Cenozoic stratigraphy of the North Carnarvon Basin: Insights for the growth history of carbonate margins of the North West Shelf

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Abstract

The stratigraphic evolution of the Cenozoic strata was investigated through the interpretation of 2D and 3D seismic surveys, integrated with wireline and biostratigraphic data. Results show that the Cenozoic stratigraphy of the Dampier and Barrow Sub-basins in the North Carnarvon Basin, NW Shelf of Australia, is characterized by two second-order sequences, separated by a late-Miocene to Pliocene sequence boundary. The Dampier and Barrow Sub-basins contain: 1) Base Paleocene to Oligocene siliciclastic-carbonates, 2) Oligocene to early-middle Miocene non-tropical carbonate ramps, 3) early-middle Miocene to late Miocene-Pliocene tropical rimmed platforms, 4) a middle Miocene to Pliocene siliciclastic deposit, 5) late Miocene-Pliocene to Pleistocene non-tropical carbonate ramps and 6) Pleistocene to Recent tropical rimmed platforms.

The initiation of tropical reef production in the North Carnarvon Basin was likely triggered by local climate, linked to the strengthening of the Leeuwin Current and the northwards migration of the NW Shelf to tropical latitudes. The temporary demise of carbonate reef production was likely a combination of 1) the closure of the Indonesian Throughflow to the North Carnarvon Basin, amplifying regional cooling trends and 2) rapid rise in relative sea-level in response to increasing subsidence rates from Australian and Indonesian Miocene to Recent collisional tectonics. The temporary onset of siliciclastic sedimentation in the Dampier Sub-basin was possibly due to 1) a fall in relative sea-level 2) tectonic uplift and 3) the onset of middle Miocene aridity, decreasing vegetation coverage and increasing the erosion rates of the Pilbara hinterland.

This study presents new insight on the evolution of carbonate margins and slopes during the Cenozoic in the context of Australia’s tectonic and climatic changes. It also provides a detailed characterization of the Cenozoic overburden in the Dampier and Barrow Sub-basins, which is essential to access for exploration geophysics and future drilling operations. Lastly, this work provides an additional analogue for mixed carbonate-siliciclastic reservoirs in SE Asia.
Acknowledgments

I would like to express my thanks to my supervisor Dr. Julien Bourget for the continuous support of my study and research, for his patience, motivation, and enthusiasm over the year.

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1. Introduction

Despite their extensive coverage and their significant thickness of over 2500 m (Quilty, 1977), the stratigraphic evolution and architecture of the Cenozoic carbonate deposits of the North West Shelf (NWS) remain poorly constrained. This Cenozoic overburden strata overlies the petroleum-producing Mesozoic sequences, providing a necessary component for NWS petroleum plays by assisting the hydrocarbon maturation process through thermal loading (Bradshaw et al., 1998). Additionally Cenozoic sequences of the NWS are linked to a history of practical problems related to drilling activities, the processing of seismic data and the interpretation of structural traps and petroleum plays (Wallace et al., 2003).

The variations in lithologies in the Cenozoic strata of the NWS are often represented by dispersed zones of highly permeable sedimentary rocks (Power, 2008; Wallace et al., 2003; Van Ruth et al., 2002; Tingate et al., 2001). Such formations represent significant drilling hazards in many exploration and production wells along the NWS (Wallace et al., 2003; Van Ruth et al., 2002; Tingate et al., 2001).

A significant proportion of wells drilled in the Northern Carnarvon Basin (NCB) of the NWS (Figs.1 & 2) have encountered difficulties related to loss circulation and overpressure in the Mesozoic and Cenozoic overburden. Studies have proven that the NWS history of overpressure and loss circulation is linked to Cenozoic burial, where incidences occur in formations with thickest deposition (Tingate et al., 2001). Loss circulation may be encountered in the NCB when drilling through lenses of porous Cenozoic sandstones such as the Bare Formation (Fig.3) whilst overpressure has been linked with basal Tertiary claystones (Tingate et al., 2001).

Remarkably few detailed interpretations have identified specific trends and depositional processes integrating a wide variety of data along the NCB carbonate margin (Young et al., 2001; Apthorpe, 1988; Heath and Apthorpe, 1984). In the interest of a safe and more cost effective industry, a study is required to predict the regional distribution of sequences within the Cenozoic interval of the NWS.

Carbonate sequence stratigraphy is largely influenced by the interaction of key environmental factors (Austin and Schlager, 1988; Eberli and Ginsburg, 1987), and therefore sequence geometries and depositional patterns will provide useful local insights on oceanography and paeleogeographic sea level changes in the NCB. Furthermore, the stratigraphic evolution of carbonate margins are controlled by a number of factors including climate, tectonics and local
subsidence (Schlager, 2005). The Cenozoic carbonate systems of the NWS therefore constitute a unique archive of the paleo-environmental and tectonic evolution of NW Australia from the onset of the Cenozoic to the present day (Cathro and Karner, 2006; McGowran et al., 1997). Finally, the Cenozoic carbonate margins of the NWS encompass both tropical reefs and cool-water (temperate) carbonate shelves and slopes, which constitute interesting depositional analogues for hydrocarbon-bearing equivalent systems elsewhere (Zampetti, 2010; Wilson 2008).

The current investigation aims to further the understanding of the broad stratigraphic evolution of the Cenozoic strata in the Dampier and Barrow Sub-basins (Fig. 2) by integrating two and three-dimensional seismic and well data. Two basin-wide transects were created by integrating the best Cenozoic lithological and biostratigraphic data available in the NCB (from open-file well data) with the available 2D and 3D seismic data sets. The depositional architecture of the mapped stratigraphic sequences was later investigated using high-resolution 3D seismic data. This process aims at improving knowledge regarding 1) the nature and stratigraphic evolution of the Cenozoic strata along the NCB margin 2) the relationship between carbonate sedimentation, climate, eustatic, tectonic and oceanographic controls along the NWS during the Cenozoic and 3) reducing the operational risk associated with exploration drilling through a poorly constrained stratigraphic succession.

1.1 Study Area

The NCB is the southernmost of the late Paleozoic to Cenozoic basins that underlie the NW continental margin of Australia (Bradshaw et al., 1988) covering an area of ~550,000km² of Australia’s NWS (Fig.1). The NCB has undergone a complex Mesozoic-Cenozoic depositional history since its original formation during late Paleozoic extension (Driscoll and Karner, 1996; Stagg and Colwell, 1994).
1.2 Tectonic History

The NCB has been shaped by the progressive and ongoing break-up of the Gondwana supercontinent and developed in response to three distinct rifting events from the Late Permian to early Late Cretaceous. Extension began in the Carboniferous-Permian intracratonic Western Australian Superbasin (Cathro and Karner, 2006). Subsequently, Triassic-Cretaceous rifting and Early Cretaceous thermal subsidence with minor structural inversion led to the development of the Exmouth, Barrow, Dampier and Beagle Sub-basins, with the Rankin Platform to the NW (Fig.2) (Bradshaw et al., 1988).
The separation of Australia and Antarctica represents the final stage of relocating the N-S axis from the Indian Ocean to the Southern Ocean resulted from the Paleogene collision of India and the Eurasian Plate (Miller et al., 1991). Extension within the Southern and Indian Ocean has led to the net northwards movement of Australia since the Oligocene (Hull, 2000). In the early Miocene the NW moving Australian continent began to collide with the Banda Arc, during the same interval the Pacific Plate collided with the Australian Plate (Fig.3).

The collision of the Australian Plate with the Banda Arc (Cathro et al., 2003; Hull, 2000; Veevers et al., 1991) has been linked to late Miocene to Pliocene reactivation (Fig.3) of NCB major structural trends, involving both uplift and accelerated subsidence NW of the Rosemary and Rankin Faults (Cathro et al., 2003; Hull, 2000).

**Figure 2**: Map of the North Carnarvon Basin (NCB), NW Shelf Western Australia. The major sub-basins and investigated in the current study (Dampier and Barrow) are indicated (courtesy of Google Earth).
1.3 Cenozoic Sedimentary History

The understanding of the offshore Cenozoic stratigraphy has improved since early investigations (Apthorpe, 1988; Heath and Apthorpe, 1984). The NWS has moved north from ~40° to ~20° since the Eocene (McGrowran et al., 1997; Apthorpe, 1988), forcing a long-term paleoclimatic shift to warmer conditions, and the progressive transition from Mesozoic siliciclastics to dominantly carbonate deposition (Apthorpe, 1988).

Carbonate development was dominant by the Eocene, with subsequent deposition of the Oligocene to middle Miocene Mandu Limestone and overlying middle Miocene Trella Limestone in the Barrow and Dampier Sub-basins (Fig.3) (Heath and Apthorpe, 1984). The Bare Formation represents an interruption of carbonate growth and the introduction of dolomitic siliciclastic sands of the middle to late Miocene-Pliocene (Fig.3) and been interpreted as a system of deltas fed by rivers (Sanchez et al., 2012; Cathro et al., 2003). The major stratigraphic unit of the Pliocene to Recent is the Delambre Formation (Fig.3) (Butcher, 1989; Heath and Apthorpe, 1984).

Figure 3: A modified stratigraphic column of the late Cretaceous and Cenozoic stratigraphy of the NCB (Geoscience Australia) including the variations of the formation names across the Dampier, Barrow and Exmouth Sub-basins. The major Cenozoic tectonic events are indicated on the right. Note the similarities between the Barrow and Dampier Sub-basins with the exception of the siliciclastic-carbonate Bare Formation.
2. Research Aims and Objectives

The following research aims to;

1) Define the general seismic stratigraphic architecture of the NCB during the Cenozoic, with an emphasis on a regional correlation between the Dampier and Barrow Sub-basins (Fig. 2). This includes an assessment of the geometries and distribution of carbonate deposits, determining their distribution in time and space using principles of seismic stratigraphy developed by (Flower and Kennett, 1994).

2) Identify and summarize the Cenozoic lithology from well completion reports and descriptions from side wall cuttings in the six selected wells within two transects, one from each of the Dampier and Barrow Sub-basins. This lithological analysis aims to identify key changes in sedimentology and link them to the stratigraphic evolution (e.g., drowning events and subaerial exposures) and identify those lithologies that potentially pose a threat to future drilling operations.

3) Use high resolution 3D seismic data to discover the geometries and depositional environments of the Cenozoic stratigraphy of the Barrow and Dampier Sub-basins. Furthermore, this study aims to investigate the possible origin, three-dimensional stratigraphic distribution and evolution of the middle Miocene to Pliocene siliciclastic Bare Formation of the Dampier Sub-basin, and provide an additional interpretation of the depositional setting and paleogeographic environment.

4) Determine the interaction between the timing of tectonic events (Keep et al., 2007; Harrowfield and Keep, 2005), eustasy (Carter, 1998), climatic variation (Clift, 2010), oceanographic influence (Gallagher et al., 2014; Gallagher et al., 2009; McGowran et al., 1997) and depositional patterns along the NCB. The investigation aims to determine the relationship between these interactions and the architecture and geometry of the carbonate depositional features on a regional (NWS) scale, by comparing stratigraphic interpretations of previous work conducted along the NWS (Smith, 2013; Rosleff-Soerensen et al., 2012; Cathro et al., 2003).
3. Materials and Methods

The stratigraphic interpretation was conducted using both standards for sequence stratigraphy (Catuneanu et al., 2009; Schlager, 2005). The interpretation presented in this study was based on the geometric configuration and patterns observed in a combination of 2D and 3D seismic reflection and well log data. The stratigraphic analysis was conducted from 2D and 3D seismic data sets along with well data distributed along the Dampier and Barrow Sub-basins (Fig. 2). An initial 2D seismic stratigraphic analysis was conducted, that was later integrated with high-resolution 3D seismic data to identify the smaller-scale geometries, depositional environments, distribution and processes of the Cenozoic margin and slope environments along the NE-SW margin.

3.1 Seismic Data

The Cenozoic stratigraphy of the NCB was unravelled using publicly available 2D seismic surveys including cross-lines and in-lines in both the Dampier and Barrow Sub-basin (Table 1, Figure 4). The 2D seismic data was obtained from Geoscience Australia and accessed in May 2014. The 2D seismic survey area covers ~60,000 km² and extends from the SW to NE margin of the North Carnarvon Basin (Figure 4) with time ranges between 0 and 7 sec two-way time (TWT).

<table>
<thead>
<tr>
<th>Survey Type</th>
<th>Survey Name/Seismic Line</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>S136:136_19</td>
<td>Barrow Sub-basin, Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>86a:86a-3151</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>86a:86a-3150</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>S136:136_23</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>S136:136_14</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>Gpdb95:gpdb95-03</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>Gpdb95:gpdb95-01</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>Gpdb95:gpdb95-10</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>Gpdb95:gpdb95-11</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>2D</td>
<td>Ct93:Ct93-406</td>
<td>Barrow Sub-basin</td>
</tr>
</tbody>
</table>
Table 1: Summary of the seismic survey types (2D = Two-Dimensional Survey, 3D = Three-dimensional Survey), names and the corresponding Sub-basin (Dampier and Barrow) from the NCB. Seismic data can be identified in the regional NCB map (Fig.4).

<table>
<thead>
<tr>
<th>Survey Type</th>
<th>Name</th>
<th>Sub-basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D</td>
<td>Demeter</td>
<td>Dampier Sub-basin</td>
</tr>
<tr>
<td>3D</td>
<td>West Barrow</td>
<td>Barrow Sub-basin</td>
</tr>
</tbody>
</table>

The 3D seismic surveys were used in the second part of the interpretation included Demeter 3D (~3600 km²) and West Barrow 3D (~7590 km²) (Fig.4) provided by Geoscience Australia and Woodside Petroleum Ltd. The survey inline range for the Demeter survey was from 1000-5142, crossline range 616-12982 and z range 0-3000 (ms). Bin spacing of the Demeter 3D survey was 25m/inline. West Barrow survey inline range was from 1673-5339, crossline range 1219-12314 and z range 0-6000ms with a bin spacing of 15m/inline.

The first 2D seismic interpretation was conducted using, IHS Kingdom Version 8.8, to investigate the seismic stratigraphy. Between seismic amplitude terminations, horizons were drawn using both manual and auto-hunt tracking tools across the seismic inlines, intersecting crosslines and wells in the study area. Two-dimensional arbitrary lines were drawn throughout the West Barrow and Demeter surveys to display profiles not covered in the 2D seismic data inlines and crosslines displayed below (Fig.4).

The 3D seismic analysis was conducted in three stages: Firstly, geological time models (Geomodels) were created from 3D seismic data sets in Ellis Paleoscan version 1.5. Geomodels were computed using algorithms and merging seismic points according to the similarity of wavelets and distance. This process automatically traced horizons within the seismic volumes to constrained grids, where a relative geological time was computed for nodes. The optimal Geomodels were obtained from this process by modifying the relationships between the auto-tracked horizons and nodes between the calculated grids. The grid parameters selected were peak and trough polarity, with a patch size of (7 px) and correlation threshold of 30%.

The second process of the 3D attribute analysis involved creating Horizon Stacks from the Geomodels, where 200 horizons were extracted from the West Barrow 3D survey and 300 horizons from the Demeter 3D survey. Selected horizons were exported to Opendtect 4.6.0 and inverse distance to power gridding was applied at a 15-25m interpolation weighted-average scale to complete the horizon distribution process.
Lastly, seismic attributes were applied to selected horizons from the 3D seismic data in Opendtect which included; root mean squared (RMS), coherency and spectral decomposition (15, 50 and 70 Hz). RMS computed the square root of the sum of squared amplitudes to measure the reflectivity of various portions of the horizon. Coherency attributes measured the similarity between adjacent traces, and were used to identifying channel edges, reefs, faults and fracture systems of the study areas. Spectral decomposition was used to map the temporal bed thickness and geological discontinuities by breaking down the seismic signals into the component frequencies (15, 50 and 70 Hz).

![Figure 4](image)

**Figure 4**: Bathymetric location map displaying the two-dimensional 2D (black lines) and three-dimensional 3D (green polygons) seismic surveys in the Dampier and Barrow Sub-basins. The relevant wells used in the current study are indicated (red nodes). Note- additional arbitrary lines were drawn through the 3D seismic surveys to display additional 2D seismic profiles over the study area.

### 3.2 Well Data

Six wells were used in the study (Table 2, Figure 4) to aid the interpretation of seismic data. Gamma logs of Finucane 1, Angel 1, Tidepole 1 and Rankin 1 in the Dampier Sub-basin and
Spar 1 and West Tryal Rocks 2 of the Barrow Sub-basin were plotted alongside seismic data in software IHS Kingdom. Publicly available lithological and biostratigraphy reports were available, and used to assist the interpretation and assign seismic packages relative ages.

Gamma logs were imported to LogVeiw+2014 to identify the response to depositional and lithological changes within seismic sequences. Responses represent coarsening and fining upwards trends in corresponding to relative changes in accommodation, deposition and production e.g. progradational, retrogradational and aggradational patterns. Biozones from well completion reports, mainly planktonic foraminifers (N-Zones) and calcareous nanofossils (NN and CN Zones) assigned the packages traced in seismic sections relative ages. Some biogeographic dating data from Gallagher et al., (2009) was used in Tidepole 1 and correlated from West Tryal Rocks 1 (WTR1) to constrain ages for the Pliocene to Recent stratigraphic sequences.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Transect ID.</th>
<th>Lat.</th>
<th>Long.</th>
<th>NCB Sub-basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angel 1</td>
<td>Transect A</td>
<td>-19.62295521</td>
<td>116.78162314</td>
<td>Dampier</td>
</tr>
<tr>
<td>Finucane 1</td>
<td>Transect A</td>
<td>19.288838</td>
<td>116.766372</td>
<td>Dampier</td>
</tr>
<tr>
<td>Tidepole 1</td>
<td>Transect A</td>
<td>-19.767396</td>
<td>115.88628901</td>
<td>Dampier</td>
</tr>
<tr>
<td>Rankin 1</td>
<td>Transect A</td>
<td>-19.797611</td>
<td>115.743398</td>
<td>Dampier</td>
</tr>
<tr>
<td>Spar 1</td>
<td>Transect B</td>
<td>-20.61306399</td>
<td>114.886387</td>
<td>Barrow</td>
</tr>
<tr>
<td>West Tryal Rocks 2</td>
<td>Transect B</td>
<td>-20.21438799</td>
<td>115.06679501</td>
<td>Barrow</td>
</tr>
</tbody>
</table>

Table 2: Summary of six wells used in the current analysis with their corresponding transects, the latitude (Lat.) and longitude (Long.) and location of the NCB. Biographic age data from West Tryal Rocks 1 (WTR1) and Tidepole 1 was correlated with the data from Gallagher et al. (2009) to date seismic packages within the Pliocene to Recent interval.
4. Results
A record of basin evolution is contained within the distribution of the sedimentary packages deposited and preserved during the basin’s history (Martin, 2006). A standard seismic stratigraphic approach was used to unravel the Cenozoic depositional history of the Barrow and Dampier Sub-basins. Seismic data from the Dampier and Barrow Sub-basins was divided into depositional packages separated by surfaces representing key seismic unconformities. These surfaces are indicated by stratal geometries and reflection terminations including toplap, downlap, onlap and truncations defined by (Flower and Kennett, 1994). The major depositional packages bound by these horizons were termed seismic packages. These packages were grouped into the formal sequences of the stratigraphic interpretation as second-order T-R sequences (Catuneanu et al., 2009). T-R sequences represent major tectonic and eustatic events (Embry, 1995; Embry, 2002; Swift, 1968). The second-order T-R sequence model is well suited to basin-scale interpretations (Embry, 2002) as it utilises both the broad transgressive systems tract (TST) and regressive systems tract (RST).

The integration of wireline logs, biostratigraphy and lithological data in Transect A and Transect B along with the 2D seismic analysis facilitated the development of a broad chronostratigraphic framework. This defined the ages of basin-forming events and processes. Additionally, biostratigraphic ages from WTR1 and Tidepole 1 were correlated from Gallagher et al., (2009). Presented below are the results of the 2D seismic stratigraphic analysis conducted in the Barrow and Dampier Sub-basins, including a summary of the results from the integrated well data analysis (Table 3).
Table 3: Compiled results of the 2D seismic stratigraphic analysis in the Barrow and Dampier Sub-basins displays the interpreted seismic packages (SPs), upper and lower seismic unconformities and relevant stratal terminations described by Vail et al. (1977). A brief summary of the well data (Overall gamma trends, SWC lithologies and biostratigraphic age estimation) is displayed, summarized from Appendix A. SWC= samples from side-wall cuttings. *Biostratigraphy has also been integrated from Gallagher et al. (2009) in West Tryal Rocks 1 (Barrow Sub-basin) and Tidepole 1 (TA, Dampier Sub-basin). SU= seismic unconformity.

<table>
<thead>
<tr>
<th>Well Transect/SB</th>
<th>Seismic Package (SP)</th>
<th>Lower SU</th>
<th>Lower Reflection Terminations (Vail., 1977)</th>
<th>Upper SU</th>
<th>Upper Reflection Terminations (Vail., 1977)</th>
<th>Large-scale Gamma-Ray trend</th>
<th>Lithological Log (SWC)</th>
<th>Sequence ages from biostratigraphy &amp; well completion reports</th>
</tr>
</thead>
<tbody>
<tr>
<td>B Barrow</td>
<td>BarrowSP7</td>
<td>BarrowSU7</td>
<td>Onlaps</td>
<td>Sea Floor</td>
<td>Toplap</td>
<td>NA</td>
<td>NA</td>
<td>&lt;1.77 Ma BP^ to Recent</td>
</tr>
<tr>
<td>B/Barow</td>
<td>BarrowSP6</td>
<td>BarrowSU6</td>
<td>Offlap/Downlaps</td>
<td>BarrowSU7</td>
<td>Truncations</td>
<td>Progradational</td>
<td>Calcarenite&amp; minor Marl</td>
<td>1.77 Ma BP^ to Recent</td>
</tr>
</tbody>
</table>
| B/Barow         | BarrowSP5           | BarrowSU5 | Onlaps                                   | BarrowSU6| Truncations/Downlap                       | Retrogradational            | Calcarenite, Calci
tilite & Calcarenite                  | late Miocene-Pliocene                                         |
| B/Barow         | BarrowSP4           | BarrowSU4 | Downlaps/Offlap                           | BarrowSU5| Truncations                               | Aggradational               | Calcarenite, Calci
tilite                                  | early-middle Miocene to late Miocene-Pliocene                |
| B/Barow         | BarrowSP3           | BarrowSU3 | Downlaps/Offlap                           | BarrowSU4| Truncations                               | Progradational              | Calcarenite, Calci
tilite& minor Marl                    | Oligocene to early-middle Miocene                             |
| B/Barow         | BarrowSP2           | BarrowSU2 | Downlaps                                 | BarrowSU3| Truncations                               | Progradational to Aggrad
tational | Marl, Claystone, Calci
tilite & Calcarenite                | early-middle Eocene to Oligocene                              |
| B/Barow         | BarrowSP1           | BarrowSU1 | Onlaps/Downlaps                           | BarrowSU2| Truncations                               | Aggradational/ Retr ograd
tational | Basal Claystone, Marl & Calci
tilite | Palaeocene to early-middle Eocene                            |
| A/Dampier       | DampierSP9          | DampierSU9| Onlap/Toplaps                             | Sea Floor| Toplap                                    | Aggradational               | N/A                      | Pleistocene^ to Recent                                         |
| A/Dampier       | DampierSP8          | DampierSU8| Downlaps/Offlap                           | DampierSU9| Toplap                                    | Progradational              | Calcaremite                                            | Pleistocene^ to Recent                                         |
| A/Dampier       | DampierSP7          | DampierSU7| Onlaps/Offlap                             | DampierSU8| Truncations                               | Retrogradational to Aggrad
tational | Calci
tilite, Calci
tilite & minor Calcarenite            | Pliocene to Pleistocene^                                        |
| A/Dampier       | DampierSP6          | DampierSU6| Downlaps                                 | DampierSU7| Truncations                               | Progradational              | Sandstone with minor Calcarente & Dolomite                  | middle Miocene to Pliocene                                    |
| A/Dampier       | DampierSP5          | DampierSU5| Downlaps                                 | DampierSU6| Truncations                               | Aggradational to Prograd
tational | Calcarenite & Dolomite                                      | early-middle Miocene                                         |
| A/Dampier       | DampierSP4          | DampierSU4| Downlaps/Offlap                           | DampierSU5| Truncations/Toplap                        | Aggradational to Prograd
tational | Calcarenite, Calci
tilite, Calci
tilite & Marl         | Oligocene to early-middle Miocene                             |
| A/Dampier       | DampierSP3          | DampierSU3| Downlaps/Offlap                           | DampierSU4| Truncations                               | Progradational              | Calcarente, Marl & minor Claystone                        | early-middle Eocene to Oligocene                              |
| A/Dampier       | DampierSP2          | DampierSU2| Downlaps                                 | DampierSU3| Truncations                               | Progradational              | Marl & minor Claystone                                      | late Paleocene-early Eocene                                  |
| A/Dampier       | DampierSP1          | DampierSU1| Onlaps                                   | DampierSU2| Truncations                               | Retrogradational            | Basal Claystone, Marl & Calci
tilite | late Paleocene-early Eocene                                  |
4.1. Sequence Stratigraphic Framework of the Barrow Sub-basin

Seven seismic unconformities and seismic packages were identified from seismic and well data in Transect B (Table 3) were used in the interpretation of two second-order sequences (S1 and S2) in the Barrow Sub-basin (Fig.5). Summarized below is the interpretation of the Paleocene to Oligocene, Oligocene to late Miocene-Pliocene and late Miocene-Pliocene to Recent seismic packages and second-order sequences.

4.1.1. Paleocene to Oligocene Stratigraphy of the Barrow Sub-basin

Seismic packages BarrowSP1 and BarrowSP2 contain the Cardabia Calcarenite and the Giralia Calcarenite of the Palaeocene to Oligocene stratigraphy (Fig. 5). Both represent the first Tertiary T-R cycle of sequence S1 in the Barrow Sub-basin (Fig.5). Paleocene to early-middle Eocene seismic package BarrowSP1 overlies the regional hiatus BarrowSU1 and displays low-
lying reflections thickening NW and SE (Figs. 6-8). Seismic onlap is found to the SE, and
downsputs to the NW are seen above seismic unconformity BarrowSU1 (Table 3). Seismic
package BarrowSP1 contains claystones, interbedded marl and trace calcilutites that fining-up
to a maximum flooding surface in West Tryal Rocks 2 and Spar 1 (Table 3). Industry well
interpretations suggest the Cardabia Calcarenite has a variable degree of carbonate to
siliciclasite content, depending on marginal and distal portions of the slope (Hocking et al.,
1987). Additionally, the Cardabia Calcarenite has formed on low energy shelf to outer-shelf
conditions (Apthorpe, 1988). From these data, seismic package BarrowSP1 was interpreted as
the late TST of second-order T-R sequence S1 (Fig.5).

Deposition of seismic package BarrowSP2 began following a maximum flooding surface at
seismic unconformity BarrowSU1 during the early-middle Eocene to Oligocene in Sequence
S1 (Table 3). In seismic package BarrowSP2, truncations were identified below seismic
unconformity BarrowSU3, and the high-amplitude, v-shaped reflection configuration (Figs.7 &
8) was interpreted as channels (Fig.9). The Giralia Calcarentite has a coarser grainsizes than
the surrounding units (Hocking et al., 1987). Similarly well data from Spar 1 and West Tryal
Rocks 2 support this observation with aggradational gamma ray trends and fine-grained
carbonate sediments (Table 3). Seismic package BarrowSP2 was interpreted an early-middle
Eocene to Oligocene regressive package, part of the RST in second-order sequence S1 (Fig.5).
Figure 6: Down-dip 2D seismic section C93:ct93-406 of the Barrow Sub-basin displaying the initial and interpreted seismic data. Seismic section shows seismic packages (BarrowSP1-7) with their corresponding seismic unconformities (BarrowSU1-7) and formation names as defined by Hocking et al. (1987). Black lines have been drawn in in seismic package BarrowSP3 to show the geometry and direction of progradation of the clinoforms with a closer view to the reefs in seismic package BarrowSP4.
Figure 7: Down-dip arbitrary line TB3 of the Barrow Sub-basin study region, displaying an overview of the interpreted seismic unconformities (BarrowSU1-7) with their corresponding seismic packages BarrowSP1-7. The overall transgressive and regressive trend of the seismic packages is presented in the transgressive-regressive triangles alongside the lower frequency second-order sequences. Intersection with arbitrary line TB2 (Fig.8) is indicated in red.
Figure 8: Arbitrary line TB2 in the Barrow Sub-basin, displaying an overview of the interpreted seismic unconformities BarrowSU1-7 with their corresponding seismic packages BarrowSP1-7. The second-order T-R sequences are displayed on the right with their corresponding triangles. Note the intersection with down-dip arbitrary line TB3 (Fig.7) is indicated in red. WTR 2= Well West Tryal Rocks 2, which displays gamma-ray log (API).
### Seismic Facies Classification and Examples

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#### B) Low frequency
- High amplitudes to reflection free
- Continuous reflections
- Parallel to divergent reflections

#### Interpretation:
- Prograding, regressive
- Shelf clinoforms

Seismic Packages:
- BarrowSP3, BarrowSP6
- DampierSP4, DampierSP5

#### C) High-amplitude and relief
- Low frequency
- Contorted
- Discontinuous

#### Interpretation:
- Carbonate reefs, barriers
  - Build-ups

Seismic Packages:
- BarrowSP4, BarrowSP6
- BarrowSP7
- DampierSP5, DampierSP7
- DampierSP8, DampierSP9
Figure 9: Summary of the seismic facies with examples of the Barrow Sub-basin and Dampier Sub-basins. The interpretation of 2D seismic facies has been categorized from A-G. The interpretations of the seismic facies are shown on the right in conjunction with the corresponding seismic packages in both the Dampier and Barrow Sub-basins. Time is given in (Sec TWT) on both down-dip and along-strike sections.
4.1.2 Oligocene to middle-late Miocene stratigraphy, Barrow Sub-basin

Seismic unconformity BarrowSU3 represents the base of the Oligocene to late Miocene-Pliocene strata of the Cape Range Group (Fig. 6). In the Barrow Sub-basin the Cape Range Group locally consists of the Mandu Limestone and Trella Limestone corresponding to seismic packages BarrowSP2 and BarrowSP3 (Fig.5).

Seismic package BarrowSP3 displays progradational clinoforms (Fig.9) that steepen NW and later flatten (Figs.7 & 8), indicative of normal regression. Likewise, the coarsening-upwards trend gamma logs (Table 3) implies seismic package BarrowSP3 was deposited during regressive conditions. Well reports indicate that the age of seismic package BarrowSP3 is Oligocene to lower-middle Miocene (Table 3) and represents the Manu Limestone (Heath and Apthorpe, 1984). Side-wall cutting descriptions indicate that seismic package BarrowSP3 consists of calcarenite, clacisiltite and calcilutites (Table 3).

Seismic package BarrowSP4 represents the early-middle Miocene to late Miocene-Pliocene Trella Limestone (Fig. 5) bound by seismic unconformities BarrowSU4 and BarrowSU5 (Fig.6). The clinoforms in seismic package BarrowSP4 prograde NW, however they are sigmoidal towards the base, suggesting the accommodation was greater than conditions during the deposition of the underlying Mandu Limestone (Fig.6). Seismic unconformities BarrowSU4 and BarrowSU5 were easily traced across seismic profiles as they represented continuous reflections consistent with small breaks in the aggradational gamma-ray trend (Table 3). High-amplitude, low-frequency, contorted seismic facies (Fig.9) to the SE of seismic profiles in seismic package BarrowSP4 were interpreted as the first visible carbonate reefs (Fig.6). The low resolution of the 2D seismic data displayed in seismic package BarrowSP4 limited the interpretation of carbonate reefs however this was further investigated using 3D seismic data. From these data, seismic package BarrowSP4 was interpreted as a regressive package that displayed the initial evidence of carbonate reef growth within the late RST of sequence S1 (Fig.5).

4.1.3 Late Miocene-Pliocene to Recent stratigraphy of the Barrow Sub-basin

Seismic unconformity BarrowSU5 marks the end of regression in second-order sequence S1 in the Barrow Sub-basin (Fig.5), and the beginning of the deposition of the late Miocene-Pliocene to Recent Delambre Formation. The Delambre Formation is bound between sequence boundary
SBB and the present day sea floor and is sub-divided into seismic packages BarrowSP5, BarrowSP6 and BarrowSP7 (Figs. 5 & 6).

Prominent onlaps found at the base of seismic package BarrowSP5 (Table 3), with backstepping reflections in down-dip seismic profiles (Figs. 7-9) suggest marine transgression occurred above sequence boundary SBB. Seismic unconformity BarrowSU6 (dated ~1.77 Ma BP from Gallagher et al., 2009), marks the upper boundary of seismic package BarrowSP5 and the end of the TST of sequence S2 (Figs. 5 & 6). Biostratigraphy dates seismic package BarrowSP5 as late Miocene to middle Miocene-Pleistocene (~1.77 Ma BP, Table 3). Seismic package BarrowSP5 consists of fine-grained carbonates including calcilutite, clacisiltite and calcarenites (Table 3). High-amplitude reef structures at the base of the late Miocene to Pliocene seismic unconformity BarrowSU5 shift progressively SE with the retrograding reflectors implying the reefs have backstepped. Several ~2km wide canyons were identified at the base of seismic unconformity BarrowSU5, and were observed throughout seismic package BarrowSP5 (Fig. 8). These canyons prograde slightly NW but mostly aggrade suggesting a significant sediment supply to the shelf during a relative increase in accommodation. The geomorphology of these canyons within seismic package BarrowSP5 was further investigated using 3D seismic attributes.

Seismic package BarrowSP6 in the Barrow Sub-basin is bound below by seismic unconformity BarrowSU6 and above by erosional surface BarrowSU7 (Fig. 5). Downlapping reflections can be seen directly above seismic unconformity BarrowSU6 (Table 3). The clinoforms steepen to the NW indicative of a fall in base level and accommodation <1.77 Ma BP. The geometry of the clinoforms in seismic package BarrowSP6 is comparable to those previously interpreted within the Oligocene to early-middle Miocene seismic package BarrowSP3 (Fig. 7 & 9). Gamma logs initially coarsen-up and later fine-up within seismic package BarrowSP6 (Table 3). Lithological data from West Tryal Rocks 2 and Spar1 show seismic package BarrowSP6 consists of calcarenite and calcicilutite (Table 3). High-amplitude, low-frequency seismic facies were interpreted as reefs (Fig. 9). These reefs appear directly above the prograding clinoforms, within the uppermost reflections in seismic package BarrowSP6 (Fig. 6 & 7). Seismic package BarrowSP6 was interpreted as a Pleistocene to Recent regressive carbonate ramp which evolved to a rimmed platform within the RST of sequence S2 (Fig. 5).
The final seismic package of the Barrow Sub-basin BarrowSP7, is dated Pleistocene to Recent (Table 3). Seismic package BarrowSP7 is bound by the erosional surface BarrowSU7 and the sea floor (Fig.5). This seismic package was interpreted using the seismic geometries, reflection configurations and terminations as no well data was available at this depth. Down-dip seismic lines display high-amplitude basal onlaps at seismic unconformity BarrowSU7, with retrograding reflectors later forming aggrading clinoforms (Figs.7 & 9). Seismic package BarrowSP7 was interpreted as a Pleistocene to Recent normal regressive to transgressive package, deposited above erosional surface BarrowSU7.

4.2 Sequence Stratigraphic Framework of the Dampier Sub-basin

Wells Tidepole 1, Rankin 1, Finucane 1 and EagleHawk 1 (Table 3), supported the interpretation of the nine seismic packages and seismic unconformities in the Dampier Sub-basin. Two second-order T-R sequences (S1 and S2) separated by sequence boundary SBD (Fig.5) define the stratigraphic evolution of the Dampier Sub-basin.

4.2.1 Paleocene to Oligocene Stratigraphy of the Dampier Sub-basin

The Paleocene to Oligocene strata was interpreted in seismic packages DampierSP1-3, between the regional hiatus (Heath and Apthorpe, 1984) DampierSU1, to seismic unconformity DampierSU4 (Fig.5). Seismic package DampierSP1 comprises both the Lambert and conformably overlying Dockerall Formations (Fig.5) and is characterized by low-lying reflectors (Figs. 9 & 10). These consist of fine grained marls with minor calcicilutites and claystones (Table 3). Previous work describes the Lambert and Dockerall Formations as fine-grained, silty claystones deposited during marine transgression (Hocking et al., 1987). A relatively high, retrogradational gamma response fines-up to a maximum flooding surface at seismic unconformity DampierSU2 (Table 3). Seismic package DampierSP1 was interpreted as a Paleocene to early Eocene, late TST of second-order sequence S1 in the Dampier Sub-basin (Fig.5).

Early Eocene to early-middle Eocene seismic package DampierSP2 (Table 3) in the Dampier Sub-basin, is bound by seismic unconformities DampierSU2 and DampierSU3 (Fig.10). Seismic package DampierSP2 is represented by low to high amplitude aggradational seismic reflectors (Figs.9-10). These are consistent with fine-grained marl and inter-bedded claystones
Seismic package DampierSP2 was interpreted as a part of the early RST of sequence S1, overlying a maximum flooding surface at DampierSU2.

Seismic package DampierSP3 represents the last pre-Oligocene seismic package that displays progradational to aggradational clinoforms in the down-dip profiles (Fig.11 & 12). Well data indicates seismic package DampierSP3 contains calcilutites with trace marls and claystones that generally produce a lower-gamma response than the surrounding clay and marl rich packages (Table 3). Seismic package DampierSP3 in the Dampier Sub-basin was interpreted as an early-middle Eocene to Oligocene regressive package within the RST of sequence S1 (Fig.5).
Figure 10: Down-dip 2D seismic line Gpdb95-11 of the Dampier Sub-basin displaying the seismic packages DampierSP1-DampierSP9 with their corresponding seismic unconformities DampierSU1-DampierSU9 and formation names derived from (Hocking et al). A well (EagleHawk1) is displayed reference also showing the gamma-ray data (API) response to the seismic packages in the to the Cenozoic strata interpretation.
Figure 11: Down-dip 2D seismic line from the Dampier Sub-basin displaying the interpretation of seismic packages DampierSP1-DampierSP9, the seismic unconformities DampierSU1-DampierSU9. The overall regressive and transgressive interpretation of the seismic packages is displayed with the T-R triangles to the right as well as the TST and RST of sequences S1 and S2 and sequence boundary SBD (displayed as the thick red line).
Along-Strike Seismic Line: S136.19

- Delambre Fm (upper Miocene to Recent)
- Bare Fm (middle Miocene to upper Miocene-Pliocene)
- Trella Limestone lower-middle Miocene to upper Miocene-Pliocene
- Mandu Limestone (Oligocene to lower-middle Miocene)
- Walcott Fm (middle-upper Eocene to Oligocene)
- Wilcox Fm (upper Paleocene to lower-middle Eocene)
- Lambert and Dockerell Fm (lower to upper Paleocene)

**Figure 12:** Along-strike seismic line S136.19 displaying the interpretation of seismic packages DampierSP1-DampierSP9, the seismic unconformities DampierSU1-DampierSU9. EagleHawk 1 and Finucane 1 gamma logs (API) are displayed for reference and the T-R cycles of the interpretation are shown on the left.
4.2.2 Oligocene to Middle-Late Miocene Stratigraphy of the Dampier Sub-basin

The Oligocene seismic unconformity DampierSU4 is the base of the seismic package DampierSP4 that includes the Mandu Limestone, the first formation of the Cape Range Group in the Dampier Sub-basin (Fig.5). Seismic unconformity DampierSU4 represents the downlap surface of the prograding clinoforms in seismic package DampierSP4 (Figs.10 & 11). These clinoforms steepen to the NW and flatten before the early-middle Miocene seismic unconformity DampierSU5 (Fig.12). With the exception of some seismic pull-up, most of seismic package DampierSP4 is represented by low to high amplitude diverging reflectors (Fig.10). Well data indicates that seismic package DampierSP4 contains basal marls and claystones that coarsen upwards to calcilutites, calcisiltites and calcarenites (Table 3). Based on the seismic geometry and well data, seismic package DampierSP4 was interpreted as Oligocene to early-middle Miocene non-tropical carbonate ramp, part of the RST of sequence S1 (Fig.5).

The second Miocene seismic package DampierSP5 contains the Trella Limestone and is bound by seismic unconformities DampierSU5 and DampierSU6 (Fig.5). As with the Trella Limestone in the Barrow Sub-basin, seismic package DampierSP5 contains progradational clinoforms with contorted, high amplitude, low-frequency reflections to the SE. These reflections were interpreted as carbonate reef seismic facies (Fig.9). Unlike the Barrow Sub-basin, the carbonate reefs were presented in several high resolution seismic inlines, where the onset and evolution of the reef structures was investigated (Fig.13). The onset of the reefs began in the early-middle Miocene at the base of the Trella Limestone indicated at (1) (Fig.13). Initiation of reefs takes place during a TST, as represented by basal onlap above surface DampierSU5. The first generation of reefs at (1) aggrade during highstand after the maximum flooding surface to (2). During lowstand the carbonate reefs prograde to the rim of the margin to (3). The reefs shift landwards to the SE during transgression to (4), where they continue to aggrade and further backstep landwards until eventually drowning in the middle Miocene to Pliocene at (5). Well data indicates the reefs consist of calcarenite and dolomites (Fig.3) around Finucane 1 (Fig.12) suggesting that some reefs have undergone a degree of diagenetic alteration. Given the assumption that tropical carbonate systems have the ability to produce wave resistant structures on the rims of margins (Schlager, 2005), seismic package DampierSP5 has been interpreted as an early-middle Miocene to Pliocene tropical carbonate platform.
1. Reefs initiate growth during marine transgression
2. Reefs aggrade and slightly prograde to the NW during highstand
3. Reefs shift basinwards in response to a decrease in accommodation space (lowstand)
4. Reefs begin to backstep landwards in response to transgression
5. Reefs aggrade and further backstep to the SE, lastly drown

Figure 13: Down-dip inline S136:136_13 of the Dampier Sub-basin showing the progradational clinoforms of the Mandu Limestone (seismic package DampierSP4) and the Trella Limestone (seismic package DampierSP5). Systems tracts including the transgressive systems tract (TST), highstand systems tract (HST), lowstand systems tract (LST) and falling stage systems tract (FSST) have been interpreted with the corresponding seismic unconformities, transgressive surfaces (TS) and maximum flooding surfaces (MFS). In the seismic section below, the interpreted onlaps and downlaps in the Trella Limestone are shown with the coloured arrows and the evolution of the reefs during the early-middle Miocene on the platform margin is outlined corresponding to the numbers (1-5).
Downlap surface seismic unconformity DampierSU6 was interpreted in the along strike profiles where the clinoforms eventually terminate towards the Beagle Sub-basin ~5km W of Finucane 1 (Fig.12). Well data indicates that seismic package DampierSP6 consists of mixed carbonate-siliciclasite sediments (Table 3) corresponding to the Bare Formation (Heath and Apthorpe, 1984). Seismic data shows the Bare Formation progrades in multiple directions to the NW, NE and NNW. This observation has a number of implications regarding the shelf depositional processes and was further investigated in the 3D attribute analysis. No seismically recognizable reef structures were identified in the interval suggesting reef growth discontinued during the deposition of the Bare Formation. The Bare Formation intersected all wells and displayed a coarsening-upwards and distinctly higher gamma response than the underlying Trella Limestone (Table 3). Well data shows that the Bare Formation consists of frosted, medium grained, sub-rounded to rounded quartz sandstones, inter-bedded with calcarenite and calcilutite deposited during the middle Miocene to late Miocene-Pliocene (Table 3).

4.2.3 Late Miocene-Pliocene to Recent Stratigraphy of the Dampier Sub-basin

The late Miocene-Pliocene to Recent Delambre Formation forms second-order sequence S2 of the Dampier Sub-basin (Figs. 5 & 11) and consists of three seismic packages DampierSP7, DampierSP8 and DampierSP9 (Fig.5). Progressive onlap and retrograding reflectors are seen at the base of the late Miocene-Pliocene to Pleistocene seismic package DampierSP7 above sequence boundary SBD (Table 3). The reflections in seismic package DampierSP7 are low amplitudes, parallel and continuous (Fig.14). Well data shows a high gamma ray response linked to fine-grained calcilutites and calcisiltites (Table 3). Seismic package DampierSP7 was interpreted as a late Miocene-Pliocene to Pleistocene TST of sequence S2 in the Dampier Sub-basin.

The second seismic package of the Delambre Formation was DampierSP8 (Fig.10) and was dated Pleistocene to Recent (Table 3). Seismic package DampierSP8 shows aggrading to prograding clinoforms to the NW (Figs. 10 & 11). The underlying reflectors downlap at the base of seismic unconformity DampierSU8, while reflectors below seismic unconformity DampierSU9 are truncated (Table 3). Reflections below erosional surface DampierSU9 are contorted and are truncated by small incisions (Fig.11), previously described as possible exposure or karst features (Cathro et al., 2003). The gamma-ray trend displayed in wells coarsens-upward corresponding to the calcarenite found throughout seismic package
DampierSP8 (Table 3). Seismic package DampierSP8 was interpreted as a Pliocene-Pleistocene regressive seismic package of the RST in sequence S2 (Fig.5).

No lithological descriptions were available within the depth interval of seismic package DampierSP9, therefore the interpretation has been based on seismic data and gamma-ray logs. Reflections within seismic package DampierSP9 onlap at the base of DampierSP8 (Table 3), suggesting a period of marine transgression post exposure of surface DampierSU9 (Fig.11 & 14). The reflections retrograde and later aggrade in response to a relative decrease in accommodation within seismic package DampierSP9 (Fig.10 & 11). Likewise the gamma logs indicated addradational deposition (Table 3). Reefs were visible within seismic package DampierSP9, which backstepped with the retrograding reflectors as found in the Barrow Sub-basin (seismic package BarrowSP7). Seismic package DampierSP9 was interpreted as a Pleistocene to Recent normal regressive to transgressive package, overlying erosional surface DampierSU9 in the Dampier Sub-basin.
4.3 Depositional Environments: Insight from Seismic Geomorphology

An examination of the relative distribution of preserved strata in three-dimensions gives insight into the paleo-geographic environment and processes that influence the slope and margin architecture through time. The seismic attribute analysis on the West Barrow and Demeter 3D surveys recognized the broad depositional systems of seismic packages in the Cenozoic strata including: non-tropical carbonate ramps, tropical carbonate platforms and a mixed carbonate-siliciclastic deposit.

4.3.1 Non-tropical Carbonate Margins and Slopes

Coherency and RMS attributes were calculated on selected horizons in the Demeter and West Barrow seismic surveys, to investigate the depositional environments of the Oligocene to early-middle Miocene and Pliocene-Pleistocene non-tropical carbonate ramps identified in the 2D seismic stratigraphic analysis. The non-tropical carbonate ramps usually displayed featureless areas and/or mass transport deposits, canyons and channels.

4.3.2.1 Non-tropical Oligocene to early-middle Miocene Ramps

The stratigraphic analysis interpreted seismic packages BarrowSP3 (Barrow Sub-basin) and DampierSP4 (Dampier Sub-basin) of the Mandu Limestone as Oligocene to early-middle Miocene non-tropical carbonate ramps. With the exception of large slump scarps displayed on some horizons, the Oligocene to early-middle Miocene carbonate ramps represented relatively featureless depositional margins and slopes in the NCB (Fig.14). The non-tropical ramps in the horizons traced in the Mandu Limestone, display low-amplitude reflectors with un-rimmed shelf-margins often appearing smooth and sometimes rounded at the shelf-breaks (Fig.14).

Slump scarps on non-tropical carbonate ramps are presented in the Barrow Sub-basin within regressive seismic package BarrowSP3 in sequence S1 (Fig.15). Coherency attributes overlain on the Oligocene seismic unconformity BarrowSU3, presents clear evidence of slumping at the base of the slope. The scarp head is relatively flat, has a low-amplitude and displays basal slump blocks (~0.01-1.5 km wide). Slump blocks represent segments of the pre-existing margin as they display similar acoustic reflection strengths as the ruptured scarp head (Fig.15).

Likewise slump scarps were observed on the non-tropical carbonate ramps in the Dampier Sub-basin. RMS attributes were overlain on two horizons in the Oligocene to early-middle Miocene
seismic package DampierSP4 (Fig.16). The geometry of the slump-scarp observed in the Dampier Sub-basin is comparable to Oligocene seismic unconformity BarrowSU3 (Fig.15) however the scarp is highly dispersed, continuous (>100 km) and located near the offlap break in the steepest-dipping clinoforms. The low-amplitude seismic reflections at the shelf margin display a similar strength to the fallen blocks to the NNW and the high-amplitude strengths are seen at the scarp and sediment surrounding the marginal blocks. The concave geometries of the scarp and rupture surfaces at the shelf margin are characteristic indicators that the downslope components of stress exceed the resisting slope strength (Nelson and Lindsley, 1987).

4.3.2.2 Non-tropical Pliocene-Pleistocene Ramps

The 2D seismic stratigraphic analysis interpreted that the lower reflections in the Pliocene-Pleistocene seismic packages BarrowSP6 and DampierSP8 were non-tropical ramps. A horizon was traced within the lower reflections of seismic package BarrowSP6 (Barrow Sub-basin, Fig.17) that displayed a relatively featureless low-amplitude margin with a large canyon system on the slope to the NNW, like the early-middle Miocene non-tropical carbonate ramp below (Fig.14). The canyons on the ramp slopes are ~0.5-1km wide, dispersed ~2.5-3km apart (Fig.17). Slope channels ~0.3km wide are seen at the base of the canyons with slump and mass-transport deposits represented by the hummocky reflections to the margin NW.

In the Demeter 3D seismic survey, coherency attributes were calculated on a horizon within the Pliocene-Pleistocene non-tropical carbonate ramp (Fig.17). Unfortunately the down-dip coverage of the survey limits the interpretation to the shelf rather than the slope and margin to the NW. The non-tropical carbonate shelf is represented by relatively flat lying reflections with a low amplitude strength, similar to the underlying shelf in the Oligocene to early-middle Miocene Mandu Limestone in seismic package DampierSP5 (Dampier Sub-basin, Fig.14).
Figure 14: Non-tropical carbonate ramps interpreted from horizon within seismic package BarrowrSP3 (Barrow Sub-basin, basin, top) and seismic package DampierSP4 (Dampier Sub-basin, bottom). The non-tropical ramps display rounded margins and slopes with generally low-amplitudes and featureless areas. The high-amplitude reflectors in the Barrow Sub-basin are seen on the upper slope were interpreted as seismic artefacts (pull-ups) from the overlying reefs in the Trella Limestone.
Figure 15: Coherency attribute map of the Oligocene seismic unconformity BarrowSU3 of the West Barrow 3D survey. Both scarps and slumps in A and B can be identified from slump blocks found down-dip at the basal portion of the slopes. Slump blocks display similar amplitude strength and shape links to the scarp head. Cross-line 9898 down-dip has been given for visual reference to show the basal location of the downlapping clinoforms of the overlying seismic Oligocene to early-middle Miocene seismic package BarrowSP3.
Figure 16: RMS attributes maps of two random horizons within Oligocene to early-middle Miocene seismic package DampierSP4 in the Demeter 3D survey Dampier Sub-basin. Map (A) shows extensive slumping across the slope using the RMS attributes in an upper horizon of the Mandu Limestone. Map (B) shows RMS attributes applied to lower horizon displaying some portions of the rounded slope to the west. Inline 3371 is shown to display the relative steepness of clinoforms at the particular intervals in A and B. Map view of the concave geometry of the rupture surface or scarp can be identified in the upper horizon (A) of Oligocene to early-middle Miocene seismic package DampierSP4.
Figure 17: Coherency attributes overlain on Pliocene-Pleistocene horizons from the non-tropical carbonate ramps from the Barrow Sub-basin (above) seismic package BarrowSP6 and the Dampier Sub-basin DampierSP8 (below). The upper horizon (Barrow Sub-basin) shows a low-amplitude shelf with steep shelf canyons and mass-transport deposits at the margin. The horizon in the Dampier Sub-basin (bottom) displays a low-amplitude shelf. The interpretation in the Dampier Sub-basin is restricted to the shelf with no downslope coverage to the NW.
4.3.3 Tropical Carbonate Margins and Slopes

In 2D seismic data, low-frequency contorted seismic facies were interpreted as carbonate reefs that were identified in the early-middle Miocene to Pliocene seismic packages BarrowSP4 and DampierSP5 and the Pliocene to Recent seismic packages BarrowSP5-7 and DampierSP7-9. The 3D seismic attribute analysis presents carbonate reefs as either continuous, elongate bodies, parallel or slightly oblique to depositional strike as barriers and ridges, or localised build-ups and patch reefs on the platform rim and shelf.

4.3.3.1 Early-middle Miocene Rimmed Margins

The first visual evidence for carbonate reef growth in the 2D seismic data of the Barrow Sub-basin was the high-amplitude, contorted reflections within early-middle Miocene to late Miocene-Pliocene seismic package BarrowSP4 (Fig.6). Coherency attributes were calculated on seismic unconformity BarrowSU4, the base of the Trella Limestone (Fig.18). This horizon displayed a number of oval shaped build-ups (<3km in diameter) on topographically-high ridges located landwards SE ~30-60 km from the platform margin. The strike-elongate belts of build-ups were interpreted as middle to late Miocene barrier reefs that were generally higher-amplitudes than the adjacent margin, scarp and slope (~12-15 km NW), ~5km wide spanning for >90 km along the platform margin. Most barrier reefs were strike-parallel (NE-SW) and sometimes slightly oblique suggesting either structural influences or alongshore waves and/or wind-induced currents.

Coherency attributes were calculated on a horizon at the base of seismic package DampierSP5 (Dampier Sub-basin) to determine the three-dimensional distribution and evolution of the carbonate reefs identified from 2D seismic data (Fig.19). A high-amplitude, strike-parallel barrier reef complex ~35km was identified on the platform margin ~6-12km to the SE of the large slump scarp. Circular-shaped (0.5-1.5km diameter) build-ups are seen on both the NW forereef and SE lagoonal setting. This horizon displays initial depositional environment of the early-middle Miocene first generations of reef growth displayed at (1) (Fig.13).
Figure 18: Coherency attribute maps overlain on seismic unconformity BarrowSU4 at the base of the Trella Limestone seismic package BarrowSP4 of the West Barrow 3D seismic survey. A) Represents the generalised orientation in map view, B) displays reef belts, slump scarp and Mass Transport Deposits the NW and C) view of the horizon displaying elongate reef belts. Cross-line 8398 has been given for visual aid and reference to the topographic highs found in two-dimensional seismic cross-lines.
Figure 19: Coherency attributes calculated on a horizon at the base of seismic package DampierSP5 (Trella Limestone) of Demeter 3D seismic survey. The horizon presents the initial evidence of tropical reefs in the form of barrier reefs, circular build-ups and patch reefs to the SE. An extensive slump scarp can be identified to the NW as indicated by the red-dashed line.
A second generation of barrier reefs in the Dampier Sub-basin was presented with coherency attributes calculated on a horizon within the upper reflections of early-middle Miocene to late Miocene-Pliocene seismic package DampierSP5 (Fig.20). The barrier reef spans >48km along-strike and is located ~18km from the sub-marine slope canyons at the NW edge of the survey. As with the older horizon (Fig.19), ~1.2 km build-ups were observed on the forereef slope and interior lagoonal setting to the SE. The progradation of the barrier reef complex as interpreted from the 2D seismic stratigraphic analysis from 1-3 (Fig.13) could again be observed when comparing the shift in position of the reefs (~5-7km) at the base of the Trella Limestone (Fig.19) to the upper horizon (Fig.20).

Mass-transport deposits and canyons were identified in the early-middle Miocene rimmed margins both the Dampier and Barrow Sub-basins. A horizon was traced overlying seismic unconformity BarrowSU4 in seismic package BarrowSP4 (Fig.21) to investigate the channelled reflectors to the NW of the reefs displayed in the 2D seismic inlines (Figs.7 & 8). Slump scarps extend NNE to SSW across the margin (>1000 km) and at the base of the scarp downslope (~1km), large canyons (~1.2 km wide) were presented at the upper slope likely feeding sediment into the gullies, and leveed channels at the slope base. Given seismic package BarrowSP4 contains mostly carbonate sediments (Table 3) with the visible basal splays and lobate masses around the <1km wide leveed channels, these deposits were interpreted as calciturbidites.

Calciturbidite deposits were not recognized in the Dampier Sub-basin, perhaps due to the lack of survey coverage; however multiple, circular low-relief seismic anomalies were recognized (Fig.22). The high-amplitude troughs are >4km wide and the circular depressions appear ~1-2.5km in diameter. These features were interpreted as mass-transport deposits located ~1-2 km NW downslope of the barrier reef complex.
**Figure 20:** Coherency attributes calculated on a random horizon within the upper seismic package DamperSP5 in the Demeter seismic survey. The fore-reef and back-reef settings are defined by low-amplitude reflectors between the high-amplitude barrier reef complex and the slope canyons to the NW. The barrier reef appears ~18km from the shelf slope where canyons and the high amplitude/relief strike-elongate feature S of the barrier has been interpreted as non-time stratigraphic associated with seismic pull-up.
Figure 21: Coherency attribute map applied to a horizon within early-middle Miocene seismic package BarrowSP4 of the Barrow Sub-basin. Using the 3D seismic attributes the v-shaped incisions/channel like features are interpreted as sub-marine canyons forming at the base of a slump (B), where down-slope they form smaller leveed channels, basal splays and lobate deposits (A) well data from WTR and Spar1 these have been geometrically interpreted as calciturbidites.
Submarine canyons were presented on the rimmed carbonate margins in several horizons traced in the early-middle Miocene to Pliocene strata of the NCB. In the Barrow Sub-basin, the horizon in seismic package BarrowSP4 (Fig.20) displays ~17 (1-2km wide) canyons 5-10 km to the NW of the tropical reefs. These canyons are connected with the smaller downslope gullies.
and the calciturbidite deposits to the NW, implying that they have a major role in the
distribution of carbonate sediments downslope.

Likewise, early-middle Miocene to Pliocene canyon systems were presented throughout the
Trella Limestone in the Demeter 3D seismic survey. Canyons were well imaged in early-middle
Miocene horizons with the barrier reef complexes on the slope margin (Fig.19). Up to 31 slope
canyons ~1.5km wide, <0.5km apart, are presented on the steep slopes to the NNW extending
>6km downslope (restricted by the survey coverage). These canyons are small but in higher
frequency across the margin than the early-middle Miocene seismic package BarrowSP4
(Barrow Sub-basin) and are adjacent to a ~36km² slump scarp in the NW of the survey.

4.3.3.2 Pliocene-Pleistocene Rim Margins

A secondary development of reef growth was interpreted in the Pliocene-Pleistocene strata in
both the Dampier and Barrow Sub-basins. A horizon overlying the middle late Miocene to
Pliocene sequence boundary SBB (Dampier sub-basin) presents patch reef ~20-25km to the SE
of the beach ridges from the underlying Bare Formation (Fig.23). Geometrically the patch reefs
are small circular to oval shaped build-ups separated by channels <1km wide. These reefs are
distributed on the topographically-high reflectors corresponding to the clinoforms of the
underlying Bare Formation. This observation suggests that the reefs have grown landwards on
the high-relief pre-existing during the late-Miocene to Pliocene major second-order TST of
sequence S2 (Fig.5).

From the 2D seismic interpretation, interpreted that carbonate reefs grew above the non-topical
carbonate ramp in seismic package BarrowSP6. Coherency attributes were calculated on a
selected horizon in seismic package BarrowSP6 above the non-tropical ramp (Fig.24). This
horizon displays high-relief and high-amplitude reflections interpreted as reefs located ~15-
16km from the platform margin and slope canyons to the NW. Using both horizons in the lower
and upper strata of seismic package BarrpwSP6 (Figs.17 & 24) the transition of a Pleistocene
non-tropical carbonate ramp to tropical rimmed platform was presented.

Coherency attributes overlain on horizons within seismic package BarrowSP7 of the West
Barrow 3D seismic survey, present reefs above the Pleistocene non-tropical carbonate ramp in
seismic package BarrowSP6 (Fig.25). The estimated percentage of high-amplitude high-relief
carbonate reefs on the platform margin was compared across three horizons: the Pleistocene
seismic unconformity BarrowSU7 and two horizons in the middle and upper strata of seismic
package BarrowSP7 (Fig.25). The decrease in reef coverage on the margin from the base of seismic unconformity BarrowSU7 (~60-70%), to the middle horizon (~40%) and upper horizon of seismic package BarrowSP7 (~30%), displays the indication of reef demise and backstepping during Pleistocene to Recent marine transgression.

Likewise coherency attributes were overlain on two horizons within the final Pliocene-Pleistocene seismic package DampierSP8 of the Demeter 3D seismic survey. A progressive backstepping of the barrier reefs over a distance of ~5 km is presented from the lower and upper horizons (Fig. 26). There are no faults observed on seismic data, suggesting that the pre-existing topography and possibly alongshore currents have shaped the depositional architecture and distribution of many Pliocene-Pleistocene carbonate reefs.

The Pliocene-Pleistocene rimmed margins displayed submarine canyons and shelf slump mass transport deposits in the 3D seismic analysis. Large incisions truncate the upper reflections of seismic package BarrowSP6 as identified from the 2D seismic analysis at the Pleistocene seismic unconformity BarrowSU7 (Figs.7 & 8). Coherency attributes overlain seismic unconformity BarrowSP7 show that these incisional features correspond to the cross-sectional view of shelf slump scarp (Fig.27). Slump blocks (<0.1 km) are smaller than those of the Oligocene to early-middle Miocene horizons and as displayed the contorted seismic reflection pattern interpreted in the 2D seismic analysis is the scarp sediment debris found at the scarp base (Figs.16 and 17).

The along-strike seismic profiles in the Barrow Sub-basin seismic package BarrowSP5 in the 2D seismic analysis displayed large aggrading v-shaped canyons (Fig.8). A horizon was traced in the middle of seismic package BarrowSP5 to display the geometry and depositional setting of the sub-marine canyons on the shelf slope aggrading through seismic package (Fig.28). Two wide (~1-5km) canyons separated by 3-4km aggrade during the deposition of seismic package BarrowSP5. These canyons differ from the tropical carbonate platform canyons SE of the calciturbidites of the Trella Limestone (seismic package BarrowSP4, Fig.21) as they appear more divergent to fan-shaped and are widely spaced. The large canyon systems appear to have formed during marine transgression (Fig.5) suggesting both the sediment supply accommodation was substantial during the Pliocene-Pleistocene in the Barrow Sub-basin.

The 3D seismic analysis of the Cenozoic strata presents a diverse range of mass-transport deposition and canyons in both the Barrow and Dampier Sub-basins, indicative of slope margin instability and increases in carbonate sediment production (Shipp et al., 2011). Widespread
evidence for mass-transport deposits since the Oligocene indicates that on a regional scale, the NCB may have been susceptible to submarine earthquakes and large increases in fine-grained, poorly consolidated sediment accumulation on both the tropical carbonate platforms and non-tropical carbonate ramps.
Figure 23: Coherency attributes overlain on time structure maps of seismic unconformity DampierSU6 in the Dampier Sub-basin, Demeter 3D survey. Inline 3075 is presented for two-dimensional seismic reference. Map view displays carbonate patch reefs and build-ups on the topographic highs from the underlying Bare Formation’s clinoforms fronts grown landwards (SE). The underlying pre-existing topography from the Bare Formation appears to have influenced the location of growth for the patch reefs as it displays similar depositional trends.
Figure 24: Coherency attributes overlain on a horizon within seismic package BarrowSP6 in the West Barrow 3D seismic survey. Map view shows that the high amplitude reflectors on the upper shelf SE correspond to carbonate reefs. In 2D seismic sections, the carbonate reefs appear in the uppermost reflections of seismic package BarrowSP6 above the interpreted non-tropical carbonate ramp clinoforms above seismic unconformity BarrowSU6.
Figure 25: Coherency attributes computed on three horizons within the Pleistocene to Recent seismic package BarrowSP7 in the Barrow Sub-basin. The first horizon in the base of seismic package BarrowSP7, seismic unconformity BarrowSU7, second image is a horizon in the middle of Pleistocene to Recent seismic package BarrowSP7 and the third horizon was selected in the upper strata of seismic package BarrowSP7. The approximate percentage coverage of reefs (high-amplitude and high relief reflectors) was estimated and compared across the three horizons.
Figure 26: Coherency attributes overlain on two horizons in the final seismic package DampierSP9 of the Dampier Sub-basin. A number of barrier reefs were observed both along strike and oblique to the shelf margin, reflecting a similar topography of the present day sea-floor. A similar reef back-stepping event in the Pleistocene Barrow Sub-basin strata is observed in the Dampier Sub-basin. Reefs appear to have shifted (comparing the position of the reef fronts 1 and 2) up to 5km to the SSE in response to marine transgression following the base level fall at seismic unconformity DampierSU9.
Figure 27: Coherency attribute map of seismic unconformity BarrowSP7 of the West Barrow 3D survey with 2D seismic line 9898. Incisions identified in the 2D stratigraphical analysis have been defined as slump scarps within the upper <1.55 M.a BP seismic packages BarrowSP6 and BarrowSP7. Seismic crossline 9898 (A) has been given to display seismic unconformity BarrowSP7 with the contorted reflections identified at the base of the slump scarps.
Figure 28: Coherency attributes overlain on horizon in seismic package BarrowSP5 of the West Barrow 3D survey. Coherency attributes overlain on this data identifies canyons feeding MTD’s downslope to the NNW corresponding to the v-shaped reflectors in seismic package BarrowSP5 (Delambre Formation) as shown in the 2D seismic data (Figs. 7 & 8).
4.3.4 Middle Miocene to Pliocene Siliciclastic Shoreline Deposition

Prograding, clinoforms were identified in early-middle Miocene to Pliocene seismic package DampierSP6 in the down-dip and along-strike 2D seismic profiles in the Dampier Sub-basin (Figs.11 & 12). Using well data, seismic package DampierSP6 was interpreted as the Bare Formation. The stratigraphic early-middle Miocene to Pliocene evolution and architecture of the Bare Formation was unravelled using coherency and spectral decomposition seismic attributes on four horizons from the base (seismic unconformity DampierSU6) to the top (seismic unconformity DampierSU7) of the Bare Formation.

Spectral decomposition attributes were calculated on a middle horizon within seismic package DampierSP6 of the Demeter seismic survey (Fig.29). The offlap break of the clinoforms sets previously observed on 2D seismic (Fig. 11 & 12) correspond to the fronts of lobate-shaped deposits. The Bare Formation was previously described from offshore wells as well sorted, sub-rounded to rounded frosted grains consisting of siliciclastic and carbonate sediments reworked onto the base of the underlying Trella Limestone (Heath and Apthorpe, 1984). Similar siliciclastic-carbonate deposits were recovered in the Bare Formation by the wells in Transect A (Table 3). The identification of mixed carbonate and sandstone sediments in the Bare Formation with a virtual absence of foraminifera (Heath and Apthorpe, 1984) suggests that the Bare Formation was deposited in a coastal setting. The maturity and frosting of the grains also suggest that the sandstones formed near shore to a beach or dune environment. On this basis the base of the Bare Formation is interpreted as frontal shoreface deposits.

A middle Miocene horizon traced within the Bare Formation (Fig.29) displays the front of the shoreline has a slightly oblique to s-shaped depositional strike. The obliqueness and s-shaped geometries of the shoreline suggest that coastal deposition was under strong influence of a NE-oriented oceanographic current. Littoral sediment transport along the shoreline was significant enough to transport sediment large distances, as the shoreline front span >90 km along strike (Fig.30). High-amplitude striations were observed in both coherency and spectral decomposition attribute maps (Fig.30). The survey displays several multiple strike-parallel striations are concave shaped and have been interpreted as beach ridges ~150m wide (Fig.31) and form a converging v-shaped geometry from both a W and E limb. Beach-ridges typically form parallel to the shoreline and are affected by the wave size and energy (Otvos, 2000). There is no seismic evidence of channels in the RMS, coherency and spectral decomposition attributes of the Bare Fm. This suggests that the Bare Formation deposits do not correspond to a river-fed
delta in the study area. Instead, the formation is interpreted as sand spit formed by the interaction between alongshore currents and wave deposition.

Investigating the changes in the paleo-shoreline of the shore face deposits through time helps identify the primary direction of the Miocene Dampier Sub-basin oceanic shallow water currents. The Paleoshore-shoreline 1 (PS1) of the Middle Miocene shows the initial deposition of the Bare Formation and shoreline (Fig. 32). Deposition appears down-dip NW as represented by the (~70km) strike-parallel front SE, away from the slope canyons (~22km) to the NW and mass-transport deposits (~10km) NW. The second paleo-shoreline (PS2) displays a change in shoreline architecture to s-shaped and oblique geometries (Fig.32). Comparing PS1 and PS2, the shoreline has prograded both down-dip (~8km shift in the shoreline position to the NW) and alongshore, as evidenced by the oblique s-shaped geometries. Paleo-shoreline three (PS3) shows the continuation of down-dip progradation during the middle-late Miocene to Pliocene (Fig.33). PS3 shows the v-shaped geometry of the prograding sand-spit system, with the tip of the spit reaching the edge of the Demeter 3D survey. The beach ridges in PS3 suggest a paleo-shoreline strike mostly perpendicular to the depositional strike of most seismic packages (NE-SW) interpreted in the Cenozoic strata. This may be indicative of a change in direction or strength of alongshore currents through time. Lastly, Paleo-shoreline four (PS4) represents the final geometry of the sand-spit system before the overlying deposition of the Pliocene to Recent TST of sequence S2 (Fig.33). Concave N-SE beach ridges are located on the western flank of the spit with NW-SE ridges to the eastern flank. From this it is interpreted that wave and or wind processes dominated depositional regime during deposition of the Bare Formation. These appear to vary over time from the initial NW or down-dip orientation, to the oblique NE and lastly N-NW direction through time.
Figure 29: Spectral decomposition (15, 50 and 70 Hz) attributes overlain on a centrally horizon traced within the Bare Formation or seismic package DampierSP6 of the Demeter 3D seismic survey. Using inline 2075 from the 3D survey, we can identify that the lowstand clinofoms correspond to lobate geometries of the shoreline deposits.
Figure 30: Coherency attributes overlain on a middle Miocene within the Bare Formation or seismic package DampierSP6. Strongly oblique to s-shaped shoreline deposits suggest the alongshore currents such as wind and or waves from the W-SW (indicated in the white arrow) have impacted the preserved depositional geometry as represented in the 3D seismic data.
Figure 31: Blended spectral decomposition (15, 25, 30 Hz) and coherency attributes overlain on the late Miocene-Pliocene uppermost horizon of seismic package DampierSP6 in Demeter 3D seismic survey. The prominent down-dip striations correspond to beach ridges, that can be observed striking NW-SE on the E limb, and NW-SSW on the W limb of the v-shaped wedge. A number of carbonate reefs have been identified landwards of the Bare Formation shoreline, interpreted to have grown during the early TST of S2.
Figure 32: Blended spectral decomposition (15, 50, 70 Hz) attributes calculated on lower horizon paleo-shoreline (PS1) (middle Miocene) and the overlying horizon displaying paleo-shoreline (PS2) (middle Miocene) within the Bare Formation and presented in map view. PS1 presents the paleo-shoreline of the Bare Formation as mainly strike-parallel (NE-SW) with PS2 showing the shift (as indicated with the arrows) of the shoreline to the NW with the transition to more oblique s-shaped paleo-shoreline geometry.
Figure 33: Blended spectral decomposition (15, 50, 70 Hz) attributes calculated on horizons displaying paleo-shoreline 3 (PS3) (Middle-Late Miocene) and horizon paleo-shoreline 4 (PS4) (Late Miocene-Pliocene) and presented in map view. PS3 presents the paleo-shoreline of the Bare Formation as slightly oblique to the regional depositional strike and PS2 shows the progradation and growth of a v-shaped protrusion and beach ridges.
5. Discussion

5.1 Cenozoic Stratigraphic Evolution and Conceptual Model

The integration of well, 2D and 3D seismic, allowed the reconstruction of the evolution of the Cenozoic post-rift sedimentation along the margins of the NCB. From the Palaeocene to the present-day, spanning ~65 Million years, five broad depositional regimes are summarized. These included alternating non-tropical and tropical carbonate margins, with a minor episode of siliciclastic sedimentation. The carbonate factories fed sediment to the slopes and basins by mass-transport processes and turbidity currents. A summary of the Cenozoic evolution of the Dampier and Barrow Sub-basins (1-5) is presented below, corresponding to schematic diagrams (Figs. 34 & 35):

1) Paleocene to Oligocene: siliciclastic to carbonate sedimentation

Seismic packages DampierSP1-3 and BarrowSP1-2 (Figs.34 & 35) were deposited during the Palaeocene to Oligocene. This succession formed a late TST to early RST of sequences S1 in the NCB (Fig.5). This consists of Paleocene low-energy, marine, fine-grained marl and claystones deposits that grade to carbonates by the Oligocene seismic unconformity (DampierSU4 and BarrowSU3).

2) Oligocene to early-middle Miocene non-tropical carbonate ramps

The Oligocene to early-middle Miocene Mandu Limestone (DampierSP4 and BarrowSP3) was deposited as the early RST of sequences S1 in the Dampier and Barrow Sub-basins. The Mandu Limestone developed as a distally steepened, non-tropical carbonate ramp (Figs.34 & 35). The non-tropical carbonate ramp developed during long-term marine regression, where a substantial quantity of sediment was exported to the shelf margin. This was represented by the extensive slump scarps on the shelf breaks (Fig.15 & 16) and channels on the slopes (Fig.14).

3) Early-middle Miocene to late Miocene-Pliocene tropical carbonate ramps

Following deposition of the Mandu Limestone, was the early-middle Miocene to late Miocene-Pliocene (Trella Limestone), presented in seismic packages BarrowSP4 and DampierSP5. The Trella Limestone developed strike elongate barrier reefs (Fig.18) initiating on the rims of the platforms to the SE, during a high-frequency TST (Fig.13) in sequences S1. Patch reefs and circular carbonate build-ups developed in the low-energy lagoonal setting of the platform.
interior (Figs.19 & 20), protected from high-energy wave action. The early-middle Miocene tropical carbonate platforms produced sufficient loads of sediment that was shed via the slope canyons and channels (Fig.20) to the mass-transport deposits and calciturbidites in the basin (Fig.21).

3b) Middle Miocene to late Miocene-Pliocene (Bare Formation, Dampier Sub-basin)

During late regression in sequence S1 (Fig.5), the Bare Formation deposited in the Dampier Sub-basin over the middle Miocene to Pliocene (Figs. 34 & 35) as a coastal sand-spit (Figs. 31 & 32) or shelf-edge delta (Sanchez et al., 2012). Siliciclastic sediments were fed to the Dampier sub-basin via an external river source and were further reworked by wind and/or wave action by a NW flowing alongshore current. Over-time the Bare Formation developed as an oblique siliciclastic sand-spit deposit by the late Miocene Pliocene (Fig.33). This formed beach ridges (Fig.31) and sets of lobate shoreline deposits (Fig.29).

4) Late Miocene-Pliocene to Pleistocene Non-tropical ramps

The Delambre Formation was deposited overlying the late-Miocene to Pliocene sequence boundaries (SBB and SBD) formed as the base of the TST of sequences S2 (Fig.5). A low frequency rise in base-level, led to an increase in accommodation, subsequently leading to a backstepping and drowning of the Miocene carbonate reefs. During low frequency transgression, the production rate significantly increased, increasing the accumulation loads of sediment on the margin. Sediment gravity flows eroded the continental slope forming the large incisional canyons in the Barrow Sub-basin (Fig.28). Following the major late Miocene-Pliocene to Pleistocene TST of sequences S2, the margin developed into a non-tropical carbonate ramp (Fig.17), forming gullies on the slopes of the ramps.

5) Pleistocene to Recent Tropical rimmed platforms

During the Pleistocene to Recent (seismic packages DampierSP7 and BarrowSP8), the margin evolved to a tropical rimmed platform. Reefs formed on the platform interior, overlying the non-tropical carbonate ramps during transgression (Fig.24). These reefs later prograded to the shelf margin during regression (Fig.25) and were later exposed as represented at erosional surfaces DampierSU9 and BarrowSU7 (Figs.7 & 11). Post exposure of the carbonate reefs was followed by Pleistocene to Recent early regression to transgression. During Pleistocene transgression, the production at the tropical factory platform was high, leading to the export and accumulation of sediment on the shelf, as indicated by the extensive slump scarps on the shelf.
break (Fig.25). During ongoing Pleistocene to Recent transgression, the reefs continued to backstep landwards SE (Fig.25), with most reefs drowning up until the present day (Ryan et al., 2009).

**Figure 34:** 2D schematic diagram of the Dampier and Barrow Sub-basin generalised stratigraphy. From the Palaeocene to the present-day, five main phases were identified and form basal fine-grained siliciclastics, alternating non-tropical to tropical carbonate margins and a minor episode of siliciclastic input. The five main phases can be linked with the schematic block diagrams (Fig.35).
Figure 35: Schematic block models of the Barrow and Dampier Sub-basin Cenozoic evolution. The five main phases identified including; the basal fine-grained siliciclastic to carbonate deposits, a siliciclastic coastal deposit and the non-tropical and tropical carbonate margins correspond to the stages outlined in (Fig.34). The key from (Fig.33) and colour scheme can be applied to these models.
5.2 Timing of the Stratigraphic Evolution, Sea-level, Local tectonics, Subsidence Rate and Climate

Correlating the stratigraphic evolution with global sea-level curves (Haq et al., 1987), local tectonics (Stagg and Colwell, 1994) and subsidence rates (Kaiko and Tait, 2000), as well as global climate (Zachos et al., 2001) provides insight into the relationship between depositional patterns and the paleo-oceanographic environment, during the Cenozoic (Fig.36). Overall, there is a good correlation between global sea-level and climate (Zachos et al., 2001; Haq et al., 1987), and the sequence stratigraphic evolution of the NCB margins (Fig.36).

The Palaeocene to the early-middle Eocene transgressive seismic packages (DampierSP1 and BarrowSP1) coincide with long-term, global relative sea-level rise (Haq et al., 1987). The early-middle Eocene to middle-late Miocene regressive seismic packages (BarrowSP2-5) and (DampierSP3-6) formed in the context of a global fall in relative sea-level (Fig.36). The Oligocene seismic unconformities (BarrowSU3 and DampierSU4), represent the transition boundary from mixed, fine-grained siliciclastic/carbonate sediments, to the formation of the prograding non-tropical carbonate ramps. This transition occurred synchronous to the shift of the NWS to lower latitudes likely increasing the potential for carbonate production in the NCB (Fig.36).

The tropical early-middle Miocene carbonate platforms overlying the non-tropical Oligocene ramps (seismic packages BarrowSP3 and DampierSP4) developed synchronously to the Middle-Miocene Climatic optimum (Flower and Kennett, 1994). Both the ongoing shift of the NWS to tropical latitudes and an increase in global temperature may have modified the climate locally, promoting tropical carbonate production (Fig.36). Additionally, the onset of reef growth in the early-middle Miocene coincides with the tectonic closure of the Indonesian Seaway, leading to a strengthening of the warm water Leeuwin Current (McGowran et al., 1997). As with climate and local tectonics, this likely triggered the onset and expansion of reef growth during the early-middle Miocene. The development of the tropical carbonate platforms during the early-middle Miocene also coincides with the highest area percentage of equatorial carbonate platforms in the SE Asian carbonate record (Wilson, 2008).

The cumulative progradation of the Middle Miocene to Pliocene siliciclastic Bare Formation (DampierSP6) and backstepping, correlates with the long-term sea-level fall and rise during the late Miocene-early Pliocene (Fig.36). The influx of the siliciclastic-carbonate Bare Formation
in the Dampier Sub-basin also coincides with global cooling and a shift to more arid conditions in Australia (Martin, 2006), possibly increasing erosion rates in the sparsely vegetated Pilbara hinterland.

Conversely, the Mio-Pliocene stratigraphic architecture of the NCB does correlate with the global eustatic trends of this period (Fig. 36). Indeed, the late Miocene-Pliocene strata of the NCB corresponds to a second-order transgressive sequence (seismic packages BarrowSP5 and DampierSP7), whilst global sea-level data indicates a long term fall >50m of amplitude (Fig.36). During the late Miocene-Pliocene, collision of the northward-moving Australian Plate with the Banda Arc, reactivated the Mesozoic faults (Tindale et al., 1998). This collision accelerated the subsidence rates of the footwall blocks NW of the Rosemary Fault (Hull, 2000). This is likely linked with the rapid increase in regional subsidence rate curves (Fig.36), and is a possible control that has led to the temporary demise of tropical carbonate production.
Figure 36: Geological time scale cross-plotted with the sequence stratigraphic interpretation of seismic packages from the Dampier and Barrow Sub-basins. The relative timing of tectonic events in the NCB (Stagg and Colwell., 1994), broad NWS tectonics is plotted with the NCB subsidence curves (Kaiko and Tait 2001), global climate (Zachos et al., 2001), long-term sea-level fluctuations (Haq et al., 1987) and Leeuwin Current Activity (McGowran et al., 1997). Bio-zones are shown at the red stars to indicate how the boundaries were positioned and the orange circles represent ages correlated from biostratigraphy from Gallagher et al., (2009).
It is difficult to determine the global variations in sea-level during the interglacial periods from the resolution of the long-term sea-level curve (Haq et al., 1977). It is possible to correlate the final reef backstepping event recorded in seismic packages BarrowSP7 and DampierSP9 (Figs. 25 & 26) with the continued increases in rates of local subsidence (>1500m) in the NCB, linked to Miocene reactivation.

5.3 Depositional Controls of the North West Shelf Tropical Carbonate Reefs during the Cenozoic

The Cenozoic stratigraphy of the Dampier and Barrow Sub-basins, present exceptional examples of dynamic, well preserved non-tropical carbonate ramps and tropical carbonate platforms. The timing and initiation of tropical reef growth on the NWS has been a subject of recent discussion, particularly in regards to the onset of the Leeuwin Current, regional tectonics and climatic changes (Wilson, 2013; Collins 2010; Wilson 2008; Collins 2002).

Recent work has suggested that in the NCB, no transition occurred from non-tropical to tropical carbonate production during the Miocene (Rosleff-Soerensen et al., 2012) instead the carbonate margin remained a non-tropical heterozoan ramp. Previous work (Rosleff-Sorensen 2012; Collins, 2002) states that the Miocene growth of tropical reefs in the NCB was restricted to isolated build-ups as the growth potential of carbonates at that time was not sufficient for developing long-lived, larger reef structures. These earlier conclusions are challenged by both the seismic and well data analysed in this study. The later show two repeated shifts from non-tropical carbonate ramps to tropical rimmed platforms during the early to middle Miocene and the Pliocene to Pleistocene (Fig. 34 & 35). The timing of the early-middle Miocene transition is coeval with the initiation of tropical carbonate growth in the NE Browse Basin (Smith, 2013; Rosleff-Sorensen, 2012) and in the Eucla Basin in the Great Australian Bight (Feary and James, 1998). In addition, the interpretation of the initial carbonate reefs in seismic and well data, contradicts previous work (Rosleff-Soerensen et al., 2012) suggesting that the Browse Basin is the southernmost limit of conditions favourable for tropical reef growth on the NWS. It is therefore proposed that southernmost-limit of Miocene tropical reef growth extends to latitudes further south at least to the Barrow Sub-basin.

A likely control for the onset of tropical carbonate development is the northwards drift of the Indo-Australian Plate, and the relocation of the NWS to tropical latitudes (Rosleff-Soerensen et al., 2012). During the Oligocene to Miocene the NWS shifted from ~30° to ~25° (McGowran...
et al., 1997) to within tropical latitudes (Schlager, 2005), furthermore this was synchronous to the Middle-Miocene Climatic Optimum (Fig.34) (Feary and James, 1998). In addition, the Indonesian Throughflow exerts a strong control on the Cenozoic palaeo-oceanography on the NWS (Gallagher et al., 2009) and controls regional carbonate development via the Leeuwin Current. Initial early-middle Miocene reefs identified in seismic (Fig.13) developed simultaneous to the maximum transport capacity of the Indonesian Throughflow (McGowran et al., 1997). Thus, it is here proposed that the Leeuwin Current, driven by the increase in Indonesian Throughflow capacity, has likely had a substantial influence on the initiation of tropical reef development along the southern margins of the NWS. Given the timing of tropical reef growth identified in the NCB dataset, it is proposed that the combination of northward migration of the North West Shelf to tropical latitudes and a strengthening of the Leeuwin Current has modified the regional climate of the NWS. A combination of these factors brought warm, low-salinity waters to the Browse Basin (Rosleff-Soerensen et al., 2012), Dampier and Barrow Sub-basins during the early-middle Miocene.

A secondary onset of tropical reef growth was observed during the Pleistocene (Figs.24 & 34). The timing of Pleistocene reef onset interpretation correlates well to recent work conducted in the NCB (Gallagher et al., 2014), and therefore the controls can be linked with the current work. As proposed by Gallagher et al. (2014), the Leeuwin Current intensity increased in at ~1 Ma BP, bringing warm waters and tropical biota to the region. Likewise, Gallagher et al. (2014) suggests a high increase in aridity at ~0.6 Ma BP has led to increase in ocean alkalinity triggering ooid formation and reef expansion.

5.4 The Demise and Backstepping of the Tropical Carbonate Reefs

Usually a combination of environmental conditions lead to the demise of a carbonate reef system often linked with either the rapid rise of relative sea-level and/or the decline of the carbonate factory production capability (Schlager, 2005; Clark et al., 1995). A decline in the carbonate factory production capability is linked to a combination of factors some including; the rapid rise in sea level such that the production of the reef lags behind the rate increasing sea-level (Schlager, 2005) and the influx of sediment to coastal waters (Schlager, 2005; Doyle and Roberts, 1987).

Carbonate reef production is highly sensitive to the input of sediments by degrading the availability of light for photosynthesis (Schlager, 2005). A demise of tropical reef
sedimentation is observed during the late Middle Miocene in both the Barrow and Dampier sub-basins (seismic packages DampierSP7-9 and BarrowSP5-7). Conversely this demise is not synchronous across the two basins and starts earlier in the Dampier sub-basin (Dampier SP6), during the onset of deposition of the Bare Formation (Figs.32 & 33). The lack of visual evidence of barrier reefs and build-up during the deposition of the Bare Formation suggests that the reef production had likely ceased during the late Miocene to Pliocene in the Dampier sub-basin. In contrast reef structures were identified throughout the early-middle Miocene to Pliocene in the Barrow Sub-basin (seismic package BarrowSP4; Figs.6 &18), without the recorded influx of siliciclastic sediments. This suggests that the input of terrigeneous sediments in the Dampier sub-basin may have inhibited the productivity of the tropical carbonate factory. Similar detrimental effects from the input of terrestrial volcaniclastic and siliciclastic sediments on Cenozoic reef growth has been documented worldwide, e.g., South Java, East Borneo and NE Spain (Lokier et al., 2009).

The demise and backstepping of reefs during the late-Miocene-Pliocene to Recent interval was observed in the transgressive packages BarrowSP5 BarrowSP7 and DampierSP7 and DampierSP9 (Fig.13, 25 & 26). Evidence for the demise of tropical reef growth occurs at the base of the Delambre Formation (seismic packages BarrowSP5 and Dampier SP7), where the reefs were subsequently drowned, onlapped and buried by the late Miocene to Pliocene outer-shelf sediments. As briefly outlined earlier, this increase in subsidence rate is well linked to the Australian Plate collision and Banda Arc collisional tectonics that reactivated Mesozoic faults (Kaiko and Tait, 2000). This collision accelerated the subsidence rate of the footwall blocks, and increased the relative sea-level to NCB. This rise in sea-level during the late Miocene-Pliocene to Pleistocene likely outpaced the capability of carbonate production (Schlager, 2005) and explains the shift from tropical to non-topical carbonate deposition in the NCB.

The most recent backstepping of tropical reefs on the platform margin was well presented in the 3D attribute analysis of the Pleistocene transgressive seismic packages BarrowSP7 (Fig.25) and DampierSP9 (Fig.26). The reefs appeared to backstep to the topographically-high, pre-existing topography to the south and SE in both the Dampier and Barrow Sub-basins. The backstepping of reefs is usually a response to substantial increases in relative sea-level (Schlager, 2005). Recent work indicates that the climatic conditions for reef growth were favourable in the Pleistocene to Recent, with the onset of aridity and an increase in the Leeuwin Current intensity (Gallagher et al., 2014). Given that the climate was favourable for reef growth, and the capability of tropical carbonate production was high (Schalger, 2005), it is assumed that
the Pleistocene to Recent back-stepping event is associated with the rapid rise in relative sea-level. Again, this is likely due to the continued increase in subsidence rates since Miocene tectonic reactivation (Fig36).

5.5 Architecture of Non-tropical Carbonate Ramps

Non-tropical carbonate ramps geometrically appear similar to siliciclastic systems in a marine environment (Schlager, 2005). Seismic packages BarrowSP3 (Barrow Sub-basin) and DampierSP4 (Dampier Sub-basin) resemble standard siliciclastic slope geometries (Figs.6 & 11) that consisted of carbonate sediments interpreted as Oligocene to early-middle Miocene non-tropical carbonate ramps. As suggested by (Hull, 2000) the Cenozoic non-tropical carbonate ramps in the NCB appear fundamentally influenced by eustasy, as indicated by the sigmoidal s-shaped geometries and progradational NW steepening clinoforms. This characteristic is often recognized in non-tropical carbonate settings, as they tend to lack the ability to produce sediment rapidly, and the potential to grow wave resistant structures (Schlager, 2005). The second Pliocene to Recent non-tropical carbonate ramps in the Delambre Formation developed a similar geometry to those found in the underlying Mandu Limestone (Fig.7). Both generations of the non-tropical carbonate ramps displayed rounded shelf breaks (Fig.14) or broad amphitheatres and cuspate morphologies at the clinoform roll-overs these corresponded to slump scarps (Fig.16). Slope lithification in carbonate settings is said to prevent slumping and stabilise the steep-angled slopes (Schlager, 2005). However, scarps and mass-transport deposits in NCB suggest otherwise. Age and geometrically similar non-tropical carbonate ramps have been identified to the NE in the Browse Basin (Smith, 2013; Rosleff-Soerensen et al., 2012). The non-topical Oligocene to Miocene carbonate ramp architecture is presented by steeply dipping slope margins, canyons and basin floor mass-transport deposits. These observations suggest that the broad NE-SW carbonate margins of the NWS were subject to similar depositional regimes during the Oligocene to early-middle Miocene.

5.6 Architecture of Tropical Carbonate Platforms

The location and patterns of reef growth on carbonate platforms can provide crucial information on the functioning of the marine environment (Schlager, 2005). The first seismic evidence of tropical carbonate structures in the NCB were found within the early-middle Miocene Trella Limestone (Fig.6 &13). In 3D seismic, these first reefs were presented as strike elongate to slightly oblique barriers on the platform margin and interior (Figs.18 & 19). The geometries of
these reefs is comparable to the first carbonate ridges that developed in the Cenozoic strata of the Browse Basin (Rosleff-Soerensen et al., 2012).

Reef build-ups and strike elongate barriers were located at no specific distance from the platform slope in the NCB (Figs.18-20) while these rims on the platform margin protecting the lagoonal settings from wave action. A number of mass-transport deposits were located to the NW of the barrier reefs and elongate reef belts in the Dampier Sub-basin (Fig.22) and Barrow Sub-basin (Fig.21). The production at barriers is said to be higher than that of the platform interior, as the barrier raises above the platform and sheds sediments both downslope and towards the lagoon (Schlager, 2005). With the assumption that these reef belts are highly productive and have shed excess sediment downslope, further analysis (high resolution), may determine whether the accumulation of sediment on the platform interior, is the driving force behind the extensive mass-transport in the Miocene to Recent tropical carbonate platforms of the NCB.

Overall the tropical carbonate platforms of the Barrow and Dampier Sub-basins present a similar selection of barrier reefs and belts during early phases of Miocene growth as the Browse Basin (Smith, 2013; Rosleff-Soerensen et al., 2012). Comparing the evolution of early-middle Miocene to Pliocene barrier reefs in the Browse Basin and NCB, similar evolutionary trends are recognized (Fig.36). Both carbonate margins display the initial onset of reefs to the SE during Miocene marine transgression, above pre-existing non-tropical carbonate ramps. Similarly, both barrier reefs aggrade during highstand and prograde NW when accommodation is reduced during sea-level lowstand. Although the evidence is uncertain in the Barrow Sub-basin, both the Dampier Sub-basin and Browse Basin display a similar Miocene reef backstepping event during low-frequency marine transgression.
Figure 36: Seismic inline comparison S136_13 (North Carnarvon Basin) and Br98-013 (Browse Basin) from (Smith, 2013) of the NWS Western Australia. The evolution of reefs from numbers 1-5 is displayed which shows similarities on the initiation, progradation, backstepping and possible drowning of the reef systems directly above a prograding non-tropical (un-rimmed) carbonate ramp. TST= transgressive systems tract, HST= highstand systems tract, FSST= falling stage systems tract and LST= lowstand systems tract. The approximate location of the inlines has been displayed on the map of the NWS (courtesy of Google Earth).
5.7 Architecture of the Bare Formation

Middle Miocene to Pliocene siliciclastic sediments of the Bare Formation (seismic package DampierSP6) are found within the otherwise carbonate dominated Cenozoic stratigraphy of the Dampier Sub-basin (Fig.5). The temporary reduction in carbonate production and shift to siliciclastic deposition may be the response of a number of highly complex, local or regional controls. The inclusion of quartz-rich sandstones (Sanchez et al., 2012; Cathro et al., 2003) within the carbonate dominated margin of the Dampier Sub-basin suggests a continuing supply of siliciclastic to the NCB during the middle Miocene to Pliocene. The 3D seismic data attribute analysis demonstrated that the siliciclastic supply of sediments to the NCB was significant enough to present a (>38km) prograding multi-directional coastal sand-spit system (Fig.32 & 33).

Past work in the Dampier Sub-basin has described the Bare Formation as a complex shelf-edge deltaic complex, based on the basis of its common lobate morphology. These interpretations were derived by mapping the clinoforms sets on 2D seismic data (Sanchez et al., 2012; Cathro et al., 2003). Such studies suggest that a few elongated incisions are likely what remains of fluvial feeders to the shelf edge (Sanchez et al., 2012). Such work has not considered the large scale three-dimensional morphology of the Bare Formation. Also it has not considered the possibility of alternate environments that can produce a common lobate morphology, particularly one that progrades along-strike, without fluvial feeders and channels. This study does not disregard the initial interpretation of the Bare Formation as a shelf-edge delta, but presents an additional hypothesis based on the new evidence provided by our 3D seismic data. Indeed, the data presented here suggests that the Bare Formation of the Dampier Sub-basin could correspond to a coastal sand-spit. By definition, a coastal sand-spit is a ridge or embankment of sediments attached to older land with the other end in open waters (Thomas et al., 2014). This implies that standard sand-spit systems form as the result of the deposition of re-worked sediments alongshore, rather than from terrestrial fluvial feeders or channels. Like previous work (Sanchez et al., 2012), no major channels or distributary mouth-bars were identified in the seismic data covering the Bare Formation (Figs. 29 & 31). Given our understanding of the depositional architecture of the Bare Formation (Figs.32 & 33), it is proposed that the terrestrial sediment input was likely carried to the basin via an external river system (outside the boundaries of the seismic data). Subsequently the middle Miocene to Pliocene terrestrial sediment input was reworked via wave energy and longshore drift. This was
further transported along the shoreline forming the coastal sand-spit system presented in the seismic data (Figs. 32 & 33).

Like previous interpretations from Sanchez et al. (2012) and Cathro et al. (2006) the Bare Formation, presented lobate morphologies in the seismic data (Fig.29). The shoreline lobes and the multiple sets of beachridges (Fig.31) bear the imprint of strong wave action originating from the SW. The proposed sand-spit system hypothesis presented, links well with the early interpretations of side wall core data (Hocking et al., 1887; Heath and Apthorpe, 1984). This analysis suggest that the Bare Formation formed from reworking processes such as coastal wave and wind direction, rather than direct fluvial input through channels and channel mouths (Sanchez et al., 2012). Remarkably, the existence of a strong NE flowing current as a driving longshore mechanism of sediment distribution in the Bare Formation (Fig.30), is inconsistent with the direction of flow of the SW flowing LC (McGowran et al., 1997). The orientation of the beach ridges observed in the Bare Formation, suggests that the coastal processes along the Dampier sub-basin shorelines were dominated by wave action (wave-induced longshore drift) rather than the SW flowing the Leeuwin Current.

Satellite imagery from modern day shelf-edge deltaic and coastal sand-spit deposits display, similar depositional geometries and features to the Bare Formation in the seismic attribute analysis (Fig.37). Walvis Bay on the Skeleton Coast, Namibia presents a ~30km long coastal sand-spit deposit, that has formed from the along shore deposition of reworked sediments from the SSE to the NNW. The oblique progradation of sediment alongshore is said to accumulate at a rate of ~15m per year (Elfrink et al., 2003). Like the Bare Formation, deposition at Walvis Bay appears oblique with a beach ridge and no visible input of terrestrial sediment from fluvial channels. Instead the primary deposition is from the reworking of sediment along shore by strong wave action and aeolian processes (Elfrink et al., 2003).

Satellite imagery of the Paribo do Sul Delta in Brazil, displays a large main fluvial river system entering the Campos Basin (Fig.37). The Paribo do Sul Delta consists of two broad depositional components; including the fluvial component, related to the delta front and the wave dominated component, specified by the multiple sets of concave beach ridges (Murillo et al., 2009). Each beach ridge represents the former position of the shoreline during deltaic progradation (Murillo et al., 2009). Both the protruding front and visible sets of beach ridges present a similar depositional setting of the middle Miocene to Pliocene Bare Formation (Fig.31), however there
is no visible evidence in seismic data for a fluvial river system such as the Rio Paraiba do Sul River.

Figure 37: Satellite imagery (courtesy Google Earth) of two modern day sand spit systems of the middle Miocene to Pliocene Bare Formation: A) is large sand-spit system of Walvis Bay on the Skeleton Coast of Namibia and B) is the Paribo do Sul Delta in Brazil. The Paribo do Sul Delta displays both 1) a fluvial component at the delta front and 2) a wave dominated component as indicated by the sets of beach ridges.
5.8 Depositional Controls of the Bare Formation

The current work considers the possible controls related to the onset of increased terrestrial siliciclastic input during the largely carbonate dominated Cenozoic. Global increases in the stability of erosion rates and weathering during the Cenozoic, has largely been linked to tectonic and climatic processes as well as falling base-levels (Willenbring and von Blanckenburg, 2010).

The preservation of terrestrial rock and soils is affected by climate through vegetation reducing erosion (Osterkamp et al., 2012). Studies have outlined the origin and control of Australia’s climate on the supply of siliciclastic sediment to the Dampier Sub-basin (Sanchez et al., 2012). Reconstructed vegetation patterns from onshore Australia indicate that, with the exception of the warm early Miocene, the climate of the Australian continent progressively became more arid since the Oligocene (Martin, 2006). Less stabilizing vegetation in association with enough seasonal rainfall from storms may have resulted in the increase in erosion rates of the hinterland and the supply of terrestrial sediments to the Dampier Sub-basin. The age of the base Bare Formation correlates with the global middle Miocene increase in $\delta^{18}O$ (Fig.34), believed to be the result of expansion of the West Antarctic ice sheet, linked with global cooling (Zachos et al., 2001; Miller et al., 1991). Here it is propose that the interplay of increases in aridity in conjunction with erosion rates from a sparsely vegetated Pilbara hinterland, may have locally amplified sediment input into the NCB during the early-middle Miocene.

An additional controlling factor related to the onset of observed siliciclastic sediment into the NCB, is tectonic uplift. Tectonic uplift and the creation of source-area relief, is another recognized global mechanism that explains higher clastic yields to global continental margins (Hooke, 2003). Ongoing collision between the Banda Arc and Australia during the late Miocene occurred as a result of convergence between the Indo-Australia and Pacific plates (Veevers et al., 1991). Cathro and Karner (2006) have suggested that this collision caused pulses of local uplift in response to the inversion of Mesozoic structures in the NCB. However, this evidence is yet to be documented in the Cenozoic strata of the Pilbara hinterland. Given the regional distribution and significant amount of relief on the inversion structures seen on seismic data, local collisional tectonics present an additional factor for an increase in siliciclastic sediment supply to the NCB.

To summarize, from the combined well and seismic data we observe that depositional processes such as winds, currents and wave action play an important role in the sediment transport and
morphology during the middle Miocene to Pliocene. This study proposes two hypotheses as to the potential depositional settings for the middle-Miocene to Pliocene Bare Formation. These include; 1) the original shelf-edge delta model (Sanchez et al., 2012; Cathro et al., 2003), however this is not supported in the 3D seismic data due to the lack of channels and 2) a shoreface sand-spit system. Both hypotheses infer the increase in clastic input to the shelf occurred during regressive conditions, linked to a change in climate, falling middle-late Miocene sea-levels and possibly tectonic uplift. The termination of siliciclastic deposition may have ceased due to the combination of the major acceleration in local subsidence during the late Miocene to Pliocene, and an increase in relative-sea level on a global scale (Haq et al., 1987). These factors increased the local accommodation triggering a transition to carbonate production during the late Miocene-Pliocene.

6. Conclusion

The Cenozoic stratigraphy of the NCB is characterized by two second-order sequences, separated by a late-Miocene to Pliocene sequence boundary. The Dampier and Barrow Sub-basins contain: (1) Paleocene to Oligocene mixed siliciclastic-carbonate deposits (2) Oligocene to early-middle Miocene non-tropical carbonate ramps (3) early-middle Miocene to late Miocene-Pliocene tropical rimmed platforms, (4) middle Miocene to Pliocene coastal sand-spit deposits (Dampier Sub-basin), (5) late Miocene-Pliocene to Pleistocene non-tropical carbonate ramps and (6) intermittent Pleistocene to Recent tropical rimmed platforms.

The initiation of tropical reef production in the early-middle Miocene was likely triggered by a combination of (1) changes in oceanography and sea temperature linked to the onset of the Indonesian Throughflow and the establishment of the southward-flowing Leeuwin Current and (2) the northward migration of the Indo-Australian plate to tropical latitudes initiating tropical reef growth in the early-Miocene. Factors leading to the demise of tropical carbonate system during the late Miocene to Pliocene are still unclear; however the timing is coeval with an increase in regional tectonic subsidence, related to the onset of collision between the Australian and Eurasian Plates. The onset of siliciclastic input in the Dampier Sub-basin during the middle-Miocene to Pliocene was likely a combination of aridity decreasing the density of vegetation coverage with regional tectonic uplift.
The understanding of the stratigraphic evolution of the NCB has greatly improved since the beginning of exploration in the 1970s, yet the Cenozoic evolution has remained largely overlooked. This study shows that the Cenozoic stratigraphy of the Dampier and Barrow Sub-basins display large variations in time and space, with strata forming diverse non-tropical carbonate ramps, barrier reefs and coastal sand-slit systems. Such variations represent pose both risks for exploration activities and substantial difficulties in the processing of seismic data. In addition, the coexistence of a large siliciclastic sand-slit deposit within an otherwise carbonate dominated succession, has a substantial impact on acoustic velocity modelling.

This work demonstrates that the Cenozoic margin and slope deposits of the NCB contain important information for the reconstruction of the NWS paleo-climatic and paleo-oceanographic changes over the past 65 Million years. The timing of transition from tropical to non-tropical carbonates is well linked to the evolution of the NE Browse Basin and should be further investigated using a range of offshore core and outcrop data to improve the regional knowledge of this trend. The timing and development of Cenozoic carbonate and siliciclastic sedimentation, is also important with many existing producing fields in analogue formations across SE Asia. The insight into the evolution, geometry and depositional setting of the Bare Formation in the NCB, provides analogue models for siliciclastic hydrocarbon plays globally.

Lastly, this work shows that the NCB represents an additional example for characterizing the depositional geometries of margin and slopes, in a wide variety of non-tropical, tropical carbonate and siliciclastic settings. Hence, this study provides a series of reservoir analogue data that could potentially forecast the depositional architecture of similar sub-surface environments.
References


Appendix List

A: Transect A and Transect B well log data: Summary tables and correlation charts

B: Research Proposal “Cenozoic Stratigraphy of the North Carnarvon Basin: Insights for the growth history of carbonate margins of the North West Shelf”
Appendix A, Fig 1: Summary chart of the well data used in the Dampier Sub-basin (Transect A). Gamma logs are plotted alongside the side-wall cutting (SWC) descriptions from completion reports and biostratigraphy. MFS = Maximum flooding surface, SBD = second-order sequence boundary. The age of seismic unconformity DampierSU8 was determined by correlating ages of biostratigraphy from Gallagher et al. (2009).
Barrow Sub-basin (TB) Well Data Summary

<table>
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<th>Seismic Package (SP)</th>
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<th>Broad GR Trend</th>
<th>Aggradational/Progradational/Retrogradational &amp; Comments</th>
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<tr>
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<td>BarrowSP7</td>
<td>1.77 M.a to Recent</td>
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Dampier Sub-basin (TA) Well Data Summary

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<td>DampierSP9</td>
<td>Pleistocene to Recent</td>
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Appendix A, Fig 2 Summary chart of the well data used in the Barrow Sub-basin (Transect B). Gamma logs are plotted alongside the side-wall cutting (SWC) descriptions and biostratigraphy. MFS = Maximum flooding surface, SBD = second-order sequence boundary. The age of seismic unconformity BarrowSU6 was determined by correlating ages of biostratigraphy from Gallagher et al. (2009). Summary tables of this well data from TA and TB transects is displayed on the left.
Appendix B:

Research Proposal

“Cenozoic stratigraphy of the North Carnarvon Basin: Insights for the growth history of carbonate margins of the North West Shelf”

Master of Science (Thesis and Coursework)

SCIE5721 FNAS Research Thesis Proposal

University of Western Australia

April 2014

Word Count: 4991

Investigator: Matthew Smith (20253877)

Supervisors: Ass/Proff Julien Bourget & Prof. Annette George
Abstract

The basins of the North West Shelf of Australia (NWS) were associated with the development of extensive carbonate margins, which evolved from non-tropical to tropical depositional systems throughout the Cenozoic. These deposits potentially yield the record of the paleoceanographic, paleo-sea level and tectonic changes that occurred during the last 65 million years of Australia’s geological history. Furthermore, these Cenozoic carbonates play an important role in the source rock maturation processes of the NWS basins through thermal loading and pose a primary risk factor associated with drilling operations and seismic processing and imaging of the subsurface reservoirs of this petroleum province. Despite the vast regional extent and stratigraphic thickness, the Cenozoic carbonates of the NWS have received relatively little attention and as a result have remained relatively poorly understood. The proposed study will use 2D and 3D seismic data, complimented with wire line logs, well biostratigraphy and lithological data to unravel the stratigraphic evolution of the Cenozoic strata along three marginal transects of the North Carnarvon Basin (NCB), from the Exmouth to Dampier Sub-basins. The results will be integrated with previous work conducted in the Browse Basin to create a regional stratigraphic framework of the Cenozoic stratigraphy. This stratigraphic framework will provide the research community with a greater understanding of the regional evolution of the NWS during the Cenozoic, and help correlate the timing of carbonate depositional controls such as eustacy, tectonics, climate and oceanography. Additionally this study will provide the petroleum industry with a regional understanding of the distribution and thickness of hazardous rock sequences and formations located in time and space for safe and cost effective drilling operations.
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1. Introduction

Seismic and sequence stratigraphic analysis of carbonate margins, such as the Bahamas (Austin and Schlager 1988, Eberli and Ginsburg 1987), Luconia Malaysia (Zampetti 2010) and the Great Barrier Reef (GBR) (Hinestrosa 2012) have demonstrated that a complex interaction of eustasy, regional and global tectonics, climate and oceanographic factors determine the distribution and evolution of carbonate systems. Despite their enormous distribution, coverage and stratigraphic thickness, the evolution of Cenozoic carbonates of the North West Shelf (NWS) remains unclear. The Cenozoic carbonates of the NWS are the dominant overburden sequences to the hydrocarbon-producing Mesozoic succession, and have been proven to assist the hydrocarbon maturation process through thermal loading (Bradshaw et al. 1998). Furthermore these overburden sequences cause considerable problems in; industrial drilling activities, the processing of seismic data and the interpretation of structural traps and petroleum plays along the NWS (Wallace et al., 2003).

The Cenozoic sequences of the NWS display unexpected variations in lithotypes and geometries (Sanchez et al., 2012), often represented by large scattered zones of highly permeable rock units (Tingate et al. 2001, Van Ruth et al. 2002, Wallace et al. 2003, Power 2008). Drilling hazards have been encountered in many exploration and production wells along the NWS (Power 2008, Tingate et al. 2001, Van Ruth et al. 2002, Wallace et al. 2003). A significant fraction of wells drilled in the Northern Carnarvon Basin (NCB) (Fig.1) have encountered difficulties related to loss circulation and overpressure. A variety of factors are well outlined displaying the risk of drilling through Mesozoic sediments of the NCB (Tingate et al. 2001), yet less is known about the evolution and distribution of the thick, potentially hazardous Cenozoic overburden. In the interest for a safe and cost effective industry, a comprehensive study is required to help predict the regional distribution and variation of lithology within the Cenozoic interval of the NWS. Several studies outline that the West Australian Margin overpressure has a link to Cenozoic burial, where incidences occur in the regions coinciding with the thickest overburden deposition (Tingate et al. 2001). Most incidents are related to loss circulation and sometimes overpressure whilst drilling through lenses of Cenozoic sandstones e.g. Bare Fm (Fig.2) in the NCB. Exploration activities in other regions of the North West Shelf (NWS) e.g. the Browse Basin shows a history of direct overpressure whilst drilling through shallow Miocene carbonates.
Overpressure and loss circulation are commonly associated with irregular, under-compacted (higher than expected porosity) sediments, such as those found throughout the Cenozoic interval. Thus, with little knowledge of the regional distribution and evolution of Cenozoic sedimentation, the drilling risk still remains a substantial issue for industrial activities along the NWS.

While several previous studies have dealt with the general stratigraphy of the NCB (Hocking 1988, Longley et al. 2002, Romine et al. 1997), relatively few detailed interpretations have dealt with the specific depositional patterns of the Cenozoic carbonates of the region (Apthorpe 1988, Heath and Apthorpe 1984, Young et al. 2001).

The primary objective of the proposed study is to further the knowledge regarding the stratigraphic evolution of the Cenozoic stratigraphy from the NE Dampier Sub-basin to the SW Exmouth Sub-basin (Fig. 3), integrating both 2D/3D seismic and publicly available well data. Three transects were selected by identifying coverage of Cenozoic lithological and biostratigraphic data with the available intersecting 2D/3D seismic data sets. This technique aims to detail the variations in lithology and distribution of carbonates across the shelf from the NE Dampier to SW Exmouth Sub-basins.

This investigation aims to improve knowledge regarding the evolution of carbonates along the NCB margin and the timing relationship between growth and climatic, eustatic, tectonic and oceanographic controls along the NWS. The study will allow reducing operational risks in future exploration drilling activities in the region by 1) helping to predict the variations and distributions of hazardous highly-permeable carbonate units and possibly interbedded siliciclastic lenses Cenozoic overburden 2) providing useful lithological information for depth conversion and seismic processing and imaging and; 3) delivering additional information to identify maturation history of potential Mesozoic petroleum plays along the NWS.
2. Background

2.1 Geological Setting

The NCB is located in predominantly offshore NW Western Australia, covering an area of approximately 535,000 km² in water depths of up to 4.5km (Fig. 1), and is one of the southernmost of the late Paleozoic to Cenozoic basins underlying the NW continental margin of Australia (Bradshaw et al. 1988). The NCB has undergone a complex Mesozoic-Cenozoic history since its original formation by extension in the late Paleozoic (Driscoll and Karner 1996, Stagg and Colwell 1994).

Figure 1: Location map of the North Carnarvon Basin, Western Australia with the adjacent basins of the North West Shelf including the Robuck, Canning, Browse and South Carnarvon Basin, modified (Hocking 1988).

Triassic to Cretaceous rifting and re-rifting events (Fig.2) created and has reactivated the NE-SW oriented basins along most of the NCB and NWS. Post-Valanginian regional subsidence has been interrupted by minor inversion that is dated between the Cenomanian and Santonian (Driscoll and Karner 1996, Romine et al. 1997, Cathro et al. 2003). Collision of the Indo-Australian plate with the Pacific and Eurasian plates to the north during the late Oligocene (Fig.2) appears to be the...
accepted source of reactivation and inversion of Mesozoic structural trends along the NWS (Malcolm et al. 1991, Struckmeyer et al. 1998, Cathro et al. 2003). The continuation of the northward drift of the Australian plate through the Cenozoic has produced a progressive change from siliciclastic to carbonate sedimentation along the majority of the NWS (Apthorpe 1988).

Figure 2: Stratigraphy of the NCB showing the Paleozoic to Cenozoic stratigraphic units from the NE Dampier to SW Exmouth Sub-basin. The major tectonic events are summarized showing the major reactivation events during the Cretaceous and the collisional tectonics commencing in the late Oligocene, modified from (Tingate et al. 2001).

2.2 Geological setting of Dampier Barrow and Exmouth Sub-basins

The Exmouth, Dampier and Barrow sub-basins are a series of large rift depocentres (Fig. 3) in the NCB, containing dominantly Triassic, Jurassic and Lower Cretaceous sedimentary infill (Polomka and Lemon 1996, Longley et al. 2002). The thickest of sediment fill exceeds 10km in the Dampier and Exmouth sub-basins and 15km in the Barrow Sub-basin. The Barrow Delta dominates the Lower Cretaceous successions in the Exmouth and Barrow sub-basins (Tindale et al. 1998, Ross and Vail 1994) and in distinction; fine grained marine sediments dominate the Upper Jurassic and Lower Cretaceous formations in the Dampier Sub-basin. All three sub-basins
comprise a series of structural highs and troughs with an overall northeast-southwest trend. The three sub-basins are separated from each other by Paleozoic-Triassic fault-blocks that have been altered by faults, rotation and uplift (Westphal and Aigner 1997, Smith et al. 1999). Several sources have outlined these structures that include the Alpha Arch between the Exmouth and Barrow sub-basins, the Sultan Nose between the Barrow and Dampier sub-basins (Polomka and Lemon 1996) and De Grey Nose between the Dampier and Beagle sub-basins (Fig. 3).

The Dampier, Barrow and Exmouth sub-basins are separated from the structurally high areas of the Rankin Platform and Exmouth Plateau to the NW and the Lambert and Peedamullah shelves (Fig. 3) to the SE by major extensional fault systems (Veenstra 1985). The Rankin Fault System (Fig. 3) separates the Rankin Platform from the Dampier Sub-basin (Stagg and Colwell 1994) and the Flinders and Sholl Island fault systems separate the Peedamullah and Lambert shelves from the Barrow and Dampier sub-basins (Kopsen and McGann 1985) (Fig. 3). Broad marginal terraces overlain by mainly Triassic to Cenozoic sediments have formed over down-faulted or rotated blocks along these faulted margins. These include the Enderby Terrace in the Dampier Sub-basin and the Bruce and North Turtle terraces in the Beagle Sub-basin. These terraces represent major Silurian-Late Permian extensional depocenters that were only moderately affected by three subsequent Mesozoic rifting events, due to a general westward shift in the locus of extension (Hocking 1988, Polomka and Lemon 1996).
3. General Review of Carbonate Depositional Systems:

3.1 Terminology and Definitions

3.1.1 Carbonate Platforms

A carbonate platform is a sedimentary body that has a horizontally flat surface higher than the adjoining area (Fig. 4) (Malcolm et al. 1991). Shoal-water carbonates form flat tops because the high production zone is limited to sea-level and waves distribute sediments and fill depressions (Schlager 2005). Carbonate platform margins tend to develop wave resistant rim structures that protects the sediment of the platform interior (Struckmeyer et al. 1998).
3.1.2 Platform Rims

Platform rims are typically barrier reefs or sand shoals (Fig. 4) with extensive syndepositional lithification and relief (Schlager 2005). Most rim structures can resist high water energy and are more productive than the surrounding lagoon or upper slope deposits (Fig. 5) (Cathro et al. 2003).

Figure 4: Carbonate depositional model displaying features of a tropical (T-Factory) carbonate system including platform rims, barriers, reefs and build-ups within the tidal flat, lagoonal, barrier reef, deep shelf and basinal environments. Note the T-factory has the ability to create wave resistant build-ups, patchreefs and barriers that grow preferentially vertically, modified from (Westphal et al. 2010).

Figure 5: The primary zones of a carbonate ramp including the inner, mid, outer and basinal regions. MSL = Mean Sea Level, FWWB = Fair Weather Wave Base, SWB = Storm Wave Base and PC = Pycnocline. Diagram modified from (Cathro et al. 2003).
3.1.3 Reefs

A carbonate reef refers to a wave resistant build-up (Fig. 4) created by the interaction of organic frame building, erosion, sedimentation and cementation (Cathro et al. 2003). The geometry as observed in map view and cross-section assists in locating reefs and provides crucial information on the influence the reef has on its surrounding topography. The basic controls on reef growth geometry are the upwards growth (Fig. 4) of the organic framework, current reinforcement of its structure and sediment export by the reef factory (Schlager 2005). The degree of symmetry or reef core and aprons indicates to what extent a reef functioned as a barrier (Cathro et al. 2003). Protective barriers pronounce the lagoon wards transport of reef debris in the form of prograding clinoforms (Schlager 2005) in the inner ramp zone (Fig. 5).

3.1.4 Build-ups

Carbonate bodies arising above the adjacent sea-floor is referred to as a carbonate build-up (Fig. 4) (Schlager 2005). The carbonate build-up is applied to a wide variety of unspecific carbonate features on a wide range of localized scales (Schlager 2005).

3.1.5 Carbonate Ramps

There are four components outlined in a carbonate ram model including the Inner ramp, Middle ramp, Outer ramp and basin (Fig. 5). Each zone displays a range of different slopes and facies associations. The inner ram zones contain predominantly organic barriers, sandy shoals, shoreface deposits and back-barrier peri-tidal areas (Cathro et al. 2003). Middle ramp zones consist of sediments and cross stratified graded beds (Struckmeyer et al. 1998). Outer ramp zones extend from deeper parts of the carbonate ramp model. Outer ramp zones display subtle evidence of storm reworking (Cathro et al. 2003).

3.2 Geometry of carbonate accumulations

An important tool for predicting the framework and distribution of sedimentary rocks is through the analysis of the depositional geometry. A series of carbonate trends have been shown in
several studies showing a number of typical geometries characteristic of carbonate margins (Catuneanu et al. 2009, Schlager 2005).

Key factors outlined suggests carbonates accelerates when a nearby production site rises above the adjacent sea-floor (Schlager 2005). The flat top of carbonate platforms forms due to production being greatest in the uppermost part of the water column and the terrestrial part of the environment above is detrimental (Catuneanu et al. 2009, Schlager 2005).

Tropical platforms form distinct rims at the slope boundary (Fig. 4) and are constructed from a variety of different processes. The outer edge of the wave side platform is the preferred location of most frame building organisms and therefore of reef barriers that form a rim. The upper slope environment is the preferential location of microbial crusts and cements that stabilize the framework of shoal-water barriers (Schlager 2005). Carbonate accumulations that form below intensive wave action are convex rather than flat topped (Schlager 2005). Carbonate slopes steepen with height and are generally known to have steeper than slopes of silliciclastic accumulations (Cathro et al. 2003, Catuneanu et al. 2009, Schlager 2005).

3.3 Carbonate Sequence Stratigraphy

General concepts of sequence stratigraphy, such as the formation of systems tracts apply to carbonate systems as in siliciclastic systems (Catuneanu et al. 2009), however there are distinct differences outlined as follows (Fig. 6). When carbonates are exposed they are more prone to dissolution than siliciclastic sediment (Catuneanu et al. 2009), therefore sequence boundaries in carbonates are expressed as karst surfaces with solution relief, breccias, paleosols and silification (Polomka and Lemon 1996). Carbonate sediment production is largely internal rather than transported from external basins as in siliciclastic deposition (Catuneanu et al. 2009). Consequently sediment is produced at a much higher rate, transgressive tracts (TST) appear thicker and highstand systems tracts (HST) appear thinner (Bradshaw et al. 1998, Schlager 2005).

Carbonate production rate ($G'$) usually keeps pace with moderate rates of relative sea-level rise and accommodation space ($A'$) (Fig. 6) (Catuneanu et al. 2009, Power 2008). This shows that carbonate sequences often represent extremely thick sections of peritidal cycles and parasequences that shallow upwards to great depths (Goldhammer et al. 1993, Bradshaw et al.
1998). Upward thickening of cycles are interpreted as retrogradational stacking patterns and upward thinning of cycles represents slowing rates of relative sea-level rise and are interpreted as progradational stacking patterns (Loucks and Sarg 1993).

Figure 6: Extract displaying the Highstand Systems Tract (HST), Transgressive Systems Tract (TST) and Lowstand Systems Tracts (LST) of carbonate sequences. Note the development of a carbonate systems tract depends on (A') the rate of change in accommodation, (Gp') the growth rate of the platform interior and (Gr') the growth rate of the platform rim, modified (Schlager 2005).

3.4 Tropical (T Factory) Attributes of Sequence Stratigraphy

The T factory is a platform variety where precipitation of carbonate sediments is biotically controlled by autotrophic organisms such as corals, algae foraminifers and molluscs, typically found in >20° C, sunlight, high oxygen low nutrient waters (Carannante et al. 1988). The T factory is a highly productive system but the depth window of production is very narrow norally <100m of the water column (Schlager 2005). The T factory can build wave resistant structures in the depositional environment by organic frame-building or cementation (Catuneanu et al. 2009, Schlager 2005). Carbonate structures in the T factory can form at a range of distances from the shoreline, usually upwards (Fig. 4), rather than horizontally (Schlager 2005).
The T factory ramp often evolves to a rimmed platform where an offshore belt of reef or sand shoals protects a lagoon (Fig.4). Large parts of this lagoon may fill up with sediment because oceanic waves are filtered out by the rim (Schlager 2005).

3.5 T Factory Sequence Geometry

As tropical carbonate platforms tend to develop ridged, wave-resistant structures at shelf breaks (Fig.4), it normally leads to elevated margin at sea level, protecting a lagoon that gently rises landwards to the coastal zone (Schlager 2005). These protected platform margins appear to be important features defining the structure of tropical carbonate accumulations.

When Tropical rims are buried by sea level, it causes the facies belts to jump and interrupt gradual shift in onlap (Schlager 2005). Additionally rims have a strong tendency to stack vertically, favoring existing trends (Catuneanu et al. 2009, Schlager 2005).

Rim building by reefs or sand shoals is important in prograding margins as rims tend to occur sporadically and as lenses (Schlager 2005). The fluctuation shelf-margins of these prograding platforms with their buried rims seem to yield the most reliable sea-level record in carbonate sequence stratigraphy (Schlager 2005).

3.6 Cool-water (C Factory) Attributes for Sequence Stratigraphy

In regards to sequence stratigraphy, C factory deposits are typically similar to the siliciclastic in a marine environment. C factory sequences consist typically of coasts formed by sandy beaches cliffs, sigmoidal shelf breaks and consistently-dipping shelves (Fig. 7) (Schlager 2005). Reefs typically have low-lying crests and are widely scattered over the outer parts of the shelf and the upper slope and shelf breaks of the C factory generally lack wave-breaking rims (Schlager 2005) (Fig.7).

Like the T factory, the C factory cannot produce above sea level only clastic accumulations of marine material may occur in the form of aeolian dunes (Schlager 2005). The lower limit of the C factory production is set by the influx of terrigenous or planktic fine material. Protective rims are uncommon in C factory settings (Fig.7) as the ability to produce complex reef building communities is limited to only a few organisms (Schlager 2005).
Figure 7: Cool water (C-Factory) carbonate depositional model. The relationship between slope zonation (Inner, Middle, Outer Shelf and Slope) is compared to the sedimentation and depositional processes. Note the C-factory lacks the ability to develop wave resistant barriers and buildups in the inner, middle and outer shelf setting. Diagram modified from (Gischler 2011).

3.7 C Factory Sequence Geometry

C factory sequences typically resemble siliciclastic sequences with rounded shelf breaks (Fig. 7) and gentle slopes (Schlager 2005). Two important differences the C factory has from siliciclastics is that C factory systems tracts lack point sources of sediment input from rivers and they have the ability to build seismically recognizable reefs, although not at sea level but a greater depth (Schlager 2005). Morphologically the C factory reefs have convex tops because they are not flanked by wave action (Schlager 2005).

Sediment reworking is fast and effective in C factory sequences, as cementation is slow (Catuneanu et al. 2009, Schlager 2005). As in siliciclastic sequences, significant portions of the HST may be shaved off during sea-level fall such that the HST has to be reconstructed from the preserved parts of the prograding cliniforms (James et al. 2000).

4. Local Review: Cenozoic Stratigraphy of the Northern NCB

We can see that carbonate sequence stratigraphy is strongly influenced by a number of key environmental factors, therefore carbonate sequence geometries and depositional patterns can provide useful local insight on oceanography and paleogeographic sea level changes in the
NCB. Although the Cenozoic is known for its widespread carbonate deposition on the NWS (Apthorpe 1988), several studies have outlined a significant observable siliciclastic progradation across the NCB shelf edge during the late-middle Miocene in the Dampier Sub-basin (Sanchez et al. 2012, Tindale et al. 1998, Wallace et al. 2003). The offshore Cenozoic carbonate stratigraphy for the NCB was earlier outlined (Heath and Apthorpe 1984, Tindale et al. 1998) (Fig. 8), however these interpretations seem confined to the Dampier Sub-Basin and northern NCB. Few published studies outline the evolution at the regional NCB scale.

Early investigations of generalized Cenozoic stratigraphy focused on the Miocene sediments of the northern NCB, dividing the middle-upper Miocene stratigraphy into groups (1) middle Miocene carbonates including the Trella Limestone (Fig. 2 & 8) and (2) the late middle to late Miocene-age Bare Fm (Fig. 2 & 8) (Heath and Apthorpe 1984). The same formations have not been identified in the Exmouth Sub-basin; instead the Cape Range Gp (Fig. 2) appears to be the dominant formation of the southern NCB margin.

Figure 8: Diagrammatic cross-section illustrating the stratigraphy of the northern North Carnarvon Basin (Heath and Apthorpe 1984) extracted from (Wallace et al. 2003). The presence of the siliciclastic Bare Fm and Delambre Fm in the Beagle and Dampier Sub-basins to the north is inconsistent with findings to the stratigraphy along the Exmouth Sub-basin margin.
4.1 Cenozoic depositional Cycles in the northern NCB

Previous research on the stratigraphic evolution in the NCB showed that the Cenozoic strata occurs as a dominantly prograding wedge, thin at the coast and thickening to 2,500 m at the shelf edge (Collins 2002, Wallace et al. 2003). Four unconformity-bound sedimentation cycles outlined below define the current understanding of the Cenozoic sequences of the NCB as identified across the northern Dampier and central Barrow Sub-basins (Fig. 9).

These cycles (Fig.9) are summarized as follows (Collins 2002, Quilty 1977, Wallace et al. 2003):

- **Cycle 1** (Late Paleocene-Early Eocene): this cycle is confined by regression and hiatuses at the Cretaceous/Tertiary and Early/Middle Eocene boundaries, with a maximum distribution found in the Late Paleocene

- **Cycle 2** (Middle-Late Eocene): is characterized by transgression in the Middle Eocene, with maximum extent occurring in the Late Eocene. It has been further subdivided by into 2A (Middle Eocene) and 2B (Late Eocene)

- **Cycle 3** (Late Oligocene-middle Late Miocene): This cycle displays large transgressive events, reaching maximum thickness during the Early/Middle Miocene, punctuated during this time by a widespread hiatus. Again this section has been further subdivided into 3A (late Oligocene-Early Miocene) and 3B (Middle Miocene)

- **Cycle 4** (Late Miocene-Holocene): This cycle appears unclear from previous interpretations. Small variations can be identified in conjunction with facies distribution of carbonates due to increased tectonisim and warming/glaciation events.

Although these studies have identified specific cycles, they do not accurately define the regional (NCB) Cenozoic depositional history, as they have not taken into account the variation of formations identified in the southern Exmouth Sub-basin (Fig.2). We understand that the Cenozoic lithology differs towards the south; therefore this study will define the depositional trends found in widespread data sets identified in both the northern and southern sub-basins of the NCB and surrounding regional basins of the NWS.
Although previously recognized as dominantly carbonates, the most recent Cenozoic studies to the northern part of the NCB have revealed some insight into a Middle Miocene-Pliocene siliciclastic influx (Sanchez et al. 2012). The Middle Miocene to Pliocene siliciclastics of the Bare Fm represent an 11Ma break in the carbonate-dominated shelf (Sanchez et al. 2012). The siliciclastic influx of resulting on the deposition of the Bare Fm has been correlated with other middle Miocene increases in siliciclastic sediment supply worldwide, and compared to a variety of global changes in climate attributing to this influx of siliciclastic sediment. However such influx has not been identified in the southern part of the NCB (Bradshaw et al. 1998) and it
remains unclear whether it is a localized or regional input. Global cooling during this time and a shift to more arid conditions, reducing vegetation cover combined with more seasonally variable rainfall generating a higher sediment supply in the region is the possible theory discussed (Sanchez et al. 2012).

Like many of the sedimentation patterns along the NWS margin oceanographic currents may have been a possible control for the deposition of the Bare Fm. Retreat of the siliciclastic deposition has been accounted for by the increase in Indonesian Throughflow (ITF) and Leeuwin Currents modifying the regional climate (Gallagher et al. 2009). The three-dimensional deposition and distribution of the Bare Fm still remains in question, particularly in conjunction with its depositional controls and stratigraphic distribution to the south in the Barrow and Exmouth Sub-basins.

4. 2 Cenozoic Facies of the northern NCB

Further stratigraphic studies into Cenozoic carbonates of the northern NCB have resulted in five major subdivisions of facies sub-divided based on basin location, lithology and seismic character (Wallace et al. 2003). These include Pliocene-Quaternary Shelf Facies, Near-shore Facies, Oligo-Miocene Shelf Facies, Slope Canyon Facies and Basinal Facies (Table 1, Fig. 10). Each facies represents a number of previously identified formations found in the NCB. The Paleocene to Late Miocene succession represents an overall shallowing-upwards depositional cycle and during the early Pliocene a major transgression occurred bringing open shelf conditions and limestone deposition to the northern NCB (Wallace et al. 2003). Such facies groups have not been identified to the southern NCB, which reinforces the argument that more work is needed integrating data sets on a regional scale for the NCB.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithology</th>
<th>Eq. Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Pliocene-Quaternary Shelf Facies</td>
<td>Uncemented coarse-grained, pure limestone Carb &gt;80wt%</td>
<td>Delambre Fm</td>
</tr>
<tr>
<td>(2) Oligocene-Quaternary Near-shore Facies</td>
<td>Dolomites, quartzose, Dolomites, quartz sands, dolomite limestones, gypsum, anhydrite Carb 0-90%</td>
<td>Bare Fm, Trella Fm</td>
</tr>
<tr>
<td>(3) Oligo-Miocene Shelf Facies</td>
<td>Pure skeletal limestones Carb &gt;85%</td>
<td>Trella Fm, Mandu Fm</td>
</tr>
<tr>
<td>(4) Oligocene-Miocene Slope canyon Facies</td>
<td>Clayey limestones Carb 60-85%</td>
<td>Trella Fm, Mandu Fm</td>
</tr>
<tr>
<td>(5) Paleocene-Miocene Basinal Facies</td>
<td>Fine-grained calcareous shales and marls Carb 60-85%</td>
<td>Walcott Fm, Dockrell Fm, Lambert Fm</td>
</tr>
</tbody>
</table>

**Table 1:** A summary of the five characteristic carbonate facies with their ages and equivalent stratigraphic units found in the northern NCB identified in (Wallace et al, 2003). Carb = Carbonate mineral percentage. Formations equivalent units, shown on the right can also be correlated with some formations in the regional stratigraphic column (Fig.2).

**Figure 10:** An extract of an interpreted seismic profile with the lithological and facies data derived from a cutting analysis of the five major facies identified (Wallace et al, 2003) along a well transect NE-SW in the northern NCB Dampier Sub-basin.
5 Aims and Objectives

The aims of the proposed study are outlined A-C:

Objective A: Define the general stratigraphic and lithological history of the NCB during the Cenozoic with an emphasis on a regional correlation between the Dampier, Barrow and Exmouth Sub-basins (Fig. 3). This objective will include assessment of the geometries and distribution of carbonate deposits and determine their distribution in time and space using seismic stratigraphy.

Objective B: To identify and summarize the Cenozoic lithology in the nine selected wells within three transects one from each of the Dampier, Barrow and Exmouth Sub-basins. Lithological information will be obtained from well completion reports and data from side wall cuttings (SWC). After the key lithotypes have been summarized a depositional model will be created relating the rock properties to seismic stratigraphic packages and the previously recognized Cenozoic sedimentary cycles (Collins 2002). This lithological analysis aims to link the crucial facies to the stratigraphic evolution e.g. drowning events and subareial exposures, and identify the key facies that may pose threat to future drilling operations.

Objective C: Summarize and compare results to previous work in the NCB and surrounding NWS e.g. the adjacent Browse Basin (Rosleff-Soerensen et al. 2012, Smith 2013). Identify the correlation/interaction between the timing of tectonic events (Harrowfield and Keep 2005, Keep et al. 2007), eustasy (Carter 1998), climatic variation (Clift 2010) and oceanographic influence (Gallagher et al. 2009) and depositional patterns along the NCB. Determine the influence of local and regional tectonics has had upon the growth, architecture and geometry of the carbonate depositional features on a local and regional NWS scale.

6. Significance of Outcomes

With information obtained from this analysis, the impact of eustatic sea-level change and effects on Cenozoic carbonate growth will be compared with characteristics previously recognized in the adjacent basins of the NWS, and provide a greater range in knowledge of the Cenozoic stratigraphy of the NCB. This analysis will provide an additional analogue study for the NCB
carbonate system evolution and additional information for carbonate margins evolving from a C to T factory particularly in regards to how this transition influences margin and slope geometries.

Additionally this study aims to provide academic insight into the interaction between tectonic, climatic and oceanographic processes, and how they have influenced the basin architecture and distribution of stratigraphy along the NWS during the Cenozoic era. Some of these include the oceanographic regime such as the onset of the Indonesian Through Flow (ITF) (Gallagher et al. 2009) and the timing of subsidence and collisional tectonics of the Indo-Australian Plate (Keep et al. 2007, Harrowfield and Keep 2005).

From an industrial perspective downhole drilling hazards such as formations, zones with a high risk of unpredictable fluid loss, damage, breakdown, swelling, moving, and/or abnormal pressures can critically impact drilling efficiency and safety causing costly overruns and operation delays. As historical data indicates, carbonate rocks in particular present seismic processing and drilling challenges due to their highly heterogeneous nature (Skirius et al. 1999, Wallace et al. 2003, Power 2008). Within many wells drilled on the NWS, it has been common to encounter tight formations, highly fractured rocks and vugular or karstified textures. It is difficult to predict when or if karsts structures will be encountered and the results can be potentially disastrous if enough detailed studies have been conducted over the specified region (Tingate et al. 2001, Wallace et al. 2003, Van Ruth et al. 2002).

For future drilling operations along the NWS, there is a need to identify patterns and the regional changes in distribution of the potentially hazardous carbonate formations. There are several benefits of this analysis for predicting where blowout, loss circulation or loss of drilling fluids may occur at depth. By identifying the key lithological changes, spatial distribution and heterogeneity of the Cenozoic carbonate rocks over the NCB, this study will help prevent several of the multiple hazards associated with drilling through an unpredicted succession. Additionally this study will assist the quality of seismic depth conversion and seismic processing in a succession with complex depositional geometries and large degrees of lateral variation.

Lastly, industry can greatly benefit from a spatial knowledge of the thickness and evolution of Cenozoic carbonates along the NWS. As previously outlined, knowledge of the evolution of the Cenozoic interval with the architecture is crucial to exploration (Bradshaw et al. 1988).
Identifying the complex Cenozoic depositional geometries is of crucial benefit as much of Cenozoic sedimentation has a crucial role as a thermal load for underlying Mesozoic source rocks. The maturation history of the NWS is in part controlled by the sedimentation rates, rock properties and thickness variations of clinoforms (Bradshaw et al. 1998), therefore this study will provide additional knowledge for the development of potential hydrocarbons in the underlying Mesozoic sediments of the NCB.

7. Data and Methodology

The NWS has been extensively drilled for petroleum over the last 40 years, and an extensive amount of well cuttings and seismic data exists. The Mesozoic sediments of the NCB have been broadly examined by industry using seismic surveys and exploration drilling, however the core and thin sections data coverage of the Cenozoic sections is particularly poor mainly because this interval has been categorized as shallow overburden with little or no economic significance. Recent economic and safety difficulties along the NWS have sparked the interest to collect the shallow formation data as it can help assist current and future drilling activities (Tingate et al. 2001, Van Ruth et al. 2002).

In contrast, there is a vast coverage of both 2D and 3D seismic data from the northern Dampier Sub-basin to the southern Exmouth Sub-basin in the NCB. The three transects (TA, TB and TC) shown (Fig. 11), for the proposed study were selected based on the combination of two primary factors; 1) the distribution and availability of biostratigraphic and lithostratigraphic record of well data in the Cenozoic interval and 2) the intersection of the selected wells with the available 2D and 3D seismic data.

Objective A will be completed by combining well data (both wireline and lithological reports) and high-resolution 2D/3D seismic data along three transects labeled TA, TB and TC (Fig. 11). Well completion reports will be obtained from The Department of Mines and Petroleum Western Australia (DMP) database (WAPIMS). The seismic surveys used are a combination of publically available 2D and 3D seismic surveys donated by Geoscience Australia and Woodside Energy Ltd. Findings from the proposed NCB interpretation will be additionally compared to previous investigations on the adjoining NCB sub basins (Hocking 1988, Tingate et al. 2001, Wallace et
al. 2003), as well as the Browse basin to the North (Apthorpe 1988, Rosleff-Soerensen et al. 2012, Smith 2013). Combining the data along several transects and adjoining margins aims to reveal some of the major changes in regional stratigraphy such as the geometric and lithological transition from non-tropical to tropical carbonates and the architectural changes in carbonate build-ups along the NWS margin.

Completing Objective B will involve the analysis of well completion reports and thin sections. Thin sections will be used to identify the key Cenozoic lithological properties including: Maturity, fragmental shapes, composition, matrix and cements, diagenetic features and porosity. This will lead to the production of a depositional model/map characterizing rock properties and the distribution of sedimentary packages containing potentially hazardous lithotypes.

Objective C will be achieved by relating findings of the proposed study related to the timing of variations in eustasy, tectonics and climate with other regional studies in the NWS. A summary will be created outlining the timing of these regional events during the Cenozoic and the results will be correlated to the depositional history and framework patterns identified in the NCB.

Figure 11: Map of the NCB stud area displaying the variations in wells with the three proposed transects A-C. The selected wells were based on the quality of the Cenozoic data including biostratigraphic age indicators, side-wall cuttings and location of the available 2D and 3D seismic data.
<table>
<thead>
<tr>
<th>Well Name</th>
<th>Transect No.</th>
<th>Lat.</th>
<th>Long.</th>
<th>NCB Sub-basin</th>
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<tr>
<td>Legendre 2</td>
<td>A</td>
<td>-19.62295521</td>
<td>116.78162314</td>
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<tr>
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<tr>
<td>Outtrim 1</td>
<td>C</td>
<td>-21.53000999</td>
<td>114.452105</td>
<td>Exmouth</td>
</tr>
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</table>

Table 2: The three transects (A-C) for the proposed study including the nine wells selected based on the quality of the Cenozoic data. The three transects are found in the Dampier, Barrow and Exmouth Sub-basins along the NCB margin.

8. Timetable and Budget

An outline of the completion dates, tasks and timetable are outlined below (Table 3). The proposed study is to be completed in October of 2014. Initial analysis of the study will be conducted from April to July 2014 and the research article will be written over the July to October period.

Preliminary research commenced on February 4 2014 and the research proposal continued to be completed from this date until April 30, 2014 when it will be handed in on May 1st 2014 (table 3). The dates of the proposal seminar were announced to be conducted on the 12th of May 2014 (Table 3).

For the research project, data collection (of seismic and well data) commenced on the 1st of April 2014 and continued for approximately one month till May 5th 2014 (Table 3). The interpretation of well, lithological reports, and seismic data commenced on the 5th May and continued through till late July. The project interpretation and analysis is due to be completed by the 20th of August 2014 with the writing of the article commencing on the 10th July and finishing on the 5th of October 2014. Lastly the completed research project will be submitted for marking on the 23rd of October 2014 and the final seminar will be conducted on the 27th October 2014 (Table 3).
Table 3: The commencement and deadlines for tasks associated with the proposed study. The project aims to be completed by the 27th October and main data interpretation commencing in April. The research article will be completed over the July-October period.

The well completion reports, samples, wireline log and 2D/3D seismic data is provided by Woodside Energy Ltd., Geoscience Australia, and The Department of Mines and Petroleum Western Australia. The Center for Petroleum Geoscience and CO2 Sequestration (GPGCO2) at the University of Western Australia has provided the use of the seismic workstation and software licenses free of charge. The key expenses of the proposed study include consumables totaling $150.00 and thesis production, totaling approximately $350.00 (Table 4).

<table>
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<tr>
<th>Task</th>
<th>FEB</th>
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<th>APR</th>
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<td></td>
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<td>27th</td>
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Table 4: Summary of the items and estimated costs of the proposed study. The seismic and well data is expense free as it is supplied by Woodside Petroleum and is publicly available data from the DMP Western Australia. The CPGCO2 has supplied the use of a seismic workstation and software licenses. Consumables and thesis production is the only predicted expenses for the project as of 30th April 2014.

<table>
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<th>Item(s):</th>
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<td>Consumables:</td>
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<td>Seismic Workstation:</td>
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<td><strong>Sub Total (AUD):</strong></td>
<td><strong>$350.00</strong></td>
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Appendix A: Referencing Style and Format


Pleistocene stratigraphy of the Boco Plain, western Tasmania

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Mapping of surficial glaciogenic sediments and logging of drill cores from the Boco Plain has revealed a more complete sequence of glacial and interglacial sediments, and a more complex history of middle to late Pleistocene depositional events than anywhere else in Australia. Radiocarbon dating of the uppermost fluvial and organic-rich lacustrine sediments indicates that a long record of non-glacial deposition followed the Penultimate or Boco Glaciation. Prior to this, a sequence of sediments indicating multiple glacial advances is intercalated with lacustrine silts and fluvial sands and gravels. Radiocarbon dates for the uppermost unit of organic lacustrine sediments show that they extend far beyond the range of the radiocarbon technique. In addition, uranium–thorium dated ferricretes from the older sedimentary sequence provide minimum ages for the glacial events, and suggest ice advances into the plain broadly correlative with marine isotope Stages 6, 8 and ≥ 10. Normal detrital remanent magnetization of the sediments confirms a middle Pleistocene age for all the glacial episodes recorded in the cores. The glacial sediments overlie Cambrian volcanic bedrock weathered to a depth of 9 m which indicates a long time gap between initial erosion of the valley and the commencement of middle Pleistocene glacial deposition.

Key words: Boco Plain, glaciation, Pleistocene, stratigraphy, Tasmania.

INTRODUCTION

The Boco Plain is a broad, flat-floored depression that extends northwards from the Pieman River (Figure 1). The surface of the plain descends southwards from 320 to 160 m in 15 km and is bounded on either side by strike ridges of Cambrian volcanics. The valley contains more than 100 m of late Cenozoic sediments. These overlie a complex topography developed on rhyolitic tuffs with intercalated sediments of the Cambrian Mt Read Volcanics (Figure 2). To the east the valley is bounded by a northeast-oriented strike ridge which is breached only by Tullabardine Gap. To the west the valley is bounded by the Pinnacles Fault, and the northeast-oriented strike ridge that includes Burnus Peak and the Pinnacles Range.

Drilling by the Hydroelectric Commission of Tasmania and Pasminco Exploration, and gravity and seismic profiling near Boco Siding by the Tasmanian Mines Department (Richardson 1989), have enabled aspects of the Quaternary stratigraphy and basement topography of the Boco Plain to be reconstructed. The stratigraphic record derived from several of the cores is variable, with poor recovery of the glaciogenic sediments from many drillholes. However, several Pasminco cores, Boco 4 and 10, and AK1 provided good sediment recovery (up to

than envisaged from the mapping of the surficial glacial deposits (Augustinus 1982; Augustinus & Colhoun 1986). In the present paper the glacial and non-glacial sediments from the drill cores are described, and the implications of the 14C and U/Th dated stratigraphy are discussed for the middle Pleistocene glacial history of western Tasmania.

PREVIOUS WORK

The Pleistocene glacial geology of the Boco Plain was first investigated by Reid (1918), who considered the flat-floored Boco Plain marked a moraine-filled pre-glacial river course that flowed northwards from the confluence of Farmhouse Creek. Augustinus (1982) and Colhoun and Augustinus (1984) argued that glacier ice diverted the Que and Bulgobac Rivers from a direct route southwards to the Pieman River to a northwesterly route through the Que Gorge during the early Pleistocene. The drainage pattern was accentuated and maintained by further ice blockage in the south during the middle Pleistocene glaciations.

The surficial glacial geology of the Boco Valley was mapped by Augustinus (1982) and Augustinus and Colhoun (1986) who suggested that at least three glacial
PLEISTOCENE, BOCO PLAIN, TASMANIA


(Received 30 November 1993; accepted 25 May 1994)
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