
<td>14</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Pelosiina sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>4a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Recurvooidea sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>44</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>36</td>
<td>*</td>
</tr>
<tr>
<td>Reophax sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>58</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Schenkiella weymouthi</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Siphotextularia sp.</td>
<td>15c</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Textularia sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Tritaxiloidea sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>55</td>
<td>13b</td>
<td>17</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Trochammina in star</td>
<td>13a</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>55</td>
<td>13b</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Trochammina sp.</td>
<td>43</td>
<td>56</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>23</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>35</td>
<td>*</td>
<td>3b</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Trochanminoa sp.</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>41</td>
<td>51</td>
<td>*</td>
<td>55</td>
<td>49</td>
<td>61</td>
<td>2a</td>
<td>*</td>
<td>42</td>
<td>33</td>
<td>3a</td>
<td>*</td>
</tr>
<tr>
<td>Trochanminoa sp.</td>
<td>3</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>41</td>
<td>51</td>
<td>55</td>
<td>49</td>
<td>61</td>
<td>2a</td>
<td>*</td>
<td>42</td>
<td>33</td>
<td>3a</td>
<td>*</td>
<td>20</td>
</tr>
</tbody>
</table>
Appendix A2ii Biostratigraphic census data continued...

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vulpina pennatula</td>
<td>15a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcareous taxa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alabama nanae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amphiporella hirsuta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amphimorpha sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amphitrite sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anomalina aulae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anomalinae macrarhiana</td>
<td>28c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anomalinae orbiculus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anomalinae sphericus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asteolus sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Astrononix sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bioculina sp.</td>
<td>8a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolivina anasomossa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolivina cf.</td>
<td>9a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bolivina sp.</td>
<td>9b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulimina papula</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulimina truncanolata</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulimina cf. striata</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulimina sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buliminella spicata</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceroberta sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chilostomella ovatae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chrysalidion genus strigatum</td>
<td>36a</td>
<td>33</td>
<td>52a</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chrysalidion sp.</td>
<td>11b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cribroceras rhingia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cribroceras novovaleanium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cribroceras perforatus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cribroceras robertsonianus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cribroceras vortex</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cribroceras sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cribroceras ornamentalis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dentalinia sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discobolites sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discobolites pennatula</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discorbis sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discorbis tenuissima</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ephoricium cf. miocenense</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euviufera sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euviufera sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glandulina sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Count values are not provided in the given text. The table appears to be a continuation of biostratigraphic data with various species listed along with their counts, but the data is not fully transcribed.
### Appendix A2iii Biostratigraphic census data continued...

<table>
<thead>
<tr>
<th>Genus</th>
<th>Specimen Numbers</th>
<th>Additional Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Globocestocyclina cuneata</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Gyroidinoides neosolidi</td>
<td>25a</td>
<td></td>
</tr>
<tr>
<td>Gyroidinoides pseudobiculcus</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Lagena sp.</td>
<td>7a,c.d,10</td>
<td></td>
</tr>
<tr>
<td>Laticostaria pustulata</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lenticulina spp.</td>
<td>12 17 36 37a 33 11,12 18 49,50</td>
<td>53a,34 35 5a,6 49 21 36,37</td>
</tr>
<tr>
<td>Marginulinia sp.</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Melonis domenii</td>
<td>26b</td>
<td></td>
</tr>
<tr>
<td>Melonis pacificamericum</td>
<td>26/27</td>
<td></td>
</tr>
<tr>
<td>Melonis maoricum</td>
<td>27c</td>
<td></td>
</tr>
<tr>
<td>Melonis sp.</td>
<td>34-36</td>
<td></td>
</tr>
<tr>
<td>Nodosaria longiscata</td>
<td>36c 34 54 49,50,51 21,58 23b 56 50 56 11a 62 39 29a</td>
<td>31a,24 50a,b 38 19a</td>
</tr>
<tr>
<td>Nodosaria spp.</td>
<td>11a,24 50a,b 38 19a 60 36r 53 21 62a,43 23 20b,23b</td>
<td>42</td>
</tr>
<tr>
<td>nodosariids</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Nonionella magnalingua</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthomorphina sp.</td>
<td>23b</td>
<td></td>
</tr>
<tr>
<td>Osangularia cutter</td>
<td>31a 25 56b 23</td>
<td></td>
</tr>
<tr>
<td>Parafissurina sp.</td>
<td>7a</td>
<td></td>
</tr>
<tr>
<td>Parvicostaria afficamericata</td>
<td>31b</td>
<td></td>
</tr>
<tr>
<td>Plicatulina sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planulina renzi</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Plectofrondiculina waingaroica</td>
<td>8b 41 5a 5a 37 32</td>
<td>4a 13 22 53 46</td>
</tr>
<tr>
<td>Pleurotomella sp.</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Polyomorphinae&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudonodosaria aperta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudonodosaria symmetrical</td>
<td>18a</td>
<td></td>
</tr>
<tr>
<td>Puffenia bulloides</td>
<td>6b 27 17 5b 7</td>
<td>42upper 22 18b</td>
</tr>
<tr>
<td>Puffenia quadridoba</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Puffenia quinqueloba</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Puffenia sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quinquelorina sp.</td>
<td>19a</td>
<td></td>
</tr>
<tr>
<td>Ramulina sp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectuvigerina striatissima</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotalia lemusi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saracenaria italic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siphonina australis</td>
<td>53a 33 56 46b</td>
<td>42 31b</td>
</tr>
<tr>
<td>Siphonodiscina plebeja</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Siphonodiscina buetticoides</td>
<td>5 21 16 25 5a 37 2 16 17 17 34,35</td>
<td>26</td>
</tr>
<tr>
<td>Spongioculina novozelandica</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stilostomella pumilgera</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stilostomella sp.</td>
<td>20a,22b,23a,38 53 56 36 19b 59 36 23 20 36-38</td>
<td>42a 41 38</td>
</tr>
</tbody>
</table>
### Appendix A2iv Biostratigraphic census data continued...

<table>
<thead>
<tr>
<th>Taxon</th>
<th>9a</th>
<th>11a</th>
<th>14a</th>
<th>15a</th>
<th>19a</th>
<th>20a</th>
<th>20b</th>
<th>26a</th>
<th>34b</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Biostratigraphic census</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trifarina sp.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vaginulina vagina</td>
<td>22a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vaginulina spp.</td>
<td></td>
<td>57,59</td>
<td>52b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vaginulinaopsis neglecta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>Vaginulinosps sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>34</td>
<td>11</td>
</tr>
<tr>
<td><strong>Planktics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catapsydrax disilinis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. brazieri</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina bulloides (group)</td>
<td>38b</td>
<td>1,6,17a</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Globigerina bulloides</td>
<td>41c</td>
<td>3,4,5</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3,4</td>
</tr>
<tr>
<td>Globigerina cf. labiocrassata</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. pacificostranoucula</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina wood (group)</td>
<td>53a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. spatulata</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. japonica</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. hongkongensis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. plicatulae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. asiatica</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. atychealis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. floridensis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. mayoica</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina cf. pachyphala</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Globigerina sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Miscellaneous bits</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Echinoid spine</td>
<td>47a</td>
<td>64</td>
<td>54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiolarian</td>
<td>47b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ostracoda</td>
<td>48a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diatom</td>
<td>48b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bryozoa</td>
<td>55a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish tooth</td>
<td>60a</td>
<td>41</td>
<td>52a</td>
<td>51a</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossilized fecal pellet</td>
<td>60b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micromolluscs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Appendix A2v. Foraminifera sample Data

**Bold = Pilot samples**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Strat. height</th>
<th>Wet weight</th>
<th>Dry weight</th>
<th>Coarse weight</th>
<th>Sand %</th>
<th>Bed</th>
<th>OU number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samp 1a</td>
<td>~03(1)</td>
<td>135.05</td>
<td>126.03</td>
<td>2.04</td>
<td>1.62</td>
<td>A02</td>
<td>76375</td>
</tr>
<tr>
<td>Samp 1b</td>
<td>A08(2)</td>
<td>151.02</td>
<td>144.03</td>
<td>1.22</td>
<td>1.01</td>
<td>C02</td>
<td>76376</td>
</tr>
<tr>
<td>Samp 3</td>
<td>228</td>
<td>105.08</td>
<td>99.5</td>
<td>1.86</td>
<td>1.87</td>
<td>D156</td>
<td>76377</td>
</tr>
<tr>
<td>Samp 3a</td>
<td>348</td>
<td>165.89</td>
<td>157.57</td>
<td>7.84</td>
<td>4.98</td>
<td>E14</td>
<td>76378</td>
</tr>
<tr>
<td>Samp 3b</td>
<td>456</td>
<td>156.4</td>
<td>144.4</td>
<td>7.51</td>
<td>5.20</td>
<td>E186</td>
<td>76379</td>
</tr>
</tbody>
</table>

*Above top of measured section*
Appendix A2vi SEM pictures of foraminifera from the measured section

**Planktonics**

- Globigerina brazieri, A
- Globigerina brazieri, B
- Globigerina woodi connecta
- Globigerina woodi woodi
- Globigerina euapertura
- Globoquadrina dehiscens
- Spiroloculina novozealandica
- Tritaxalina zealandica

**Benthics**
### Appendix A3i Spectral analysis data

#### Table 1

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Table 2</th>
<th>Table 3</th>
<th>Table 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.177</td>
<td>0.375</td>
<td>38.82</td>
<td>590598</td>
</tr>
<tr>
<td>0.015</td>
<td>0.048</td>
<td>36.53</td>
<td>589990</td>
</tr>
<tr>
<td>0.057</td>
<td>0.379</td>
<td>30.56</td>
<td>590598</td>
</tr>
<tr>
<td>0.366</td>
<td>0.283</td>
<td>19.1111</td>
<td>590598</td>
</tr>
<tr>
<td>0.064</td>
<td>0.854</td>
<td>19.61</td>
<td>590598</td>
</tr>
<tr>
<td>0.057</td>
<td>0.568</td>
<td>13.18</td>
<td>590598</td>
</tr>
<tr>
<td>0.024</td>
<td>0.556</td>
<td>11.11</td>
<td>590598</td>
</tr>
<tr>
<td>0.006</td>
<td>0.746</td>
<td>10.43</td>
<td>590598</td>
</tr>
<tr>
<td>0.113</td>
<td>0.335</td>
<td>8.89</td>
<td>590598</td>
</tr>
<tr>
<td>0.124</td>
<td>0.574</td>
<td>6.06</td>
<td>590598</td>
</tr>
<tr>
<td>0.139</td>
<td>0.3811</td>
<td>5.71</td>
<td>590598</td>
</tr>
<tr>
<td>0.125</td>
<td>0.628</td>
<td>5.71</td>
<td>590598</td>
</tr>
<tr>
<td>0.172</td>
<td>0.245</td>
<td>5.69</td>
<td>590598</td>
</tr>
<tr>
<td>0.182</td>
<td>0.377</td>
<td>5.46</td>
<td>590598</td>
</tr>
<tr>
<td>0.170</td>
<td>0.368</td>
<td>5.08</td>
<td>590598</td>
</tr>
<tr>
<td>0.228</td>
<td>0.677</td>
<td>4.72</td>
<td>590598</td>
</tr>
<tr>
<td>0.271</td>
<td>0.189</td>
<td>4.69</td>
<td>590598</td>
</tr>
<tr>
<td>0.217</td>
<td>0.3765</td>
<td>4.55</td>
<td>590598</td>
</tr>
<tr>
<td>0.261</td>
<td>0.526</td>
<td>4.35</td>
<td>590598</td>
</tr>
<tr>
<td>0.254</td>
<td>0.279</td>
<td>4.25</td>
<td>590598</td>
</tr>
<tr>
<td>0.271</td>
<td>0.191</td>
<td>4.17</td>
<td>590598</td>
</tr>
<tr>
<td>0.281</td>
<td>0.356</td>
<td>4.05</td>
<td>590598</td>
</tr>
<tr>
<td>0.254</td>
<td>0.3765</td>
<td>3.94</td>
<td>590598</td>
</tr>
<tr>
<td>0.271</td>
<td>0.189</td>
<td>3.94</td>
<td>590598</td>
</tr>
<tr>
<td>0.292</td>
<td>0.279</td>
<td>3.85</td>
<td>590598</td>
</tr>
<tr>
<td>0.326</td>
<td>0.279</td>
<td>3.75</td>
<td>590598</td>
</tr>
<tr>
<td>0.326</td>
<td>0.326</td>
<td>3.65</td>
<td>590598</td>
</tr>
<tr>
<td>0.335</td>
<td>0.335</td>
<td>3.56</td>
<td>590598</td>
</tr>
<tr>
<td>0.336</td>
<td>0.377</td>
<td>3.47</td>
<td>590598</td>
</tr>
<tr>
<td>0.357</td>
<td>0.283</td>
<td>3.37</td>
<td>590598</td>
</tr>
<tr>
<td>0.395</td>
<td>0.283</td>
<td>3.27</td>
<td>590598</td>
</tr>
<tr>
<td>0.357</td>
<td>0.283</td>
<td>3.17</td>
<td>590598</td>
</tr>
<tr>
<td>0.395</td>
<td>0.283</td>
<td>3.07</td>
<td>590598</td>
</tr>
<tr>
<td>0.395</td>
<td>0.283</td>
<td>2.97</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.87</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.77</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.67</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.57</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.47</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.37</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.27</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.17</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>2.07</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.97</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.87</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.77</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.67</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.57</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.47</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.37</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.27</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.17</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>1.07</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>0.97</td>
<td>590598</td>
</tr>
<tr>
<td>0.413</td>
<td>0.283</td>
<td>0.87</td>
<td>590598</td>
</tr>
</tbody>
</table>
### Appendix A3ii Spectral analysis data continued...

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Table 6</th>
<th>Table 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.0 - 158.4m (A)</td>
<td>158.4 - 264m (B)</td>
<td>264 - 369.6m (C)</td>
</tr>
<tr>
<td>spec powa</td>
<td>spec powa</td>
<td>spec powa</td>
</tr>
<tr>
<td>589.6 - 158.4m (A)</td>
<td>158.4 - 264m (B)</td>
<td>264 - 369.6m (C)</td>
</tr>
<tr>
<td>spec powa</td>
<td>spec powa</td>
<td>spec powa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0.066</th>
<th>0.674</th>
<th>166.67</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.046</td>
<td>51.66</td>
<td>264</td>
</tr>
<tr>
<td>0.036</td>
<td>45.45</td>
<td>264</td>
</tr>
<tr>
<td>0.022</td>
<td>40.40</td>
<td>264</td>
</tr>
<tr>
<td>0.017</td>
<td>35.35</td>
<td>264</td>
</tr>
<tr>
<td>0.012</td>
<td>30.30</td>
<td>264</td>
</tr>
<tr>
<td>0.008</td>
<td>25.25</td>
<td>264</td>
</tr>
<tr>
<td>0.005</td>
<td>20.20</td>
<td>264</td>
</tr>
<tr>
<td>0.002</td>
<td>15.15</td>
<td>264</td>
</tr>
<tr>
<td>0.001</td>
<td>10.10</td>
<td>264</td>
</tr>
<tr>
<td>0.0005</td>
<td>5.05</td>
<td>264</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0.066</th>
<th>0.674</th>
<th>166.67</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.046</td>
<td>51.66</td>
<td>264</td>
</tr>
<tr>
<td>0.036</td>
<td>45.45</td>
<td>264</td>
</tr>
<tr>
<td>0.022</td>
<td>40.40</td>
<td>264</td>
</tr>
<tr>
<td>0.017</td>
<td>35.35</td>
<td>264</td>
</tr>
<tr>
<td>0.012</td>
<td>30.30</td>
<td>264</td>
</tr>
<tr>
<td>0.008</td>
<td>25.25</td>
<td>264</td>
</tr>
<tr>
<td>0.005</td>
<td>20.20</td>
<td>264</td>
</tr>
<tr>
<td>0.002</td>
<td>15.15</td>
<td>264</td>
</tr>
<tr>
<td>0.001</td>
<td>10.10</td>
<td>264</td>
</tr>
<tr>
<td>0.0005</td>
<td>5.05</td>
<td>264</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0.066</th>
<th>0.674</th>
<th>166.67</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.046</td>
<td>51.66</td>
<td>264</td>
</tr>
<tr>
<td>0.036</td>
<td>45.45</td>
<td>264</td>
</tr>
<tr>
<td>0.022</td>
<td>40.40</td>
<td>264</td>
</tr>
<tr>
<td>0.017</td>
<td>35.35</td>
<td>264</td>
</tr>
<tr>
<td>0.012</td>
<td>30.30</td>
<td>264</td>
</tr>
<tr>
<td>0.008</td>
<td>25.25</td>
<td>264</td>
</tr>
<tr>
<td>0.005</td>
<td>20.20</td>
<td>264</td>
</tr>
<tr>
<td>0.002</td>
<td>15.15</td>
<td>264</td>
</tr>
<tr>
<td>0.001</td>
<td>10.10</td>
<td>264</td>
</tr>
<tr>
<td>0.0005</td>
<td>5.05</td>
<td>264</td>
</tr>
</tbody>
</table>
### Appendix A3ii Spectral Analysis Data Continued...

<table>
<thead>
<tr>
<th>Table 8</th>
<th>Table 9</th>
<th>Table 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3ii Spectral Analysis Data continued...</td>
<td>A3ii Spectral Analysis Data continued...</td>
<td>A3ii Spectral Analysis Data continued...</td>
</tr>
<tr>
<td>0.211 2.3</td>
<td>0.211 2.4</td>
<td>0.211 2.5</td>
</tr>
<tr>
<td>0.208</td>
<td>0.209</td>
<td>0.208</td>
</tr>
<tr>
<td>0.193</td>
<td>0.194</td>
<td>0.193</td>
</tr>
<tr>
<td>0.178</td>
<td>0.179</td>
<td>0.178</td>
</tr>
<tr>
<td>0.163</td>
<td>0.164</td>
<td>0.163</td>
</tr>
<tr>
<td>0.149</td>
<td>0.150</td>
<td>0.149</td>
</tr>
<tr>
<td>0.134</td>
<td>0.135</td>
<td>0.134</td>
</tr>
<tr>
<td>0.119</td>
<td>0.120</td>
<td>0.119</td>
</tr>
<tr>
<td>0.104</td>
<td>0.105</td>
<td>0.104</td>
</tr>
<tr>
<td>0.089</td>
<td>0.090</td>
<td>0.089</td>
</tr>
<tr>
<td>0.074</td>
<td>0.075</td>
<td>0.074</td>
</tr>
<tr>
<td>0.059</td>
<td>0.060</td>
<td>0.059</td>
</tr>
<tr>
<td>0.044</td>
<td>0.045</td>
<td>0.044</td>
</tr>
<tr>
<td>0.029</td>
<td>0.030</td>
<td>0.029</td>
</tr>
<tr>
<td>0.014</td>
<td>0.015</td>
<td>0.014</td>
</tr>
<tr>
<td>0.009</td>
<td>0.010</td>
<td>0.009</td>
</tr>
<tr>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 11</th>
<th>Table 12</th>
<th>Table 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3ii Spectral Analysis Data continued...</td>
<td>A3ii Spectral Analysis Data continued...</td>
<td>A3ii Spectral Analysis Data continued...</td>
</tr>
<tr>
<td>0.211 2.6</td>
<td>0.211 2.7</td>
<td>0.211 2.8</td>
</tr>
<tr>
<td>0.208</td>
<td>0.209</td>
<td>0.208</td>
</tr>
<tr>
<td>0.193</td>
<td>0.194</td>
<td>0.193</td>
</tr>
<tr>
<td>0.178</td>
<td>0.179</td>
<td>0.178</td>
</tr>
<tr>
<td>0.163</td>
<td>0.164</td>
<td>0.163</td>
</tr>
<tr>
<td>0.149</td>
<td>0.150</td>
<td>0.149</td>
</tr>
<tr>
<td>0.134</td>
<td>0.135</td>
<td>0.134</td>
</tr>
<tr>
<td>0.119</td>
<td>0.120</td>
<td>0.119</td>
</tr>
<tr>
<td>0.104</td>
<td>0.105</td>
<td>0.104</td>
</tr>
<tr>
<td>0.089</td>
<td>0.090</td>
<td>0.089</td>
</tr>
<tr>
<td>0.074</td>
<td>0.075</td>
<td>0.074</td>
</tr>
<tr>
<td>0.059</td>
<td>0.060</td>
<td>0.059</td>
</tr>
<tr>
<td>0.044</td>
<td>0.045</td>
<td>0.044</td>
</tr>
<tr>
<td>0.029</td>
<td>0.030</td>
<td>0.029</td>
</tr>
<tr>
<td>0.014</td>
<td>0.015</td>
<td>0.014</td>
</tr>
<tr>
<td>0.009</td>
<td>0.010</td>
<td>0.009</td>
</tr>
<tr>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Stratigraphic Symbol Key

Bedding Features

- Fluid escape structure
- Coal lens/streak
- Concretionary horizon
- Concretions
- Sand lens
- Mud lens
- Laminar bedding
- Rip up clast
- Burrowing
- Banded bedding
- Convolute bedding
- Shell fragments
- Whole shells
- Bryozoan
- Foraminifera
- Trace fossil
- Micaceous
- Variable thick

Lithology fills

- Sand
- Mud
- Shelly material
- Limestone

Sampling features

- Marker
- Fault
- Thin section sample
- Biostratigraphic sample
- Paleomagnetic core sample
- Sample locator

Weathering features

- Conoidal weathering
- Iron oxide weathering
- Flute cast weathering
- Jointing
- Calcite jointing / veining

Foraminifera

- Globigerina braziari
- Cataplydrida dissimilis
- Globigerina woodi woodi
- Spiroloculina novozelandica
- Globigerina woodi connecta
- Trithixina zealandica
- Globorotalia dahliens
- Karrenella novozelandica
- Globigerina eucapurrea
- Valvulina pannatula