Tectono-stratigraphic evolution of the Cenozoic
Great Australian Bight

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DECLARATION

“No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning” – Alexander G.W.D Sharples.

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THE AUTHOR

In my 7 years at the University of Manchester I have graduated through a B.Sc Geology, M.Sc Petroleum Geoscience and I am now approaching the submission and final stretch of my Ph.D in geophysics. It was not until the latter stages of my M.Sc degree did I first encounter seismic interpretation, which over everything else captured my attention and interest. Owing to this, I wanted to further improve my academic potential within the seismic interpretation niche and undertook the Ph.D project self-funded. Fortuitously, I was able to attain full second and third year funding from the BP Australia exploration outfit, and the days and nights of selling sweets on a market stall came to an end, which allowed me to give my undivided attention towards the Ph.D.

BP was kind enough to grant me full fee, stipend, hardware and conference admission funds. I was also able to partake in two intense summer internships. The first within the BP exploration group where I undertook geohazards based projects looking at the shallow sections within the Great Australian Bight. The second internship was ironically within the geohazards group but working on a shallow section seismic stratigraphy project. The internships provided me with an abundance of new and applicable technical skills to take back for my Ph.D project. More importantly, they provided me with an understanding of the delicate relationship between academic research and industry driven goals.

Since the successful completion of the internships I am due to commence work with BP in September 2014 as a geohazards specialist (following completion of the Ph.D). However, I am also keen to keep open my academic ties and foresee a return to academia in the future with postdoctoral opportunities already discussed and open. Regardless of a future decision to return to academia or stay within industrial geoscience, I intend to continue actively working and publishing within peer-reviewed science journals, as I have found it to be one of the most rewarding and fulfilling accomplishments resulting from this Ph.D.
ABSTRACT

*The University of Manchester, Alexander Gabriel William David Sharples, August 2014*

Ph.D Geophysics/Geology and Basins Studies

**Tectono-stratigraphic evolution of the Cenozoic Great Australian Bight**

The Great Australian Bight (GAB) is an extensive W-E striking continental margin basin that drifted northwards during the Cenozoic following rifting and separation from Antarctica in the mid/late Cretaceous. Seafloor spreading accelerated in the mid-Eocene and was associated with local volcanism. The mid-Eocene succession of the GAB is conspicuously mounded and separates a dominantly siliciclastic succession below from a fully marine carbonate succession above. The mounded succession was penecontemporaneous with major changes in global climate, oceanographic conditions and tectonic re-organization in the region, and thus may hold important clues as to the palaeoenvironmental changes associated with these changes. The mid Eocene has so far only been described locally or in passing, usually by studies focused on either the siliciclastics below or the carbonates above. It was therefore chosen as a major focus point for the research project reported herein. Exploration activity in the GAB has been limited despite the presence of a working petroleum system and large target structures, but industry interest has increased over the past few years leading to 3D seismic surveys being acquired in the GAB. The focus for exploration is the Cretaceous succession beneath the relatively thin Cenozoic cover, which however, is still important in terms of shallow hazards and as overburden to the anticipated productive sections. As is often the case, the new 3D seismic data shows many overburden features in great detail and thus affords new insights to be gained that improve our understanding of the post-rift evolution of the margin.

This thesis expands upon and reinterprets a pre-existing sequence framework in the Cenozoic GAB based from ODP Leg 182 results. A vast database of 2D and 3D seismic surveys has been integrated with exploration wells and borehole data and several surfaces have been calibrated to borehole and well constraints, then mapped to the maximum lateral extent across the available dataset. Surface mapping provided new insight into sequence deposition and palaeoenvironmental settings. Structure maps and thickness maps highlight key depocentre locations and trends over the Cenozoic GAB as well as stacked mass debris aprons. The newly discovered sequences raise new questions regarding trigger mechanisms in a-seismic areas and feed into industry geohazard perception models.

The base surface of the Cenozoic framework hosts a plethora of mounded features across shelf and basinal section. All mounds within the dataset have been mapped. A set a bryozoan reef mounds have been interpreted lying parallel to the margin as linear complexes over 500 km. They coincide with the underlying siliciclastic delta clinoform breakpoints and provide insight into the changing palaeoenvironment at the 43 Ma mark, cessation of siliciclastics and regional marine transgression. Further mound mapping aided by 3D attribute extractions along the base Cenozoic unconformity led to the interpretation of a series of enigmatic igneous-based mounded features. The discoveries have been included in a comparative study, comparing all mounded features (igneous or carbonate) and contrasting their individual characteristics of geometry, seismic facies, dimension in order to understand mound origin and emplacement. A new grouping of mounds in the GAB has been established, the origin and emplacement mechanisms of which contribute to the global knowledge base.
ACKNOWLEDGEMENTS

Several key people have played major roles from the outset; first and foremost I would never have been able to achieve my Ph.D without the guidance and support from my dear parents. I cannot begin to thank them for their sacrifices in both time and finance. They are both an inspiration to me.

My supervisor Dr Mads Huuse is simply one of the finest Ph.D supervisors available in Geosciences. His support and guidance on both a technical and social level has been second to none, and I am forever indebted to him for taking on the challenge to polish a somewhat average masters student into becoming a true geoscientist worthy of a Ph.D and major journal publications. I look forward to keeping academic ties open and working with Mads in the future.

I owe much to employees of BP with whom I have worked side-by-side and learned so much about the industry. In particular I must mention Prof Richard Dixon for his guidance and initial set up of my BP sponsorship. I will truly miss teaching with him on the December M.Sc exploration course unit. A special mention must also be given to Dr Ashley Price to whom my family and I are indebted for his decision to fund the Ph.D and application for a Geoscience career with BP. Other notable mentions go to Dr Mark Thompson, Dr Cheree Stover, Dr Simon Shoulders and Gareth Wood - whatever their input, positive or negative, has helped shape and forge the path of the Ph.D and in one way or another contributed to my arrival for a Ph.D thesis submission.

A huge thanks to Jenny Totterdell and Robert Langford at Geoscience Australia, for making so much of the Bryozoan geology publication possible, as well as their guidance and help in Australia and this academic journey.

To the BP Australia team and BP Geohazards teams' outstanding geoscientists - I owe many a good discussion and look forward to working with them in the future.

To my colleagues at Manchester University I thank them for their help and support over the years. In particular Jess, Atunima and Tobi.

Finally to ‘Button’, ‘Bug’, ‘Ryu’, ‘TheDentist’ and 'ROC' - you’ve each had your impact in its own way and I’m eternally grateful for your support.
ABBREVIATIONS AND REFERRALS

- CWC - cool-water carbonate(s)
- GAB - Great Australian Bight
- SCS – siliciclastic sediments
- BRM – bryozoan reef mound(s)
- VM – volcanic mound(s)
- H1a - unconformity surface bounding Mesozoic siliciclastics from Cenozoic cool-water carbonates
- BBIC – Bight Basin Igneous Complex (~Sensu Schofield and Totterdell, 2008)
CHAPTER 1: INTRODUCTION

1.1. Rationale

The Southern margin of Australia and its conjugate margin on northern Antarctica are perhaps the final frontiers for hydrocarbon exploration in the world. As such, with relatively low industrial investment in the offshore section of the GAB until recent, many of the geological curiosities have been left untouched. Two main framework studies (Totterdell et al, 2000; Feary and James, 2000) have been undertaken in the western GAB. The former lacks detailed resolution within the cool-water carbonate sequences and is based on a “Supersequence” scale. The Latter is integrated with borehole analysis (Leg 182 ODP) and more detailed but is laterally limited to the Eucla basin where it overlies the Eyre Sub-basin only. Cenozoic GAB stratigraphy shows a major change from siliciclastic to cool-water carbonate domains in the mid-Eocene (c. 43 Ma); the bounding surface (“H1a”; see Chapter 3) is represented as a regional unconformity.

Sequences within the Cenozoic stratigraphy are host to an array of unconformities and past studies have tended to be biostratigraphic based, 1-Dimensional and lithological. Without lateral connectivity provided by 2D seismic reflection profiles, many geological features have been overlooked leading to a lack of chronostratigraphic and palaeoenvironmental information regarding Cenozoic cool-water carbonate sequences. A key task still remaining is to make detailed links between global tectonics to the Cenozoic sequences.

The central and eastern GAB has some of the thickest sediment deposits in the world owing to its extensive and deeply set Jurassic rifted Ceduna and Eyre Sub-basins. A variety of well-imaged siliciclastic delta deposits stack up to 5 km of vertical sediment thickness in the syn-rift stratigraphy. Bounding this is a major compound regional unconformity with abundantly documented volcanics and enigmatic and numerous geobodies, followed by the largest Cenozoic cool-water carbonate province in the world (Eucla Basin).

With so many geological uncertainties coupled with the potential for successful hydrocarbon exploration the GAB is one of the most exciting areas to study geologically. This thesis provides a revised and more detailed seismic stratigraphic framework based on all available data, setting the scene for studies focused on deposits, unconformities and volcanics around the siliciclastic–cool-water carbonate transition.
1.2. Aims

1. Unravel the post-rift tectono-stratigraphic evolution of the GAB
2. Elucidate the impact of tectonics, climate and sediment supply on the mid-Eocene evolution of the GAB

1.3. Objectives

A.) Construct a new sequence framework for the Cenozoic section of the GAB based on ODP Leg 182 results as a starting guide and expand across the available dataset

1. Integrate seismic and ODP borehole database.
2. Map proposed Leg 182 seismic sequences and expand across the dataset using seismic stratigraphic principals. Add new sequences where appropriate.
3. Construct TWT structure maps for each bounding surface.
4. Construct TWT thickness maps for each sequence.
5. Record package observations, seismic facies and character of each sequence.

B.) Gain further understanding of the bounding surface to the SC–CWC domain.

1. Document all the SC-CWC geological features including an array of mounds, intrusives, extrusives, faults, canyons, mass transports complexes and sediment waves
2. Produce a set of representative regional seismic sections through the GAB dataset with annotations, explanations and chronostratigraphic significance for each sequence.
3. Document features relative to deduction palaeoenvironmental, palaeoecological and palaeogeographic settings throughout the Cenozoic.
4. Quality-check and expand on 2D seismic data interpretations with 3D Ceduna (in-house, BP internships Sunbury).
5. Explore the 3D Ceduna data using 3D attribute extractions and document features found relating them to point
1.4. Data and Methods

This study is based on interpretation of a regionally extensive database of open-file high and medium-quality, post-stack time-migrated multi-channel 2D seismic reflection profiles calibrated with log data over the western GAB (Figure 1).

Seismic surveys include:

- 2D high-resolution multi-channel seismic lines (Australian Geological Survey Organisation, 1995). Acquired on the ‘R/V rig seismic’ in support of the Leg 182 drilling proposal (Chapter 1 Appendix, Figure 2) with a dominant frequency of approximately 80 Hz and a total line length of 1800 km.
- 2D high resolution seismic lines (Galathea Danish Expedition 1998) with a dominant frequency of 75 Hz and approximately 5 m vertical resolution (Chapter 1 Appendix, Figure 1; 3).
- Medium resolution 2D seismic lines (ESSO, 1979) with 1380 km$^2$ and a dominant frequency of approximately 35 Hz (Chapter 1 Appendix, Figure 1; 4).
- Medium-resolution 2D seismic lines with further 2D lines (Japan National Oil Company, JNOC, 1990/1991) with 2350 km$^2$ grid line length and dominant frequency of 27 Hz (Chapter 1 Appendix, Figure 1; 5).
- 2D medium-resolution "Flinders deep-water" seismic lines (Chapter 1 Appendix, Figure 6) with a dominant frequency of approximately 30 Hz and a total line length of 15,600 km.
- 2D “Deep-water GAB” (DWGAB) survey, 1998 – provided by Geoscience Australia with a vertical resolution of approximately 25 m and a total line length of 5315 km.
- 3D Trim Survey (Woodside Energy, 2006) over 1250 km$^2$ (Chapter 1 Appendix, Figure 7) with a medium vertical resolution of approximately 20 m.
- 3D Ceduna Survey (BP Australia Exploration Pty Ltd, 2012) over 12,500 km$^2$ (Chapter 1 Appendix, Figure 8) with a high resolution of approximately 12 m.
Figure 1: data map of project area showing full suite of 2D seismic, 3D seismic, boreholes and exploration wells. Dark green: ESSO and JNOC 2D Seismic lines, Light green: AGSO and Galathea high resolution 2D seismic lines, Pink: Flinders 2D seismic lines, light blue: Deepwater GAB survey
Across the project area, line spacing is highly variable, from less than 1 km to more than 40 km. The seismic data were integrated with well logs and cutting descriptions from exploration wells (Potoroo-1, 33.385°S, 130.770°E and Jerboa-1 33.502°S, 127.602°E) and ODP Leg 182 boreholes (Figure 1; Chapter 1 Appendix – Figure 10). Logs were attained from the International Ocean Discovery Program (http://brg.ldeo.columbia.edu/logdb/holes.php) for Leg 182. The following standard logs were integrated into an excel spread sheet (ASCII format) and converted using a best estimate of velocity for total well depth where sonic data was missing, (not all boreholes had all logs available and logs usually not available for entire drilled interval - Chapter 1 Appendix, Figure 9; 11, see DVD Folder: Appendix, Chapter 1; Ref #1 Log data~):

Key logs included:

- Accelerator Porosity Sonde
- Caliper-Hostile Environment Lithodensity Sonde
- Gamma Ray Spectrometry Tool-Formation Microscanner Tool String-Pass 1
- Sonic Digital Tool-Linear Mode-Pass 1

Seismic observations in Two-Way Time (TWT) were converted to depth using an interval velocity of 2200 m/s, based on sonic velocities recorded in the Potoroo-1 well and ODP Leg 182 boreholes (estimated error +/- 10%). Hence, this was applied for all velocity calculations regarding cool-water carbonate overburden within the Dugong Supersequence.

Software used to interpret the seismic database was primarily SMT Kingdom 8.6 for the first 2 years of the Ph.D owing to superior mapping algorithms and 2D mapping interface. The implementation of the vastly improved version 2013 in the third year and access to the 3D Ceduna survey, however, resulted in a total move of project database to Schlumbergers Petrel 2013. Adobe Illustrator CS6 has been used extensively to add annotations to maps and seismic sections.
During a conference trip to Canberra, Australia to the Geoscience Australia headquarters, the outfit generously provided several reports and raw data sets including:

- Gravity and Magnetic maps across the Bight Basin
- Dredging Survey
  - ARC GIS data base and survey map
  - Report including videos and photographs of results
  - Pers. Comm. Information regarding results and methodology (Cameron Mitchell)
- Several Geoscience Australia reports

A variety of methods have been employed to achieve the various aims and objectives as outlined. Each chapter which specifically addressed a selection of aims has a detailed methodology outlined (See Chapters 3; 4; 5; 6). In principle, seismic stratigraphic interpretation based on observations of reflection geometries, seismic facies and acoustic change were widely used throughout the project to map a variety of key surfaces. Discovery of the bryozoan reef mound complexes, their full documentation and interpretation played a major role in the project. The BRMs were calibrated with a selection of cutting samples from Potoroo-1 and identified by Bryozoan experts at the London Natural History Museum. Cutting samples were also mounted to polished thin section and integrated with x-ray diffraction analysis where anomalies were found (Chapter 1 Appendix, Figure 13).

The two BP internships gave rise to an integrated geochemistry seismic reflection data project, which, fundamentally fueled a geohazards discussion towards the likelihood of presence of hydrogen sulphide in the Ceduna Sub-basin. This equally benefited the Ph.D with modeling of the palaeoenvironment over the Eyre Sub-basin including sedimentation rates, migration pathways and geothermal gradients. Following the completion of this project, further geohazard assessment was considered, this time to map and document the series of mounded features in the Ceduna 3D. These are described in detail in Chapter 6.

A second BP internship allowed for expansion and integration of the 2D structural framework surfaces in to the 3D Ceduna and further analysis of acoustic properties using 3D attribute extraction. Again, the context was written and discussed from a mounded features and palaeoenvironment angle which was complimentary to geohazards.
Figure 2: Flowchart of integrated workflow, Ph.D project structure and results. Internship projects have not been included as individual sections.
1.5. Thesis Structure

Thesis structure is in an alternative format with three main components: 1. Two scientific journal papers/chapters; one submitted and published, another in preparation to be submitted 2. Three technical thesis-style chapters and 3. A detailed appendix. The first published paper submitted and accepted to the Geological Society of America’s Geology Journal. This does not breach confidentiality clauses with funding body BP as the paper is written and uses entirely open-source 2D seismic data provided by Geoscience Australia. Both bodies have been acknowledged for their various data and financial contributions. A toll-free download link is available here for 2 years duration:

http://geology.geoscienceworld.org/cgi/content/full/42/8/683?ijkey=TNHkFSRoi2YOI&keytype=ref&siteid=gsgeology

The second paper is aimed at the AAPG bulletin and requires further drafting at the time of submission. Ideally, remarks from the Ph.D Viva session can be implemented as a pre-peer review function and the paper can be fully submitted following this.

It is hoped that further Ph.D chapters can become published works as and when data confidentiality is relinquished in the future. However, at present the remaining chapters are formatted as data reports, framing and supporting the main novel findings reported in the published papers. The appendix, although large, does not contain all images and documents; it is designed as a "best of" booklet to accompany and compliment the thesis and relevant chapters. A DVD has been made containing all data used to fuel discussion/thought for the Ph.D thesis.

1.6. Confidentiality Status

This Ph.D thesis has a 2 year confidentiality clause applied from submission (20/08/2014–20/08/2016) stipulated by project sponsors BP. This does not apply to published works for which either permission has been granted or the work was undertaken during year 1 of the Ph.D prior to funding. Within this two year period, none of the work herein can be cited or used for reference without the permission of the funding body. Any requests for access to this Ph.D thesis must be taken through the appropriate body at both the University of Manchester and BP. Please see sponsorship agreement for further information.
CHAPTER 2: PROJECT BACKGROUND AND PREVIOUS WORKS OF RELEVANCE IN THE GREAT AUSTRALIAN BIGHT

2.1. Introduction

The GAB is still under-explored in terms of its scientific and economic potential. Exploration well data is sparse through the Bight Basin with only three wells drilled over the thickest sedimentary deposits in the Eyre and Ceduna Sub-basins (Jerboa-1, Potoroo-1 and Gnarlyknots-1) of nine wells in total. All exploration wells drilled showed dry returns and unfortunately mainly ignored the CWC overburden without acquisition of log data. A detailed logging suite is provided however, with the ODP Leg 182 boreholes. One exploration well (Jerboa-1) over the Eyre Sub-basin suggested presence of a palaeo-oil column (Ruble, et al., 2001) which may also be linked to hydrogen sulfide formation in the Pleistocene prograding CWC platform (Swart et al., 2000; Wortmann, 2006; Sharples, 2012, Report – Chapter 3 Appendix, pages 295–348). The acquisition and reprocessing of several 2D seismic surveys in the mid-nineties and especially the deep-water Flinders 2D seismic survey in 2006 did however, allow for the production of integrated well and seismic reports by Geoscience Australia.

This led to a much greater understanding of the tectonostratigraphic geological evolution of the GAB, by combining new findings with older models and emphasizing basin evolution in the chronological not lithological sense. The majority of these studies typically focus on deeper Mesozoic syn-rift siliciclastic deposits to develop interest in the GAB hydrocarbon prospectivity. The most prospective petroleum systems are interpreted to be thick mid–Late Cretaceous deltaic and marine sediments, which integrated studies suggest contain the full suite of a working petroleum system; the main issue of which is interpreted as hydrocarbon charge (or lack of). In 2007 Geoscience Australia undertook a sampling survey (R/V Southern Surveyor) to test the source potential in the Jurassic–Cretaceous section of the Bight basin. The outcome resulting in successfully recovered samples of Cenomanian–Maastrichtian rocks with several samples showing excellent source potential Totterdell et al., 2008.

The overburden of the GAB however, is arguably just as under explored and geologically interesting as the deeper sections. The Bight Basin is a vertically stacked basin and unconformably overlain by the Eucla basin which is host to the world's largest Cenozoic
cool-water carbonate province (James and von der Borch 1991; Feary & James, 1995, 1998; Feary et al., 2000; James et al. 2000; Sharples et al, 2014). The unconformity which separates these two geological domains is complex, consistently varying across its contact with respect to underlying basins and distance from the southern margin shelf. 3D observations suggest this unconformity is actually composite between several unconformities (see Chapter 3). The unconformity not only represents a major lithological shift from siliciclastic to CWC domains, but importantly coincides with several globally and regionally significant geological events; including the northward tilt of Australia (DiCaprio et al., 2009; Heine et al., 2010), accelerated Southern Ocean opening (Exon et al., 2002), onset of warm-water currents sweeping the GAB (McGowran et al., 1997; Li et al., 2003), mid-Eocene global sea-level fall (Miller et al., 2005), and regional sea-level rise due to enhanced subsidence associated with acceleration in seafloor spreading and transition of the GAB from rift to drift domain (Li et al., 2003).

The result appears to be recorded as emplacement of an array of geobodies across the Bight Basin which were the focus of this Ph.D thesis. The CWCs of the Eucla span extensively landward and basinward and are well exposed inland along the Southern Australian coastline. They have been documented and referred to extensively (Clarke et al., 1993; 2003; Sharples et al., 2014; Taylor, 1975; Totterdell et al., 1990; Totterdell and Mitchell, 2009; James, 1997; James and Bone, 2010; James and Von Der Borch, 1991; James et al., 2000; Li et al., 2003; 2004) and have been sampled meticulously by the Ocean Drilling Program in Leg 182. Such sampling has led to a further array of borehole analysis integrated with seismic studies (Feary, 1993; 1998; Feary and James, 1995; Feary et al., 1995; Feary and James, 1998; Huuse and Feary, 2005; James et al., 2006; Mitterer et al., 2001; Swart et al., 2000; Wortmann, 2006; Anderskouv et al., 2011) with focus mainly on seafloor and Pleistocene sequences. With a present day hot topic of scientific debate regarding climate change and ice growth at the poles, understanding the conjugate margin and timing of events may provide key insight. The cool-water carbonate palaeo-ecological growth models and advent of the proto-Leeuwin current in the mid-Eocene draw many new questions regarding biosphere interactions around a time of global climatic cooling in combination with the wealth of studies into the complex rifting and passive margin spreading regime in the GAB (Bijl et al., 2013; Stagg et al., 1990; Sayers et al., 2001; Reynolds et al., 2005; Li et al., 2003; 2004; Blevin and Cathro, 2008; Cande and Mutter, 1982; Brown et al., 2003; McGowran et al., 2004; Norvick and Smith, 2001; Norvick, 2005; Teasdale et al., 2003; Veevers, 1987; Veevers et al., 1991; Wallace et al., 2002; Muller et al., 2008; 2012; Zachos et al., 2001).
2.2. Project Area

The project area (Figure 1) covers an area of approximately 40,000 km² between the central and eastern Bight Basin and the overlying Eucla Basin. The study area mainly focuses on Eucla Basin Cenozoic stratigraphy above the Eyre and Ceduna Sub-basins. However, all available 2D seismic data were utilized and interpretation was extended into the deeper sections of the Recherche Sub-basin. The project area is extensive and contains a plethora of scientific topics worthy of study. For this reason it was decided to progress no further west than the Eyre Sub-basin and no further east than the Ceduna Sub-basin (Figure 1; red outline).

Figure 1: Map to show structural elements of the Bight Basin (modified from Bradshaw et al, 2004) and highlighted Ph.D project area. Note, the overlying Eucla basin not shown for clarity purposes but is depicted in future figures.
2.3. Geological Setting

2.3.1. Basin Arrangement and Structure

The Great Australian Bight is located on the passive continental margin offshore southern Australia which rifted from Antarctica during the late Jurassic, which saw thick deposits of following Mesozoic fill accommodated by large and extensive depocentres. Active rifting ceased in the late Cretaceous and the margin has been in drift ever since. The Bight Basin comprises of 8 sub-basins in total, of which, the Eyre and Ceduna Sub-basins and the overlying, vertically stacked Eucla Basin are central to the study. The Eyre and Ceduna Sub-basins are Mesozoic to Cainozoic depocentres which developed during extension and rifting in the Jurassic, followed by Cretaceous to recent thermal subsidence (Fraser and Tilbury, 1979; Bein and Taylor, 1981; Wilcox and Stagg, 1990; Stagg et al., 1990; Totterdell et al., 2000, Norvick and Smith, 2001, Sayers et al., 2001, Teasdale et al., 2003). The Southern Australian margin has been shaped by four broadly correlating tectonic events: 1.) Supercontinent break-up of Rodinia from the Mesoproterozoic to Cambrian, 2.) Intra-continental and back-arc settings to the initiation of the active eastern margin of Gondwanaland, 3.) Break-up of Gondwanaland active rifting in the Late Jurassic – early Eocene and 4.) Passive and tectonic divergence owing to increased seafloor spreading rates from the middle Eocene to the present day (Blevin and Cathro, 2008). Although structurally complex and chronologically littered with a plethora of unconformities, the geological evolution of the Great Australian Bight and its component sub-basins has led to two simplified and distinct domains (Figure 2).

The first and older is the lower lying thick siliciclastic-rich, syn-rift to early post-rift domain with depocentres located mainly above the half-graben structures which form the Eyre and Ceduna Sub-basins. This is overlain by a thin cool-water carbonate overburden mostly located in the Cenozoic Eucla Basin (Figure 2). The siliciclastic domain has been separated into Supersequences based on seismic stratigraphy from Totterdell et al., 2000. In the Totterdell 2000 study, the CWC domain is entirely within the Dugong Supersequence. This was split into several other sequences where the Eucla Basin overlies the Eyre Sub-basin from work preceding ODP Leg 182 (Feary et al., 1993; 1998; Feary and James, 1995; 1998) and summarised in Feary et al., 2000.
Figure 2: Interpreted geo-seismic section through Eyre and Ceduna Sub-basin modified from Totterdell et al., 2003 to show proportions of siliciclastic and cool-water carbonate lithologies. Wobbegong siliciclastic not shown but lies chronostratigraphically separate to Mesozoic siliciclastics.
The Ceduna Sub-basin:

The Ceduna Sub-basin is connected to the east by the Duntroon Sub-basin and west by the Recherche Sub-basin and is overlain by the Ceduna terrace. The terrace is part of a series of thin platform covers to the north and east (the Madura and Couedic Shelves; Totterdell et al., 2003). The Ceduna basin contains major accumulations of sediment up to 15 km thick (Totterdell et al., 2000; 2003) and covers an area of approximately 90,000 km² with water depths ranging from 200 m to 4000 m (Stagg et al., 1990). The Sub-basin is renowned for incredibly thick siliciclastic delta deposits and it is the primary depocentre for Middle Jurassic – Early Cretaceous strata (Figure 3). The distinguishing geological feature in the Ceduna Sub-basin are the sets of extensional gravity-driven detachment faults within ductile shales (Reynold et al., 2005; Blevin and Cathro, 2008). The Ceduna Sub-basin is also host to the Bight Basin Igneous Province (Sensu- BBIP; Schofield & Totterdell, 2008) with a variety of large sills, dykes and volcanic mounds. The volcanic episode is suggested to have occurred during the early middle Eocene and many of the mounds and their relationship to underlying sills have been reported in detail by Jackson 2012; Holford et al., 2012; Jackson et al., 2013; Magee et al, 2013.
Figure 3: Sediment thickness map of the southern Margin taken from FroGTech Southern Margin Synthesis Project based on Teasdale et al., 2004. Red outline is project area.
The Eyre Sub-basin:

The Eyre Sub-basin appears connected to the north west of the Ceduna Basin and sits as a “perched” extensional basin that underlies the Eyre terrace trending east-north-east with an area of approximately 8000 km squared (Totterdell et al., 2000, Stagg et al, 1990). It is characterised by a series of half grabens also filled with Jurassic to mid Albian sediments of the order of 3.5 km in thickness. Similar to the Eucla basin, the Eyre is bounded by basement highs, to the north, west, and north east but does appear to connect to the Ceduna, as they share the same Supersequences with exception to the Hammerhead Delta which resides only in the Ceduna.

The Eucla Basin:

The Eucla Basin is a cratonic Cenozoic – present day onshore basin, lying between Southern and Western Australia stretching approximately 2000 km east to west and 500 km north to south. Although mainly on-land it does have an offshore component which unconformably and vertically stacks above the Bight Basin with the southernmost margins bordering the Ceduna and Eyre Sub-basins. The Basin fill is primarily carbonate facies (up to 1 km thick) and with an initially thin siliciclastic (Hampton Sandstone Formation) followed by thick extensive carbonate formation (Wilson Bluff Formation). The Wobbegong supersequence is also grouped within the Eucla basin as it shows significantly different character to the Mesozoic siliciclastic deposits of the Bight Basin. The hiatus between the Eucla Basin and the Bight basin (H1a unconformity: Chapter 3) is complicated and consists of composite unconformities. The oldest lithological formations within Eucla stratigraphy is the Wilson Bluff Limestone Formation. This records interactions with various mounds across the GAB area and aids in dating and mound growth style using seismic stratigraphic techniques. This is detailed by Schofield and Totterdell, 2008 and further clarified by Jackson, 2012 and Magee et al., 2013. The difficulty arises when relating mound ages to each other, as not all the same Wilson Bluff sequence reflectors are deposited above each mound. Furthermore, complications owing to erosion and canyoning make interpretation challenging.

2.3.2. Structural Setting

The basement structure is mainly composed of Neoproterozoic metamorphic rocks separated into early Proterozoic basins. The basement becomes particularly shallow (< 1 second TWT) towards the present day shelf under the Eucla Basin, the Albany-Frazer
province in the west and the Officer basin to the north. Interpreted basement and precambrian metamorphic rocks were penetrated and sampled at the bottom of Jerboa-1 in the Eyre Sub-basin (Huebner, 1980). To the east of the Ceduna Sub-basin the basement rocks are Proterozoic crystalline and part of the Gawler Craton. The basement "pick" under the thickest sections of the Ceduna basin however, is still a point of debate with multiple candidates for picks available on seismic lines. This has been an issue with all 2D seismic data in the GAB and is still an issue even with the 3D Ceduna survey, with two main candidates existing. A point of intense debate (BP Australia Exploration Team; Pers. Comm). The basement rock structure is of significant importance and acts as a guide for the lineament and trending of the development of the Bight Basin (Stagg et al., 1990; Totterdell et al., 2000) and is strongly represented in the east-west trend development of the Eyre and Polda basins.

Integrated geophysical studies have provided a wealth of information regarding the structural evolution of the basement and basin architecture. Work by Wilcox and Stagg, 1990; Wilcox, 1990; Stagg et al., 1990; Stagg and Wilcox, 1990, developed the concept of the Southern rift System (SRS) which describes the rifting and extensional regime in the Bight Basin and across the Southern Margin. More importantly the SRS concept covers two phases of extension both of which are orientated differently. This model suggests the initial extension (mid–Late Jurassic – Early Cretaceous) to the NWSE, which resulted in the formation of half-graben structures in the Eyre, Duntroon and partial sections of the Ceduna Sub-basins as well as reactivation of older structures in the Polda trough. This was followed by a suggested change of lineation in the Cretaceous to NNE-SSW, in line with global tectonic reconfiguration which manifested itself mainly in the Otway, Sorrel and Gippsland Basins but only resulted in structural reactivation in the Bight Basin (Wilcox and Stagg, 1990). The Bight Basin boundaries to the north were placed at major basement faults, which define the thickest sections of Mesozoic strata. The southern Bight Basin boundary is defined as a basement ridge representing continent–ocean boundary (Veevers, 1986).

In 2001 Sayers et al., developed a break-up model invoking lithosphere-scale shear extensional processes, whereby the crustal structure of the GAB could be explained by differences in upper and lower crust plasticity. Post-rift thermal subsidence was followed by a phase of accelerated subsidence (late Albian to early Campanian in which a series of thin-skinned gravity driven extensional faults propagated throughout the Ceduna Sub-basin; Totterdell and Krassay, 2003). Observations from 3D seismic data suggest these faults were in cases active until the early Oligocene (See Chapter 3).
Figure 4: Subdivisions of Bight Basin superimposed over a magnetic anomaly image. Also shown are the outlines of major crustal elements (AFTB = Adelaide Fold-Thrust Belt) and the interpretations of Continental Ocean Transition and Continental Ocean boundary by Sayers et al., 2001. Taken from Totterdell et al., (PIRSA). Note the red highs above the Eyre Sub-basin.
2.3.3. Plate Tectonics, Spreading Rates and Directions

The Bight Basin developed in the Middle–Late Jurassic following break-up of the Gondwanan supercontinent. The extension along the southern margin formed one arm of a triple junction, the others saw the advent of incipient rifts between India and Western Australia and India and Antarctica (Norvick and Smith, 2001; Fig. 4.26a). Seafloor spreading occurred, but failed between Australia and Antarctica, forming the Australo-Antarctic Gulf (AAG). To the east of the AAG the margin was convergent and destructive with a subduction zone where present-day New Zealand and New Caledonia are. During subduction at approximately 95 Ma (Korsch and Wellman, 1988) the area was subject to regional uplift and erosion; the counter effect being regional tilting and reorganisation of the drainage network to the west. Fission track studies support the erosion event and it is possible that sedimentation in the Bight Basin depocentres source directly from this event (Veevers et al., 1991, Totterdell et al., 2000).

Continental break-up in the Bight Basin has various models based on a.) magnetic anomalies (Cande and Mutter, 1982), b.) seafloor spreading rates (Veevers, 1986) and c.) structural analysis across the margin (Stagg et al., 1990). Dates range from as early as ~125 Ma (in the West of the Bight Basin) to 83 Ma. Models by Geoscience Australia which reviewed magnetic and deep 2D seismic reflection data concluded the oldest seafloor spreading anomaly to be ~ 83 Ma (Sayers et al., 2001; Fig. 4.26c). This relatively slow spreading phase (1.5–10 mm/y - Tikku and Cande, 1999) continued until the Middle Eocene when global tectonic reorganisation occurred in line with a great increase of seafloor spreading rates (~ 20–30 mm/y Veevers et al., 1987; Royer and Rollet, 1997; Veevers, 2000; Li et al., 2003)

2.3.4. Stratigraphic Setting

Initial studies in the GAB focused on primarily lithostratigraphic (formation-based) approaches to interpret sedimentary fill for depositional basins, and as such, individual and unique nomenclature were established for each Sub-basin of the Bight Basin. Lithostratigraphic schemes however, have the potential to obscure chronostratigraphic relationships, which often prove more valuable in correlating basin-wide events and the complex mechanics between sediment supply, basin processes, accommodation space, sea-level relativity and tectonics. Totterdell et al., 2000; produced a sequence stratigraphic based basin framework based on the same extensive set of 2D seismic lines used as part of this
thesis. The framework mainly focuses on the siliciclastic deposition interval of Jurassic to Middle Eocene age with the entire overburden of CWC grouped into the Dugong Supersequence (Figure 5, 6).
Figure 5: Chronostratigraphy correlation chart for the GAB from Totterdell et al., 2003; showing relationship between sequence stratigraphic supersequences, lithostratigraphic formations, basin tectonics and sea-level change. Sea-level curve modified form Haq et al., 1988 to Geoscience Australia timescale after Totterdell et al., 2000. Red outline is studied interval.
Figure 6: Cross-section through the Eyre Sub-basin, western Madura Shelf and northwestern Ceduna Sub-basin (taken from Totterdell et al., 2003).
With reference to Figure 6, the majority of the sequences (Sea-lion, Minke, Southern Right, Bronze-Whaler, Blue Whale, White Pointer and Tiger) represent Fluvial–Lacustrine cyclic siltstones, mudstones and sandstones and can be confidently interpreted as syn-rift owing to observed thickening of sequences into the hanging walls of listric faults bounding half grabens. Syn-rift deposits preside from Early Jurassic (Callovian) up until the Late Santonian and introduction of the Hammerhead Supersequence. The Hammerhead is a thick Cretaceous succession in the GAB and represents a deltaic system with cyclic sandstones and mudstones of the order of 3 km vertical thickness.

Across the GAB the majority of the Paleocene is missing, either owing to erosion or non-deposition Totterdell et al., 2000. The cessation of siliciclastics and reworked nature of the Palaeocene to mid-Eocene Wobbegong Supersequence suggest this is leaning more on the side of non-deposition, albeit erosion has been observed along the H1a unconformity (Chapter 3). This chronological boundary is the end of deposition into the Bight Basin depocentres and the beginning of the Eucla Basin. The Eucla Basin records one final episode of siliciclastic deposition in the form of the Wobbegong Supersequence (Totterdell et al., 2000). The Wobbegong supersequence represents a siliciclastic deltaic episode from the Paleocene–Early Eocene (Spore-pollen zones Lower L. blamei–Upper M. diversus / M. crater foraminifera zone; Totterdell et al., 2003). The Wobbegong is defined as being part of the Eucla Basin due to its observed difference in sequence stratigraphic character and cutting sample grain characteristics (smooth, rounded, well sorted) which are indicative of re-worked sediments compared to Mesozoic siliciclastics (sub-angular, rough and sub-sorted) - Jennie Totterdell; Pers. Comm; 2012.

The hiatus between the Hammerhead and Wobbegong Supersequences appears to be of the order of 5-7 Ma, although it varies across the southern margin. Lack of biostratigraphic dating or presence of indicative fossils means there is no way yet to accurately quantify the magnitude of the hiatus. The deltaic Wobbegong Supersequence consists mainly of marginal marine to delta sandstones with minor siltstones. Gamma ray log signatures are obvious and blocky, distinct from the overlying CWCs of the Dugong supersequence. The detailed character of the Wobbegong and its sequence stratigraphy is discussed in Chapter 4. The Wobbegong plays an important role, governing the location of giant bryozoan reef mounds (Sharples et al., 2014) which are discussed in detail in Chapter 5. The gap between the bryozoan reef mounds and the Wobbegong delta is an unconformity, again lacking in biostratigraphic data with an unknown hiatus. However, this hiatus is reflected on the
regional scale and has been dubbed “The Lutetian Gap” owing to lack of data by McGowran et al., 2004. This gap has been suggested to be in correlation with global tectonic events and global tectonic transgression such as the Khirthar transgression.

This gap fits well with '43 Ma event' as suggested by Li et al., 2003. This is actually a series of events on a regional and partially global scale such as tectonic reconfiguration (Veevers, 2000). A time of significant palaeoenvironmental change owing to a rise of regional sea-level at a time of global fall (Miller et al., 2005), in conjunction with basin subsidence catalysed by doubling of seafloor spreading rates (Tikku and Cande, 1999). The drastic change in palaeoenvironment appears to reflect a change in sedimentation style and cessation of siliciclastics. This is probably a function of cooling by initiation of the Tasman Gateway opening and onset of the Proto Leeuwin current as traced by McGowran et al., 1989. Tectonophysic reconstructions using sediment back-stripping, topographic and inundation modelling techniques by DiCaprio et al., 2009 suggested a tilting of the southern margin to the north-east during the mid-Eocene. In conjunction with the other processes, along with the cooling climate (Bijl et al., 2013; 2013) this may have contributed to the SC cessation and CWC initiation.

The vast majority of overburden in the GAB is constituted by CWCs, which are incorporated into the Dugong Supersequence. This mid-Eocene to Pleistocene CWC veneer has one thin (<10 m) basal siliciclastic sandstone and chert-rich layer (Hampton Sandstone Formation), the rest being a variety of CWC wedges (Clarke et al., 1993; 2003; Hou et al., 2006). The basal carbonate ramp units onlap onto the Wobbegong across the GAB and are suggestive of a major transgression with deposition during seafloor spreading and basin subsidence (Veevers et al., 1987; Li et al., 2003; 2004; McGowran et al., 2004). Importantly basal Dugong layers also provide an indication to the timing and duration of various mounded geobodies and record the final stages of gravity-driven growth faulting into the early Oligocene. The Dugong Supersequence has been studied in-depth as the main aim and objective of ODP Leg 182 and is detailed in Chapter 3.
Leg 182 resulted in nine drill sites, each composed of multiple boreholes (Figure 1; Data map, Chapter 1 Appendix; Figure 13), drilled in the Eucla Basin where it overlaps the Eyre Sub-basin; sites 1127, 1129, 1131 (eastern transect - Figure 5), 1130, 1132 (western transect - Figure 6), 1126, 1128, 1133 & 1134. Results included a framework of seismic stratigraphic sequences which were derived on integration of biostratigraphy, isotopic dating and coring efforts:

**Sequence 7:** Early to middle Eocene progradational siliciclastic wedge (i.e. Wobbegong Supersequence, Totterdell et al., 2000), the top of which was poorly recovered from most sites owing to loose sand and core drop-outs

**Sequence 6A:** Middle Eocene to late Oligocene multi-lobed deep-water carbonate apron with hiatuses between lobes

**Sequence 6B:** Middle Eocene to Oligocene cool-water carbonate ramp with biogenic bryozoan mounds further past the palaeoshelf-break
**Sequence 5:** Estimated middle Miocene aerially restricted sediment wedge (not cored)

**Sequence 4:** Early Miocene: extensive aggradational deep-water carbonate ramp with three internal hiatal surfaces

**Sequence 3:** Late Miocene to early Pliocene: aggradational carbonate ramp sequence with a basal hiatus of 0.5 Ma duration

**Sequence 2:** Pleistocene: thick carbonate sigmoidal clinoform succession at shelf break-point forming the majority of the modern outer shelf. Large bryozoan isolated mounds are present throughout

**Sequence 1:** A thin deepwater drape of latest Quaternary age

The CWC section is host to some of the most spectacular geological mounded features seen in seismic cross sections. Mounded features in seismic section are common geological phenomena which occur in a variety of geological and physiographic settings worldwide. Most are poorly sampled, not exposed or heavily eroded and interpretation of such usually falls into the realms of carbonate, volcanic or mud based compositions; each of which have complex and ever evolving definitions i.e. reef vs. reef mound (Flügel and Kiessling, 2002; Riding, 2002; Wood, 2012). Often grounded and with limited data, geologists cannot provide evidence for a mechanically sound geological model, and mound types remain anomalous. Geophysical data highlights enigmatic mounded features on a regional scale, with both sampled and unsampled mound specimens forming in the mid-Eocene at approximately 43 Ma in the GAB. Along this 43 ma horizon marked by a regional unconformity and shift from siliciclastic to CWC regime, volcanics (Schofield and Totterdell, 2008; Jackson, 2013; Holdgate et al, 2012; Magee et al, 2013) and bryozoan reef mounds (Sharples et al, 2014) have already been reported and documented. The bryozoan reef mounds documented in Sharples et al., 2014; are the largest seen on record so far and appear to form in conjunction with global tectonic reconfiguration and significant palaeoenvironmental change in the AAG at the 43 Ma mark.

All mounded studies in the GAB have been mapped using 2D and 3D seismic data and linked to exploration wells where possible (Potoroo-1) or deduced to be linked to seafloor dredging survey results (Clarke and Alley, 1993) which returned basaltic volcanic clasts and hyaloclastites. Access to the 3D Ceduna seismic survey has provided pristine
imaging of a submarine volcanic mound facies which allows for a facies based categorization of other mounded features in the area and is discussed in detail in Chapters 5 and 6.

A larger scale of ‘mounding’, Feary and James, 1995; interpreted the presence of a ‘little barrier reef’ in the Eucla basin where it overlies the margin of the Eyre Sub-basin. This reef adheres to a more classically true ‘reef’ definition, occurring in the Middle Miocene and extending over 500 km parallel to the modern shelf edge. The reef represents an episode of warm-water influx into the GAB during a global climatic optimum and allows insight into palaeoclimate, ecology and the ocean current system (proto-Leeuwin). More so, the study highlights the transition from carbonate ramp to rimmed carbonate platform. Mounds were also documented in younger Pleistocene sections of the Dugong Supersequence (James et al., 2000; 2004) with much smaller bryozoan based (cored) reef mounds interpreted to grow and stack with respect to glacial lowstands coincidental with ocean upwelling. Huuse and Feary, 2005; proposed the mounds were actually sediment wave events, which inspired the Galathea-3 Leg 8 expedition and acquisition of multibeam bathymetry. The sediment wave theory was confirmed and detailed by Anderskouv et al., 2011.

With the acquisition of various suites of data from ODP Leg 182 followed focused studies into CWC sequences of the GAB. Some of the highest hydrogen sulphide concentration (up to 158,000 ppm) ever recorded were experienced during the eastern ODP transect (ODP boreholes 1128; 1130; 1132). These were reported by Swart et al, 2000; Mitterer et al., 2001 and Wortmann, 2006; and gave significant insight into the palaeoenvironmental conditions in the GAB over approximately the past 30 or so million years. Such extraordinary accumulations of $\text{H}_2\text{S}$ fittingly deserve extraordinary geological circumstances and theories of extensive back-lagoon settings and the production of hypersaline brines and sulphate-reducing bacteria have been put forward.

This specialist focus on $\text{H}_2\text{S}$ is of particular interest to exploration with the possibility questioned of $\text{H}_2\text{S}$ forming in CWC sequences above the Ceduna Sub-basin. This has been addressed and is documented in Chapter 2 Appendix (pages 295–348) as a report produced during a BP internship for use in further understanding the shallow CWC paleoenvironments to meet particular aims of this Ph.D thesis. ODP Leg 182 also allowed the complex unconformities which exist between CWC sequences to be studied in more detail with significant gains of insight towards sea-level change in the GAB since the middle Eocene (Li et al., 2003; 2004). The unconformities within the CWCs are found to be varied and regular.
Chapter 3 looks towards the integration of the individual sequences of CWC deposition and their internal unconformities with the 3D Ceduna dataset.

2.3.5. Exploration History in the Project Area

The Bight Basin extends across the southern Australian margin for approximately 2000 km from the southernmost tip of Western Australia to the southernmost top of Southern Australia at Kangaroo Island. Initial search for oil and gas began in the early 1900s inspired by the wash-up of bitumen and hydrocarbons onto southern margin beaches (probably through natural seepages further offshore), perhaps also inspired in part by the southern margin’s similar geological appearance to that of California and the huge hydrocarbon success encountered there (O’Neil, 2003). The earliest exploration efforts often ended in the abandonment of license blocks. Despite their failure, a positive outcome was the acquisition of initial exploration datasets i.e. regional gravity, aeromagnetic surveys, reconnaissance seismic reflection and refraction surveys followed by wild-card exploration wells and log suites. Costs in early GAB exploration were simply too high and the technology lacking to make plays economically viable (O’Neil, 2003). Between 1972 and 1993, a total of 8 exploration wells were drilled in the GAB by a variety of companies (BP, Shell, BHP, Outback Oil). All wells turned up dry owing to a variety of missing petroleum elements, in particular, lacking source and migration conduits. However, an interpreted palaeo-oil column in Jerboa-1 (Ruble et al., 2001) was encountered. Inspired by the palaeo-oil column, the Japan National Oil Company (JNOC) then went on to acquire 5500 km of seismic data over the Eyre Sub-basin, and link Jerboa-1 to Potoroo-1 in 1990, with a hope to generate prospective leads.

Offshore exploration in the GAB was struggling up until the late eighties and with the aim of promoting the GAB for hydrocarbon exploration, the early nineties saw a major review of geological, geophysical, seismic, well, maps and literature. This was integrated into a comprehensive report (Basins of the Great Australian Bight region: geology and petroleum potential) to show the greatly increased understanding of the Bight Basin geological setting. The report was undertaken by the Bureau of Mineral Resources and South Australia's Department of Mines and Energy (now Geoscience Australia). At the dawn of the millennium Woodside Energy and partners, in venture with Anadarko Australia Company and PanCanadian Petroleum were granted three license blocks which led to the acquisition of the
Flinders 2D Deep Water seismic survey and the drilling of Gnarlyknots-1 exploration well. The GAB remains one of the most difficult environments to undertake hydrocarbon exploration (Hughes et al., 2009) with some of the most hostile metocean (oceanography and meteorology) conditions on the planet; epitomised when in 2003 deepwater exploration well Gnarlyknots-1 was pushed off course by 10 m swells and abandoned by operator Woodside after only reaching 4700 mbsl (2000 m short of target).

In 2011 BP Australia Exploration returned to the GAB and was awarded 4 exploration blocks covering 24,000 km² of acreage (Figure 8). The blocks are based in the offshore Ceduna Sub-basin and BP undertook one of the company's largest ever 3D seismic mega-surveys. This is coupled with commitment to 4 exploration wells during the tenancy of the license blocks. In 2012 Statoil bought into the BP Ceduna project and exploration in the GAB totalled $1.1 Billion Australian dollars when Chevron, Santos and Murphy Oil were also awarded license blocks with commitments to further seismic surveys and exploration wells.

Figure 8: Map to show structural elements of Bight Basin and new license blocks in project area (EPP = BP, S12 = Chevron)
The next few years (from submission of this thesis) are without doubt going to be the defining moments of the exploration history of the GAB, with all companies investing serious capital and working closely with academic partners to better understand the geological setting and potentially exploit economical hydrocarbon reserves.

2.4. Summary

The Southern Margin of Australia and the GAB in particular, represents a natural laboratory to study a number of geological topics in relation to global geological events (Table 1). These events include tectonic reconfiguration, continental flexure, rifting and basin evolution, seafloor spreading, sedimentary deposition, sea-level change, erosion and non-deposition, growth and emplacement of enigmatic mounded features. Such studies have raised significant and new questions regarding world biosphere interactions coupled with global geological events. With such topics as climate change presently in fierce debate amongst the scientific community, the GAB likely holds and records many answers in the shallow cool-water carbonate overburden from the Oligocene onwards. Such information may play a significant role regarding the advent of circum ocean currents and dramatic palaeoclimatic change from hot house to icehouse conditions around the middle Eocene and initial perma-ice formation around the Antarctic South Pole in the early Oligocene.

A detailed and high quality fundamental dataset is already in place with extensive 2D seismic grids and the public release of the 3D Ceduna mega-survey (as of May 2015). This is soon to be followed by a wealth of information from future exploration wells. The regional documentation and corroboration of various institutes have provided a solid stratigraphic and structural framework assessment, the geochemical analysis of which appears to exhibit all components of a working petroleum system. With further geological understanding and potential for exploration success, the GAB may soon become one of the world's most sought after hydrocarbon provinces for investment and a keystone in the understanding of geological evolution.
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<th>Basin</th>
<th>Study</th>
<th>Geographical Exploitation</th>
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5  Table 1b: Corresponding half of Table 1a
2.5. References


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Velocity, Submarine Canyons, and Burial Diagenesis in Oligocene–Holocene Coolwater 


CHAPTER 3: SEISMIC STRATIGRAPHIC FRAMEWORK

3.1. Introduction

The seismic stratigraphic architecture of the GAB falls into two hierarchical frameworks with relation to chronostratigraphic interpretation. The first is the Supersequence scale separation of the Wobbegong and Dugong Supersequences by Totterdell et al., 2000; which represents a lithological transition of in the GAB, from siliciclastics to cool-water carbonates; which also makes the distinction from the underlying Bight Basin into the Cenozoic Eucla Basin (with exception to the Wobbegong SC Supersequence) (Bradshaw et al., 2003). The second framework; is the more detailed breakdown of these Supersequences into internal sequence divisions undertaken as part of the ODP Leg 182 study in the GAB (Feary and James, 1998, Shipboard Scientific Party, 2000). Leg 182 further divided the Wobbegong and Dugong Supersequences into a total of seven sequences based on integrated seismic and borehole studies. However, these sequence divisions were laterally limited to the Eucla Basin were it overlies the Eyre Sub-basin in the close proximity of the ODP borehole transects. This chapter provides the regional seismic stratigraphic context and framework for the more detailed chapters (4; 5; 6) focused on specific features or intervals such as the mid-Eocene unconformity and associated igneous and biogenic structures.

3.2. Aims and Objectives:

The aim was apply the Leg 182 sequence divisions established by the ODP Leg 182 Shipboard scientific crew, over an extensive grid of 2D seismic data across the eastern GAB and into the 3D Ceduna survey, observing and testing each stratigraphic package with respect to lateral extensity and continuity. This was to aid further understanding regarding deposition of the cool-water carbonate realm on a margin-wide scale and to test the applicability of primarily 2D based seismic stratigraphy. The following assumptions were made prior to the exercise which spanned approximately 9 months:

- Biostratigraphic dating by Leg 182 shipboard party was correct and the sequence framework already in place was well calibrated
- New packages can be introduced on the basis of reflector geometries and age-estimated using relative adjacent packages with a greater confidence

The following objective methodology was undertaken:
• Obtain and re-table key LEG 182 wireline logging suites of Gamma Ray, Neutron Density, Sonic and Caliper with Leg 182 reports and annotated seismic surveys to establish bounding surfaces to sequences 1-7 within seismic project (Sequence 7 already mapped as part of previous study)

• Calibrate seismic sequences to the Leg 182 log data and expand bounding surfaces with resolution of Leg 182 boreholes using the JNOC and ASGO 2D seismic lines

• Expand the framework east to the central Eucla Basin over the Madura Shelf and link sequences to exploration well Potoroo-1

• Using Potoroo-1 well completion report and best known velocity intervals coupled with biostratigraphic analysis and cutting samples test framework suitability in Potoroo-1 proximity via tightly spaced 2D Flinders seismic grid

• Expand sequence framework further into the Eucla basin over the Ceduna Sub-basin until meeting with 3D Ceduna survey with dataset adjustments (i.e. static shifts, phase reversals) to maximize continuity as necessary

• Continue original sequences where possible and create new divisions as necessary to feed into BP internship shallow section stratigraphic framework project

• Create GAB wide TWT structure maps using both 2D and 3D observations of each sequence and from these create TWT thickness deposition maps

• Construct schematic model to link sequences and document any uncertainties, assumptions, limits of confidence and understanding

• Use all data to gain best possible understanding of environment of deposition and significant geological features.

Sequences will be presented in chronological order and not order mapped. Exploration of the data in both 2D and 3D seismic provided a plethora of geological features to be documented and studied; these will be presented in the following chapters and are shown in detail in the Chapter 3 Appendix amplitude extractions (Figures 15–57). Focus here is directed to the tectonostratigraphic framework, its structure, uncertainty, shelf–basinward correlation, facies descriptions, depositional trends and the confidence limits beyond borehole constraints.

3.3. Data set

This study utilized the entire available dataset of 2D and 3D seismic surveys (Figure 1), ODP boreholes and exploration wells the details of which are discussed in Chapter 1.4.
Figure 1: data map of project area showing full suite of 2D seismic, 3D seismic, boreholes and exploration wells.
3.4. Framework Overview

In total 10 sequences have been interpreted to occupy the Cenozoic Eucla Basin (Figures 2; 3) where it overlies the Bight basin and its Eyre and Ceduna sub-components. Original Leg 182 sequences are only extensive in the Eucla Basin where it overlies the Eyre Sub-basin (Figures 4; 5) and partly the Madura Shelf (Figures 6; 7). It is interpreted that at least 3 of these sequences are extensive across the entire GAB from shelf-break to deep-water basin margins. Seismic stratigraphic observations in the 3D Ceduna led to the correlation of three sequences defined in the Leg 182 divisions extending into the deep-water environment (Figures 8; 9 - MTC Sequence and Upper Apron). Although the major bounding surfaces were continuous, the packages changed significantly. Three new sequences were also interpreted in the deep-water sections which terminate prior to leg 182 seismic sections (Figures 2; 3; Middle Apron, Lower Apron, Paleocene Wedge).

<table>
<thead>
<tr>
<th>Leg 182 surfaces and sequences</th>
<th>3D Ceduna surfaces and sequences</th>
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<tbody>
<tr>
<td>Seafloor----------------------------------------------------------</td>
<td>Horizon 4</td>
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<tr>
<td>Sequence 1 and 2</td>
<td>Upper MTC Sequence</td>
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<td>Base Pleistocene---------------------------------------------------</td>
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<tr>
<td>Sequence 2b</td>
<td>MTC Sequence</td>
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<tr>
<td>Base Pliocene--Truncated--Sequence 3 (+Sequence 5 Restricted)</td>
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<tr>
<td>Base Mid-Late Miocene-----Sequence 4</td>
<td>Horizon 3</td>
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<td>Base Early Miocene -----Truncated--</td>
<td>Upper Apron Sequence</td>
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<td>Horizon 2</td>
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<td>Lower Apron</td>
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<td>Base “Tertiary”----------------------------------------------------</td>
<td>Horizon 1a</td>
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<td>Paleocene Wedge</td>
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Figure 2: Theoretical link between Leg 182 surfaces and sequences and equivalent 3D Ceduna surfaces and sequences (to be read in conjunction with Figure 3)
Figure 3: Schematic framework showing sequence linkage between relative sub-basins. Representative as a composite figure based on Figures 4, 5, 6 and 7 seismic sections.
Figure 4: Uninterpreted seismic section through the Eucla Basin where it overlies the Eyre Sub-basin.
Figure 5: Corresponding interpreted section through the Eucla Basin where it overlies the Eyre Sub-basin with extended Leg 182 framework sequences.
Figure 6: Uninterpreted seismic section through the central southernmost Eucla Basin.
Figure 7: Corresponding interpreted section through the Eucla Basin with extended Leg 182 framework sequences.
Figure 8: Uninterpreted seismic section through the Eucla Basin were intersected by Potoroo-1 exploration well.
Figure 9: Corresponding interpreted section through the Eucla Basin
Cool-water carbonate sequences are mostly consistent with low sedimentation rates (Feary and James, 1998). When coupled with the GAB deepwater environment, they by and large form layer-cake, stacked and relatively simple reflector geometries. The vast majority of overburden sediment in the GAB (Sampled in ODP Leg 182, gravity drop cores and dredging) is composed of carbonate muds and lithofacies. Leg 182 boreholes report a standard velocity of 2215 ms through the CWC section. This low velocity accounts for the mostly low amplitude seismic facies seen in seismic sections throughout the Cenozoic. The majority of different and/or distinct seismic facies sets occur on palaeo and present day shelf sections. The seismic facies of each sequence changes (expectantly) as individual sequences are tracked from shelfal to basinal sections and each is documented in Table 1. The advantage of generally low amplitude seismic facies is that significant changes in acoustic impedance (amplitude) are exaggerated and the subsequent features become well imaged.
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<td>Sequence 1</td>
<td>Seafloor/Drape</td>
<td>Extensive seafloor drape unit encountered in all Leg 182 boreholes and consists of deep water carbonate muds and pelagic ooze. Significantly less continuous and subject to canyoning and incision further seaward</td>
</tr>
<tr>
<td>Sequence 2a</td>
<td>MTC Upper [Not Interpreted]</td>
<td>Thick Pleistocene sequence mostly located over the Eure Sub-basin margin. Can be seen over the Eure basin however basal pick is severely obscured by large and prevalent seafloor multiples. Facies exhibits large progradationally stacked, mid-high amplitude continuous reflectors with a mostly lower frequency to surrounding sequences. No equivalent basal horizon was picked in the 3D Ceduna. However, upper sections of the MTC sequence provide strong candidate horizons where distinct change in reflector amplitude and continuity is present. The interpreted Pleistocene package over the Ceduna 3D is much thinner than the shelf equivalent. Reflectors are mostly linear, aggradationally stacked, low amplitude and continuous.</td>
</tr>
<tr>
<td>Sequence 2b</td>
<td>N/A</td>
<td>Thin Pleistocene wedge encountered in the Leg 182 CDP. This wedge is interpreted mainly as a function of biostratigraphic analysis and is not present on seismic sections other than a slightly lower amplitude continuation of Sequence 2a at the base of the prograding clinoform package. This may be linked to the Ceduna 3D upper MTC package although cannot be proved.</td>
</tr>
<tr>
<td>Sequence 3</td>
<td>MTC</td>
<td>Thick mid-late Miocene aggradational shelf ramp which is interpreted to pinch out as a thin wedge in original Leg 182 model. This is replaced based on observed continuity across the dataset. In shelf sections the aggradation is distinct and thick mostly consisting of moderate amplitude layer-clay reflectors with a distinctly lower frequency then surrounding packages. Off shelf influence brings plastic MTC debris apron. The basal Sequence 3 surface correlates with the base surface of the MTC sequence. The package however, changes significantly to a spectacular stacked MTC debris apron covering the entire 3D area. Reflector geometries are high amplitude, chaotic, discontinuous and evolve to lower basal sequences. Lower amplitude stacked packages make up the upper section of the MTC sequence.</td>
</tr>
<tr>
<td>Sequence 4</td>
<td>N/A</td>
<td>Sequence is interpreted an extensive aggradational deepwater ramp. Off shelf sections sequence 4 begins as a wedge shaped geometry of low-moderate amplitude, wave and low angle onlapping reflectors which quickly become MTC debris flows over the Eure Sub-basin margin. In the Eure basin and over the Ceduna Sub-basin margin sequence 4 geometries are much more planer and extensive, eventually truncated by the overlying mid-late Miocene stacked MTC package. This truncation point occurs before the 3D Ceduna survey but is well imaged on 2D seismic sections. Reflectors are continuous, low amplitude and high frequency with occasional limestone and is shown here.</td>
</tr>
<tr>
<td>Sequence 5</td>
<td>N/A</td>
<td>Sequence 5 is an internally restricted and interpreted wedge which is the debris slope associated with the Little Barrier Reef. This can only be seen on far landward section of 2D survey in the Eure Basin.</td>
</tr>
</tbody>
</table>

*PTO*
Table 1: Table of to show representative seismic facies observed within distinguished sequences and change in lateral character between Shelf (Leg 182) and deep-water basin (Ceduna 3D) sequences.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Facies</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence 6a</td>
<td>Upper Apron</td>
<td>Sequence 6a is interpreted as a Middle Eocene to Oligocene multi-lobe deepwater turbidity apron. The lobed aspect of the package appears to be true as observed further basinward and over the Ceduna. The package is mostly consisting of low amplitude plane reflectors which gradually overlap the base tertiary unconformity.</td>
</tr>
<tr>
<td>Sequence 6b</td>
<td>N/A</td>
<td>Sequence 6b is the shelf continuity of sequence 6a and is mostly a low amplitude and appaitently stacked package with localised sediment wave accretions. This package passes on to form the main structure of the Little Barrier Reef and shows a higher amplitude and steep ramp geometry with a chaotic internal structure.</td>
</tr>
<tr>
<td>Sequence 7</td>
<td>N/A</td>
<td>Sequence 7 is a Paleocene to mid Eocene stratigraphic package (Webbong Supersequence) and is defined by its spectacular pre decompressing reflector geometries and overall wedge shape. The top and basal surfaces are marked by high amplitude continuous reflectors which form regional unconformities across the GAB. Internal facies is mostly low-amplitude amplitude with higher amplitude major surfaces.</td>
</tr>
<tr>
<td>N/A</td>
<td>Lower Apron</td>
<td>The Lower Apron sequence is an extension and repetition of Sequence 6a and deepwater apron sequences. The lower apron, middle apron and upper apron all show the same cyclic seismic facies. The lower and middle apron however contain bounding surfaces which are subject to fault-reactivation-seismic, producing lobate seismic geometries. All bounding surfaces show the same regular discontinuity features.</td>
</tr>
<tr>
<td>N/A</td>
<td>Wedge</td>
<td>The wedge sequence only appears in distal sections over the Ceduna Sub-basin. The package is laterally limited by extensional trailing, and thickening into the fault hanging walls is present. Seismic facies is mostly high amplitude, continuous but offset reflectors which are truncated above.</td>
</tr>
</tbody>
</table>
3.5. Structural Controls

Over shelfal sections, all faulting in the project area terminates against the H1a unconformity. Faulting only effectively enters the framework sequences over the Ceduna Sub-basin. Faulting is more prevalent further basinward, with final offsets terminating in the Middle Apron Sequence or older. Exceptions occur in conjunction with major seafloor canyons and headwall scarps of MTCs. The vast majority of faults are growth faults and these mostly affect the H1b and H1a surfaces. Faulting for this project is split into two components; basement faults (i.e. Potoroo, Pademelon, and Wallaroo families) and listric growth faults (Mulgara family) as interpreted by Totterdell et al., 2000; Totterdell and Krassay, 2003.

Basement faults delineate and control sub-basin structure (Blevin and Cathro, 2008) but do not directly contact or offset any of the Cenozoic framework sequences. Faults affecting the Cenozoic sequences are of the listric growth fault nature and are associated with gravity-driven shale tectonics. Only the Potoroo fault family shows one exception of faulting which transcends from the basement architecture into the Cenozoic. This particular fault show a very small (<1 reflector) offset of the H1a surface and the fault head terminates within the Wobbegong Supersequence. Reflector geometries show no evidence of thickening and the fault is assumed to be young (early Paleocene). This fault is imaged in Chapter 4 with key-line B, taken through the Wobbegong, which shows a slightly greater offset.

South west and basinward over the Ceduna Sub-basin, sets of listric growth faults (Mulgara family) propagate regularly through the lower Cenozoic surfaces terminating in Middle Apron Sequence. These faults have been mapped in detail within the 3D Ceduna and correlate with the previously interpreted trend of the Mulgara Fault family (Totterdell et al., 2003). These faults are extensive across the 3D area and frequent (Figure 10), most aptly shown by variance amplitude extractions along the H1a surface boundary (See Chapter 3 Appendix; Figures 20–26). It is likely all offsets within Cenozoic sequences are a function of gravity driven slumping along pre-existing fracture planes, which is arguably still on-going (BP exploration team pers comm). Some localized erosional ‘lobe’ structures can be seen in direct correlation with the major fault planes of the Mulgara family and are annotated and shown in Chapter 3 Appendix, Figure 34.
Figure 10: Regional map of major fault groups in project area. Faults in black are picked mostly using the 3D Ceduna and are correctly georeferenced in relation to the basin outlines. The 3D Ceduna faulting pattern is picked on a detailed basis using variance surveys (see Chapter 3 Appendix). Faults in red are based on Totterdell et al., 2003 structural maps and are not precisely georeferenced. Red faults are picked entirely on 2D seismic data with large (up to 25 km) grid spacing.
3.6. Bounding Surfaces and Structure Maps

Surfaces have mostly been picked along a positive peak reflector trace, chosen in respect to continuity and bounding of termination points if available. Where no termination geometries were present, change in package amplitude was used. Mostly, this resulted in clear and efficient picks, however, unconformable surfaces with significant hiatuses of erosion or non-deposition i.e. H1a had to be mapped across a variety of sub-cropping surfaces and thus localised choices had to be made to which would best benefit surface and thickness map construction. Erosion surfaces such as H1a and H1b also presented significant issues in 3D auto-tracking and had to be smoothed and gridded on a larger interpretation interval. Each surface created, was done so with the fusion of fault polygons for improved surface structure accuracy. These appear as linear connected white lines (gaps) in the surface. Contours are shown where appropriate and not where poorly drawn by the computing algorithm (often difficulties with faults and mounds). All surfaces and thickness maps are shown in two-way travel time. Finally, surfaces constructed within the 3D Ceduna had to be done so swath by swath (northern, central, and southern) owing to rendering issues. As a result this sometimes left a line of missing data between swath surfaces.

H1b: Base Paleocene Wedge Sequence:

The H1b surface is the lower most surface picked within the 3D Ceduna. This surface was not extended beyond the 3D Ceduna owing to difficulties in continuity mainly caused as a function of significantly higher frequency reflectors in the 2D Flinders lines. The main use of this horizon was to help distinguish the nature of the major siliciclastic–carbonate unconformity in the 3D Ceduna. The total coverage does not exceed the northern and central swaths. The surface terminates where the Ceduna Terrance gradient significantly increases. The surface is bounded below by truncation and erosion, and above by low angle onlaps thus; it is an unconformity. The surface is regularly offset by listric growth faulting. The surface is relatively continuous, with high amplitude, low frequency reflector picks. This is disrupted mostly by faulting offsets. Towards the BBIC and in association with higher frequency faulting near volcanics, the surface becomes challenging to track. The surface character forms the base of a set of stacked sediment waves across the entire 3D survey area, imaged in Chapter 3 Appendix, Figure 18.
Figure 11: Two-way travel time structure map of H1b (base wedge sequence) surface. Sequence age estimated to be early Paleocene within the 3D Ceduna survey.
**H1a: The siliciclastic–carbonate unconformity**

This surface is arguably the most significant in the project. It acts as the boundary between the significant change in the GAB’s palaeoenvironmental setting, change from siliciclastic sediment deposition to cool-water carbonates and is the physiographic host-surface for the mid-Eocene mounded succession (see Chapter 5 and 6). This major unconformity has been mapped across all seismic lines available and had a highly variable and challenging to interpret character (see Chapter 3 Appendix; Figures 11, 1, for horizon interpretations and picking extents). Importantly, interpretation of the surface defines the siliciclastic from cool-water carbonate packages, and hence the surface links the Bight Basin separating Sequence 6 apron units from underlying Cretaceous /Paleocene units into the Eucla basin as the top of the Wobbegong Supersequence where the hiatus is significantly smaller of the order of hundreds of thousands of years. This is hence not a chronological bounding surface but a lithological one with a varying hiatus.

The 2D pick of H1a was relatively simplistic in near-shelf sections. In particular, difficulties were encountered caused by palaeocanyons and their respective sediment fill; when including it within the siliciclastic or carbonate deposition. The structure maps produced, mimic the present seafloor map and exemplifies the sharp and steep gradient of the Eyre Sub-basin in comparison to the low angle extensive Ceduna terrace. 2D mapping became more difficult basinward, but owing to the significantly lower amplitude seismic facies of the cool-water carbonates a reasonable interpretation could usually be made, smoothing over reflector inconsistencies.

The 3D Ceduna with its superior resolution and reflector frequency highlighted the true nature of the H1a surface. With each swath from north to south the surface increases in complexity. The surface is regularly offset by faults with several erosional lobes (see Chapter 3 Appendix; Figures 21, 22 and 28) cut out within fault hanging walls. The autotrack function was not possible for much of the surface and an intense grid of 2D picks made-up the majority of surface control points. The erosional nature of this surface is extremely complex and variable, and the degree of erosion into the basal wedge sequence varies between growth faults. Where fault offset is large, the H1a surface has been observed to cut through the Paleocene Wedge sequence into the base of the H1b horizon; creating a compound unconformity. Margin wide, the surface is irregular but well exemplified by an increase to mod–high amplitude where the CWC package (overburden) ends. Localised interpretation is
more challenging, especially when associated with mounded features owing to velocity pull-up effects.
Figure 12: Two-way travel time structure map of H1a (top wedge sequence) surface. Sequence age estimated to be early–mid Paleocene within the 2D seismic database.
Central swath most complex area with greatest degree of discontinuity

Faulting contorts contours

H1a cut by Nullarbor canyon (seafloor)

Volcanic mound

H1a cut by palaeocanyon

H1a cut by Nullarbor canyon (seafloor)

Figure 13: Two-way travel time structure map of H1a (top wedge sequence) surface. Sequence age estimated to be early–mid Paleocene within the 3D Ceduna survey.
Sequence 7 / Wobbegong Delta

Sequence 7 was mapped at its base and top units and covered in detail in Chapter 4. The top pick was the more straightforward surface to interpret with a regular high amplitude, good continuity and low frequency to the above cool-water carbonate package. Clear progradational clinoform geometries in the delta lobes D1 and D2 delineated the surface pick well. The D3 lobe was slightly more difficult, mostly owing to poor data quality near Potoroo-1. The basal surface was more complex to pick, in part owing to similar reflector geometries from underlying cretaceous sediments without obvious distinction. However, using sequence stratigraphic reflector termination points, key boundaries could be established and the surface was calibrated using a GR log overlay at Potoroo-1 (See Chapter 1 Appendix, Figure 13). In the best interests of defining thickness maps, the top and base surfaces of Sequence 7 were mapped to meet if possible (i.e. create a zero point), and thin drape/distal facies <1 reflector thick were ignored.

Figure 14: Two-way travel time structure map of Sequence 7 (Wobbegong) Top surface (above) and bottom surface (below). Sequence age estimated to be mid-Paleocene to mid-Eocene within the 2D seismic database.
The H2 surface is another regionally extensive surface and perhaps the highest quality
surface to track in the entire dataset minus the seafloor. This surface forms the boundary
between the middle-apron sequences which translate into Sequence 6a from the ODP legs.
This surface does not actually extend into the Leg 182 seismic lines to be calibrated by
boreholes, and pinches out prior to the Wobbegong delta Supersequence. The surface shares
the same properties on 2D and 3D data. It is a moderate amplitude continuous reflector
bounded on both sides by low amplitude parallel deep-water apron units.

The surface onlaps onto the H1a unconformity at a low angle (<3°) and drapes all
mounded features with exception to the bryozoan reef mounds. The surface is challenging
towards the southern sections of the Ceduna 3D survey where canyoning is frequent and
erosion of greater capacity. A key feature of the surface character is presence of small but
regular offsets, which appear to be linked with the presence of listric growth faults from
deeper Mesozoic sections. Further south, these offsets appear to become a semi-developed
polygonal faulting pattern. As with the H1a surface, large lobe-shaped erosional geometries
are observed towards the easternmost sections of the central swath (see Chapter 3 Appendix;
Figures 21, 22 and 28)
Figure 15: Two-way travel time structure map of Sequence 6 base (middle apron) surface. Sequence age estimated to be mid-Eocene to be early Oligocene within the 2D seismic database.
Figure 16: Two-way travel time structure map of Sequence 6 base (middle apron) surface in 3D Ceduna. Sequence age estimated to be mid-Eocene to be early Oligocene within the 3D Ceduna survey.
Base Early Miocene / Base Sequence 4

Base Early Miocene is a major surface from the Leg 182 reports. The surface does not extend as far as the 3D Ceduna and is mostly located on 2D seismic grids within confines to the east and south of Potoroo-1 over the Ceduna Sub-basin. The sections to the west are mapped with a lesser degree of confidence owing to larger 2D seismic line spacing, lower resolution of data and very thin sedimentation. The surface changes character from a moderate amplitude, discontinuous basal to debris flows over the western Eyre Sub-basin, to a very thin package of extensive low amplitude parallel units over the Ceduna Sub-basin. The surface completely truncated where steep gradient assist erosive capacity of canyons at the east of the Eyre Sub-basin. Over the Ceduna Sub-basin, the surface (and package above) becomes very thin (<2 reflectors) and is eventually truncated by the H3 surface (stacked MTC debris units).
Difficulty extending surface further owing to several seafloor canyons and limited data.

Figure 17: Two-way travel time structure map of Sequence 4 base. Age estimated to be early Miocene within the 2D seismic database.
Base Sequence 5

The Little Barrier reef and its constituent sequences (5 and 6b) were documented comprehensively by Feary, 1998. The bounding surfaces (base sequence 5 and top sequence 5) were not deemed necessary for the scope of this project owing to restricted lateral deposition. The base of Sequence 3 was extended up to the top of Sequence 5, but not beyond the ‘Little Barrier Reef’.

H3: MTC Sequence / Base Sequence 3 Mid–Late Miocene

The base of Sequence 3 is interpreted to stop and terminate as pinch-out by the Leg 182 model over the Eyre Sub-basin. Here that is rejected owing to observations on other surrounding seismic lines showing continuity. The surface can be readily extended and is prevalent across the GAB. The surface is marked as a strong moderate amplitude reflector with aggradationally stacked units above in shelfal sections. Basinward, as observed in both the Eyre and Ceduna Sub-basin margins, the surface loses continuity and evolves into sheet-like mass transport units (stacked). This extends into, and is documented meticulously, in the 3D Ceduna with individual blocks trails and gravitational slides preserved in the surface structure. Attribute extraction (see Chapter 3 Appendix; Figures 40–48) demonstrate clearly the nature of the stacked MTC sheets and downslope orientations. The presence such large scours within this surface raises serious shallow section geohazard questions regarding slope stability within the Ceduna Sub-basin overburden.
Figure 18: Two-way travel time structure map of Sequence 3 base (H3/MTC Sequence base 3D Ceduna). Sequence Age estimated to be mid to late Miocene within the 2D seismic database.
Figure 19: Two-way travel time structure map of Sequence 3 base (H3/MTC Sequence base 3D Ceduna). Sequence Age estimated to be mid to late Miocene within the 2D seismic database.
Base Sequence 2b: Pliocene

This surface was interpreted mostly as a function of biostratigraphic results from Leg 182 and a change in foraminifera groups. The seismic facies (see Table 1) is only applicable and visible in a select few 2D lines over the Eyre Sub-basin. Owing to this exclusivity, the surface was not mapped further and its basinward lateral extent over the Ceduna is unknown. Potentially the Pliocene may be represented in the upper sections of the MTC sequence, but this will remain speculative until further sampling.

Base Sequence 2a: Pleistocene

Owing to the limited nature of the Pliocene base surface, the base of this boundary was actually picked based on package observations of terminating prograding clinoforms in shelfal sections. Above the Eyre Sub-basin and within the resolution of the Leg 182 study area, this surface is easy to distinguish as a major unconformity. However, beyond the thick western deposits the base Pleistocene becomes possibly the most challenging surface to interpret in the study area. It is truncated by several seafloor canyons and more crucially, obscured by a large and pervasive seafloor multiple over the entire eastern Eucla Basin section towards Potoroo-1. Furthermore, 2D seismic lines in proximity to Potoroo-1 are hampered by poor quality imaging and noise. Such issues forced that the surface was tracked no further across the margin than the extent of Potoroo-1 exploration well. The surface does not extend into the 3D Ceduna, but is likely present. Interpretation was mostly a function of package identification/separation; as the amplitude, frequency and character of the surface varied significantly and regularly.
Figure 20: Two-way travel time structure map of Sequence 2 base. Sequence Age estimated to be early Pliocene (thin wedge at base) to late Pleistocene within the 2D seismic database.
H1 / Seafloor / Sequence 1: Present Day

The seafloor was mapped as a strong amplitude positive peak reflector across the entire dataset including the 3D Ceduna. Mostly the pick was simplistic and easy to autotrack, with occasional input of manual dexterity required in deep-water Fresnel zones. The surface effectively highlights the main depocentre and structure of the western GAB as well as significant and deep canyoning.
Nullarbor Canyon

Seismic line grid spacing ~ 100 km and surface not extended

Steep gradient indicative of hinge point

Limited data, prone to artefacts

Figure 21: Two-way travel time structure map of Seafloor within the 2D seismic database.
Figure 22: Two-way travel time structure map of Seafloor within the 3D Ceduna survey.
3.7. Sequence Architecture and Deposition

Paleocene Wedge Sequence:

This wedge sequence is bounded below by the H1b surface and above by the H1a surface. Both surfaces are observed to be unconformable with truncation above and below. The Paleocene wedge has been date-interpreted on the basis of surrounding sequences and for several reasons: 1. It shares an apparent genetic connection to the Wobbegong Supersequence – albeit there is no well report dating information from Potoroo-1. 2. Gnarlyknots-1A exploration well dates the underlying Hammerhead Supersequence as late Cretaceous to earliest Paleocene, 3. The wedge sequence is offset largely by the Mulgara group 4. It is draped by the earliest Dugong Supersequence intervals (middle Eocene in age), therefore a constraint on the wedge sequence age within the Paleocene seems reasonable. The wedge can be tracked landward beyond the 3D Ceduna survey using the Flinders 2D seismic survey and appears to connect to the basal units of the Wobbegong Supersequence which suggests a siliciclastic composition. Bounding surfaces are complicated and less confident further basinward, owing to the increased frequency and offset of faulting and this reflects in the sequence thickness maps. The wedge sequence is only present in the northern and central swaths of the 3D Ceduna and is eventually truncated by the H1a unconformity. This sequence is not present west of Potoroo-1 towards to Eyre Sub-basin.

The wedge sequence owes its name to the cross-sectional geometry and apparent repetition of wedging where the sequence lies between two extensional fault planes. In cross section this appears as thickening into the fault hanging walls planes and thinning towards the footwall of the next (Figure 23 thickness map). The wedge sequence internal reflectors serve as an important marker of the H1a large unconformity with toplaps and truncations being numerous. Interestingly, the wedge sequence contains a spectacular, stacked set of deep-water bottom current (early speculation) sediment waves, which cover the entire sequence ranging in size. The sediment waves are only visible using 3D attribute extraction and are only present in seismic sections as changes in amplitude. The sediment wave features are presented in the accompanying Chapter 3 Appendix; Figures 18, 24 and 25.
Figure 23: Two-way time thickness map between surfaces H1a and H1b showing the depositional trend of the wedge sequence within the 3D Ceduna survey.
Sequence 7:
This Leg 182 sequence represents the Wobbegong Supersequence (Totterdell et al., 2000) and final siliciclastic input into the GAB. The sequence is documented in detailed terms of its sequence stratigraphic architecture in Chapter 4.

Figure 24: Two-way time thickness map between surfaces 'top' and 'base' Sequence 7, showing the depositional trend of the Delta Supersquence within the 2D seismic database.
Lower Apron Sequence

The lower apron is one of three observed cyclic packages bounded below by the H1a unconformity and above by moderate amplitude continuous surfaces that eventually onlap and pinch out onto the H1a unconformity. The top surface of this package has not been mapped owing to its presence only in the southern-most sections of the 3D Ceduna. Significant canyoning and seafloor gradients towards the Ceduna Sub-basin margin along with the Recherche Sub-basin make accurate mapping a task demanding of significant time and investment. Such investment was used to explore the dataset in other ways.

Middle Apron Sequence

The Middle Apron sequence is bounded above by the H2 surface and its internal units onlap gently onto the H1a unconformity. Although it is the Upper Apron sequence that correlates directly to Sequence 6a from Leg 182 it is observed that the Middle Apron sequence has exactly the same facies, although subjected to slightly different geological phenomena (i.e. erosional lobes – see Chapter 3 appendix; Figures 28, 34). Given the internal onlap to the H1a unconformity and positioning relative to sequence 6a we can assume a mid-Eocene to Oligocene age is suitable. The middle apron is extensive across the GAB dataset from just basinward of Potoroo-1 to the BBIC. This can be clearly seen on the 2D Flinders seismic survey. The majority of the sequence is composed of very low amplitude transparent facies indicative of carbonate mud. Importantly, the Middle apron sequence records the majority of the final offsets of Mulgara listric growth faults, and contains a variety of lobe-shaped erosional features which formed in conjunction with extensional faults. These offsets are laterally connected and extend across the entire surface in the 3D, where in the southern swath they appear to form proto-polygonal faulting.
Figure 25: Two-way time thickness map between surfaces 'H1a' and 'H2', showing the depositional trend of the Middle Apron sequence within the 3D Ceduna survey.
Upper Apron / Sequence 6a

Sequence 6a is a repetition of the Middle Apron and mimics the structure on a higher stratigraphic level, onlapping the H1a unconformity further towards the shelf. Where the sequence is present over the 3D Ceduna, a thickness can be generated but not with 2D coverage. This is because the sequence interacts with 5 different major surfaces and such a task cannot be implemented in Petrel (to be best of the author’s knowledge). The sequence is eroded above by the mid–late Miocene MTC stacked debris flows, and forms the in-fill to large erosion lobes associated with listric growth faulting. In the Leg 182 shelf section, this sequence extends above Sequence 7 and drapes Middle Eocene bryozoan reef mounds. The geometry of the Upper Apron Sequence is defined overall as a wedge, which thickens basinward, but with a much greater degree of erosion than the Middle Apron as shown in the TWT thickness maps (Figures 26 and 27).
Figure 26: Two-way time thickness map between surfaces 'Sequence 6 base' and 'Sequence 3 base', showing the depositional trend of Sequence 6 within the 2D seismic database.
Anomalous thickness owing to un-eroded high, unaffected by MTC sequence

Lobate erosion in-fills

Thickening owing to canyoning

Seafloor canyoning and genuine sediment removal

Effects of MTC sequence above shown as scours

Surface quality effected by volcanic mounds. Deep circle = artefact

Figure 27: Two-way time thickness map between surfaces 'Sequence 6 base' and 'Sequence 3 base', showing the depositional trend of Sequence 6/Upper apron within the 3D Ceduna survey
Sequence 4 is defined as a laterally extensive deep-water aggradational carbonate ramp in Leg 182 results. When tracked across the dataset this is mostly true, although south of Leg 182 transected sequences are prone to collapse and mass transport exhibit chaotic MTC-like mixed amplitude reflectors. Over the Eucla basin on the shelf, the sequence is less obvious to distinguish from the Sequence 3 Mid–late Miocene aggradational ramp. However, where Sequence 4 is present over the Ceduna basin, it is represented by a thin extensive aggradational ramp package which is eroded and eventually truncated by the unconformable stacked Sequence 3 MTC complex. The package becomes challenging to track beyond the Nullarbor canyon which entirely truncates it. Areas of high confidence are limited mostly to the Leg 182 project area and the more obvious ramp geometry south of Potoroo-1.
Figure 28: Two-way time thickness map between surfaces 'Sequence 4 base' and 'Sequence 3 base', showing the depositional trend of Sequence 4 within the 2D seismic database.
MTC Sequence / Sequence 3: Mid–Miocene

This Mid–Miocene sequence is interpreted as an aggradational shelf ramp in Leg 182 results. The proposed model (Figure 3) suggests the sequence pinches out or is truncated by the base Pliocene/Pleistocene. In some seismic lines this is true; there are ample lines to extend the sequence further basinward with high confidence. The sequence shows a variety of erosive scour marks which appear to be present day seafloor features. Such features are indicative of contourites if assuming lateral connectivity. Heavy erosion by canyoning is also present across the entire project area. Thickness maps in the 3D Ceduna (Figure 30) show a variety of down-slope scours and flow features, with varying orientation as well as the structural high which they diverge around.
Figure 29: Two-way time thickness map between surfaces 'Sequence 3 base' and 'Seafloor', showing the depositional trend of Sequence 3 within the 2D seismic database.
Figure 30: Two-way time thickness map between surfaces 'H3' and 'Seafloor', showing the depositional trend of Sequence 3/MTC Sequence within the 3D Ceduna survey.

- Surface eroded by seafloor canyons
- Detailed MTC channels and increasing erosion downslope with increased gradient
- Thickness still effected by faulting although to a lesser degree than lower sequences
Sequence 2: Pleistocene to Present Day

The Pleistocene prograding carbonate shelf sequence is present only in the 2D seismic sections and is mostly located to the present day shelf-break. South of the Eyre Sub-basin margin, the sequence is either truncated by canyoning or lost owing to the steep gradient and transition into the Ceduna/Recherche Sub-basins. The thickest succession is encountered under the eastern Leg 182 borehole transects. The sequence here contained a surprising amount of H$_2$S gas and is documented as part of an internship project coupled with further understanding of the shallow section (see Chapter 3 Appendix, pages 295–348). The sequence is so heavily eroded that no consistent tie can be made east to the Eucla Basin. The package is difficult to interpret owing to the combination of clinoforms obliquely cut by seismic lines, and a large obscuring seafloor multiple. A small package of Pleistocene clinoforms can be observed in 2D seismic lines in proximity to Potoroo-1, however data resolution is poor and again hindered by seafloor multiples. Given the apparent trend of greater sedimentation centered around an Eyre Sub-basin margin location, we expect the clinoform sequence to be further east of Potoroo-1 but probably only in thin successions.
Figure 31: Two-way time thickness map between surfaces 'Sequence 2 base' and 'Seafloor', showing the depositional trend of Sequence 2 within the 2D seismic database.
3.8. Discussion

Leg 182 ODP reports provided a clear and detailed sequence framework in the shallow carbonate overburden (Feary, 1993; 1998; Feary and James, 1998). This was integrated with biostratigraphic analysis and the aim met that using seismic stratigraphic principles, sequence boundaries and packages have been extended eastwards across the 2D seismic dataset eventually tying into the 3D Ceduna seismic survey. Mostly, the original sequences were calibrated to borehole log data (Leg 182) and checked roughly against biostratigraphic age constraints derived from cutting samples at Potoroo-1. Horizons were then successfully extended over the Ceduna Sub-basin however distinct differences in continuity of packages were observed. This is likely owing to a different environment of deposition resulting from the extensive and lower gradient slope of the Ceduna terrace. Interpretation confidence and integrity varied, data issues and significant canyoning made interpretation challenging however, a consistent methodology utilizing reflector geometries, onlaps, downlaps, allowed the methodological aim of extensive seismic stratigraphic analysis to be met. The reported muddy nature of offshore cool-water carbonates lithofacies results in a low amplitude seismic facies which help to exemplify and exaggerate major sequence boundaries (Huuse and Feary, 2005) This was used to advantage wherever possible when interpreting, albeit acknowledgment of lacking calibration has accepted. Noting the issues discussed, the thickest depocentres are located above the Eyre Sub-basin, (Figure 32) owing mostly to the Pleistocene prograding carbonate clinoform sequence where it overlies the thickest sections of the Wobbegong Supersequence. This thickness is exaggerated on the flanks by deep canyoning and incision.

Initial Cenozoic sedimentation is captured as an interpreted siliciclastic wedge sequence which appears to be the basinal extension of the Wobbegong Supersequence (as interpreted also by Totterdell et al., 2000). The thickening of this wedge into the hanging walls of faults does not suggest syn-rift deposition, but rather, given the immense thickness of the Bight Basin, a degree of gravitational slip along pre-existing fault, effective at least until the mid-Oligocene. The wedge is host to a plethora of stacked sediment waves of varying size and scale. The waves are suggestive of marine ocean-bottom current formation, and together with seismic facies, indicative of a fine grained silty composition (Wynn and Stow, 2002). The H1a unconformity eroding into the wedge can be tracked to lie above the Sequence 7 delta further towards to the shelf. This makes dating the wedge to Paleocene a reasonable
assumption. It also helps to clarify the nature of the H1a unconformity hiatus further basinward.

The shift from wedge deposition across the Ceduna terrace to the shelf location of Sequence 7 suggests a major transgression in the early Paleocene. The Sequence 7 depocentre location is split into three components, with D1 and D2 forming thick lobes (up to 500 m if assuming 2700 ms velocity) with relatively steep clinoform slopes (10°) and a strongly lowstand dominated architecture. This is not the case for D3, which forms an elongated front of thin (up to 200 m thick) shallowly dipping clinoforms (3°). Although suggestive of two different sources of sediment, the question is raised of is it coincidence that the Eyre Sub-basin margin appears to house the thickest Cenozoic deposits? This is true for Sequence 7, Sequence 3 and Sequence 2. The fact that Sequence 7 is siliciclastic and not cool-water carbonate, suggests a structural control is responsible for the increased sedimentary thicknesses found over the Eyre Sub-basin.
Anomalous thickness over Eyre Sub-basin, mostly owing to Pleistocene succession, but also Sequence 7, D1 lobe.

Ceduna Terrace significantly affected by canyoning and mass transport complex movements.

Figure 32: Two-way time thickness map between surfaces 'H1a' and 'Seafloor', showing the depositional trend of the Cenozoic GAB within the 2D seismic database.
Large thickness extremities shown clearly with reactivated growth faulting

Detailed erosional effect of canyons and MTCs

Figure 33: Two-way time thickness map between surfaces 'H1a' and 'Seafloor', showing the depositional trend of the Cenozoic GAB within the 3D Ceduna survey.
Structural control is probably why the deep-water apron sequence (lower, middle, upper aka Sequence 6a) is mostly located over the Ceduna Sub-basin. The sequence is relatively thin, but extensive – owing to the extensional and flat nature of the Ceduna terrace. Such deposits would likely become unstable and chaotically transport off the steeper Eyre Sub-basin margin. The initial carbonate aprons are mostly drape-based and infill all pre-existing sequence structures. This includes drape of all mound successions which helps constrain mound growth to an episode that last no longer than late Eocene. Variance extractions (Chapter 3 Appendix; figures 33, 34, 35) through the basal surface of the middle apron show well imaged faulting patterns and the effect of gravity deduced movement along listric growth faults; recorded as lobe-shaped erosional depressions.

By and large the CWC Cenozoic evolution of the GAB is recorded in parallel stacked units which gently onlap as laterally extensive wedges with many internal unconformities (Li et al., 2003, Clarke et al., 2003). This cyclic repetition is broken by the basinal advance of Sequence 3 aka the MTC sequence. The basal units of this laterally extensive sequence, transform from aggradationally stacked thick units, (150 m, assuming 2215 ms velocity) to a series of between 1-3 stacked MTC units. Over the Eyre Sub-basin this is mostly owing to the significantly steeper gradients associated with the continental slope. However, the Ceduna Terrace does not share these gradients, and as such, raises important questions as to what and why the MTC sheets were triggered. Both attribute extractions and thickness maps highlight a vast array of cannibalized scours and block slides suggesting that the MTC debris flow took place over a relatively prolonged period of time and/or were episodic. The basin–shelf relationships south of the Eucla Basin are unclear owing to lack of data, although a significant seafloor canyon can be perpetuated from the 3D in the orientation to lie in that area.

Comparatively the Cenozoic CWCs of the GAB are thin to underlying syn-rift Jurassic–Cretaceous siliciclastic sequences (Totterdell et al., 2000). The 43 Ma mark and mapping of the H1a unconformity marks a significant change in regional tectonics and subsidence and deepening of the basin (Li et al., 2003). The localized phenomenon of significantly thicker sediment deposits above the Eyre Sub-basin remains mysterious as to what controlled the depocentre location. However, thickness maps are suggestive of a trend between the underlying basin structure left by the H1a unconformity and slope gradients. Volumetric studies cross-correlated with area mapping may prove insightful.
3.9. References


CHAPTER 4: SEQUENCE STRATIGRAPHY OF THE WOBPEGONG
SUPERSEQUENCE/SEQUENCE 7

4.1. Introduction

Sequence stratigraphy has been an ever evolving geological concept since basic recognition took place of unconformities, sedimentation, erosion and cyclic repetition in the mid nineteen hundreds (Sloss et al., 1949; Wheeler and Murray, 1957; Wheeler, 1958; 1959; 1964; Sloss, 1962; 1963). However it was not until Mitchum, (1977) introduced the concept of seismic stratigraphy based on concepts from Vail et al., 1977, did sequence stratigraphy as we know it today really begin its transformation. Mitchum assumed that seismic reflectors are representative of geological timelines and stratigraphic surfaces, and hence, by observing the reflector geometrical interactions, one could piece together the suitable sequence stratigraphic model. Complications arose however, because based on the underlying principles of Vail et al., 1977, one assumes a sequence stratigraphic associated with global eustacy as the unparalleled geologic parameter to drive sequence stratigraphic change.

This model soon came under strong critique, and the early nineties saw the advent of "relative sea level" change sequence stratigraphic modelling studies, which worked on the crux of local sea-level changes in combination with tectonics and accommodation (Hunt and Tucker, 1992; Posamentier and James, 1993; Helland-Hansen and Martinsen, 1996; Posamentier and Allen, 1999). Ultimately, this led the scientific community to become distracted on the focus of theoretical debate, rather than practical applicability, and a variety of overlapping definitions and jargon complexities were attributed by different authors. This was reported for 'sequences' and 'system tracts' by Catuneanu, 2002; (Fig 29); 2006 and also for 'orders' by Schlager, 2004. This confusion of terms has somewhat diminished the reputation of the effectiveness of sequence stratigraphy, and in place of development of application came scepticism towards its empirical usefulness.

In 2009, Neal and Abreu proposed an accommodation succession method, defined as a regional sedimentary package resulting from changes in rates of shelfal accommodation creation and depositional fill in response to changes in base level. This framework falls into a hierarchy of sedimentary units which are based entirely on the geometrical relationship of the strata. This method complimented, and was made compatible with previous definitions of modification of frameworks, with the aim to describe the depositional units which resulted
from accommodation successions of varying magnitude and duration. The principle behind this methodology is to provide the seismic interpreter with an observation based model without control points, and develop a framework to allow revisions as and when higher-resolution data becomes available. The stacking patterns fall into 4 distinct styles (Figure 1):

1. Progradation–Aggradation (PA) = Lowstand systems tract (LST) = \( \frac{\Delta A}{\Delta S} < 1 \), increasing

2. Retrogradation (R) = Transgressive systems tract (TST) = \( \frac{\Delta A}{\Delta S} > 1 \)

3. Aggradation–Progradation–Degradation (APD) = Highstand systems tract (HST) = \( \frac{\Delta A}{\Delta S} < 1 \), decreasing to negative

4. Aggradation–Progradation–Degradation (APD) = Highstand systems tract = \( \frac{\Delta A}{\Delta S} < 1 \), decreasing to negative followed by a basinward shift of coastal onlap, marking a depositional sequence boundary and renewal of PA stacking

Figure 1: Taken from Neal and Abreu, 2009, showing stratal stacking patterns in association with changing rates of coastal accommodation (\( \Delta A \)) and sediment fill (\( \Delta S \)).
This methodology was employed for the interpretation of the Wobbegong Supersequence owing to the complete reliance on 2D seismic data and lack of any available well data. Conveniently, Abreu (of Neal and Abreu, 2009), provided a 3 day seismic sequence stratigraphy course at the University of Manchester in 2011, which covered the accommodation succession method in detail. Hence, we employ its uses and applicability here with the aim to test the methodology effectiveness using only 2D seismic sections through the Wobbegong Supersequence. Owing to time limitations and detailed sequence stratigraphy not being a major focus within the Ph.D thesis, the methodology has only been applied over three 'hero-line' 2D seismic sections. However, the Wobbegong delta sequence falls within the Cenozoic timeframe and hence zone of interest and as such this chapter is aimed at providing more detailed observations regarding the basin evolution of geological switch from siliciclastic–carbonate palaeoenvironments. This extra knowledge was aimed to compliment the geological background to the bryozoan reef mounds which are discussed in Chapter 5. ‘Hero-line’–sections were chosen to best represent the nature of the three individual delta lobes which were determined as part of the methodology of discussed in Chapter 3 (of which the remaining Wobbegong Supersequence was mapped across the entire dataset (Figure 2)). ‘Hero-lines’ were chosen to best represent the delta lobe style with geometrical clarity, seismic tuning and as little geological (or sequence stratigraphic) ambiguity as possible.
Figure 2: Map to show location and thickness of Wobbegong Supersequence delta lobes (colour) and chosen key section positioning (red) and from 2D seismic data coverage.
4.2. Geological Setting and Background

The Wobbegong Supersequence represents the final major siliciclastic input into the GAB and is dated as from early Paleocene to mid-Eocene (Lower *L. balmei* – Upper *M. diversus* spore-pollen zones/*M. crater* foram zone) age. Work by Totterdell et al., 2000; Totterdell and Krassay, 2003; shows the Wobbegong Supersequence to overlie the late Cretaceous upper Hammerhead Supersequence unconformably. This base Tertiary unconformity is present across the entire GAB and exposed in landward cliff sections as an angular unconformity (Figure 3).

**Figure 3**: A photograph (Photographer: Robert Langford) taken at the shoreline cliffs west of St Vincent’s Bay showing the angular nature of the base tertiary unconformity.

The nature of this unconformity is less obvious in 2D seismic sections. However, the sequence stratigraphic representation of the Wobbegong Supersequence differs significantly from the underlying Hammerhead and the unconformity can be indirectly distinguished. Biostratigraphic data from offshore exploration wells (Potoroo-1 and Gnarlyknots-1) suggests the gap between the Wobbegong and Hammerhead Supersequences in the GAB is on the order of 5–7 m.y. Cutting samples and biostratigraphic analysis also suggest the Wobbegong contains a significant amount of reworked material. While the Wobbegong is siliciclastic, like the Bight succession, it clearly sits above the regional (in places angular) unconformity.
between the two basins (Totterdell et al 2000). Seismic sections confirm erosion of the
Hammerhead Supersequence near the inner and outer edges of the Ceduna Sub-basin with
Wobbegong Supersequence infilling the gaps. The Wobbegong also represents a completely
different style and scale of shelf-margin delta than that seen in the underlying Hammerhead.
More so, the Wobbegong lobe depocentres are located much further north and west.

The Wobbegong Supersequence is placed within the Eucla basin in the GAB, not the
Bight Basin. This definition favours and compliments a more holistic angle of tectono-
stratigraphy and geo-history, unlike some previous older studies which have approached
definition of the Wobbegong from a more lithological approach and extended it as part of the
Bight Basin. The top of the Wobbegong is also unconformable to the overlying cool-water
carbonate sequences of the Wilson Bluff limestone. The hiatus is as yet undetermined owing
to poor core recovery during ODP Leg 182 and that exploration wells bypassed any
biostratigraphic interpretation until depths bearing Cretaceous intervals (more prone to
hydrocarbon prospectivity). The hiatus of the unconformity between the Wobbegong and the
Dugong Supersequences has been interpreted ‘the Lutetian gap theory’ (McGowran et al.,
2004) and is suggested to be a regional unconformity spanning between ca 50 and ca 42 Ma.
The hiatus is interpreted to loss of biostratigraphic control and missing data (hence gap
theory).

McGowran et al., 2004; also suggest that the uncertainty in marine
micropalaeontology exacerbates the central biostratigraphic problem in terrestrial palynology
of poorly constrained zones. The theory goes on to suggest that despite lacking data there is
no coincidence between the timing of the gap being coeval with the Laramide and Alpine
regimes. Furthermore, the onset of cool-water carbonates is part of the global Khirthar
transgression (B. McGowran, Pers. Comm) – of which the tectonic mechanics are not
obvious nor explained. However, other studies in the area regarding the interplay of Cenozoic
unconformities (Li et al., 2003; 2004) take note of the hiatus between the Wobbegong and
overlying cool-water carbonate apron, but suggest that it cannot be dated accurately in the
western and northern GAB owing to lack of diagnostic fossils and poor data recovery. The
studies by Li et al., 2003; 2004; differ significantly and with much less speculation. It is
suggested the hiatus varies across the margin, but evidence of diagenetic hardgrounds
indicate an order of hundreds of thousands of years.
2D seismic mapping of the Wobbegong Supersequence across the dataset shows three distinct lobes (D1, D2 and D3 Figure 2). These lobes were shown by Sharples et al., 2014; but the study focused on the systematic location of bryozoan reef mounds in correlation with delta clinoform structure, and hence the entirety of the delta lobes was not shown. Here, the same lobes are presented, but with full coverage of the dataset. The lobes are mapped by interpreting the top and base of the delta using seismic stratigraphic principles, subtracting the difference alongside picked sections then contouring the results to produce a thickness map in TWT (Figure 2). First principle observations show lobes D1 and D2 possess almost identical reflector geometries, geographical outline, isopach thickness and area (~10 km²). D3 however, differs significantly; it is significantly thinner and wider, with a “front-like” trend as opposed to lobate geometry.

The D3 lobe is poorly covered by the seismic grid in comparison to D1 and D2 and it was deemed necessary to take two sections (Line A and B) to determine the sequence stratigraphic pattern. The Wobbegong supersequence has no provenance studies to date, and it is hoped that future sampling will shed light on timing and origin. The sequence stratigraphy applied here is done in order to make first principle observations on which to base a discussion towards the evolution of the Supersequence, the apparent differences in the lobes, the interplay of tectonics, sea-level change, shoreline facies shift, sedimentation rates, accommodation space and palaeobathymetry, and how these fit into the GAB’s geological evolution around the Middle Eocene.
4.3. Sequence Stratigraphic Methodology

Prior to application of the practical methodology one must first understand a given preset of definitions. These are taken directly from the hand manual provided by Exxon Mobile (Figure 4) and taught by Neal and Abreu. Specifically, these definitions target reflector geometries, chronostratigraphic bounding surfaces and stacking patterns:

**Depositional Sequence**: a relatively conformable succession of genetically related strata at base and top by unconformities and their correlative conformities.

**Parasequence**: a relatively conformable succession of genetically related beds or bedsets bounded below and above by flooding surfaces and their correlative surfaces (after Van Wagoner et al., 1988; 1990)

**Flooding Surface**: A practically isochronous surface separating younger from older strata across which there is evidence of an abrupt increase in water depth. The flooding surface has a correlative surface in the coastal or lake plain and out in the basin. (also called “parasequences boundary”, and specific flooding surfaces are also interpreted as TS or MFS, depending on their position within a depositional sequence – after Van Wagoner et al., 1988; 1990; Bohacs, 1998)

**Maximum Flooding Surface (MFS)**: A surface representing the maximum landward extent of basinal facies. This surface defines the top of the transgressive systems tract. Separates retrogradationally stacked parasequences below, from aggradationally to progradationally stacked parasequences above. (Also called “surface of maximum transgression”)

**Transgressive Surface (TS)**: the first major flooding surface across the shelf in a depositional sequence. Defines the top of the lowstand systems tract and separates progradationally to aggradationally stacked parasequences below from retrogradationally stacked parasequences above. (Also called “surface of maximum regression”)

**Sequence Boundary (SB)**: a laterally extensive (regional scale) unconformity and its correlative conformity marked by truncation and toplap below, and onlap and downlap above, over which there is an abrupt basinward shift of facies (best developed in medial reaches).
Figure 4: Idealised sequence stratigraphic sections, termination types, surfaces and systems tracts taken from Neal et al., 2010.


4.4 Practical Application

1. Data preparation

Hero lines were selected on the basis of their seismic tuning and clarity, and with the best geological representation of individual delta lobes in mind. The majority of interpretation took place on standard two way time vs. amplitude 2D seismic sections. To aid where low amplitude seismic facies made interpretation difficult, each chosen 2D seismic section was also converted to the apparent polarity attribute (using Petrel 2013). This attribute (similar to instantaneous phase) essentially produces a positive (white) and a negative (black) absolute value and reflector/line with all other values outside of the zero phase in grey-tone. By placing the apparent polarity section directly behind the TWT vs. amplitude section, one can utilise the "layering" effect in the digital art software of choice (in this case Adobe Illustrator CS6) and alternate between the seismic backgrounds to buffer interpretation. It should be noted the apparent polarity has been used with care and is secondary and an aid to the TWT amplitude section.
Figure 5: Example of TWT amplitude 2D seismic section through key-line section A

Figure 6: Corresponding apparent polarity 2D seismic section through key-line section A
2. **Reflector Terminations**: Arrows are used to designate reflector geometry terminations of downlap, onlap, toplap and truncation/erosion (Figure 7) and then applied to the seismic sections.

**Figure 7**: Seismic section with interpreted terminations of downlap, onlap, toplap and truncation from key-line section A.
3. Sequence and Surfaces: Using the termination points we can delineate key surfaces as per model definitions keeping to the same style as in the Exxon Mobil workbook. General rules of thumb are:

**Maximum Flooding Surface:** “Downlaps beyond the clinoform break point, no onlaps”

**Sequence Boundary:** “Onlap and downlap above, Toplap and truncation below”

**Transgressive Surface:** “Top of the lowstand, base of the transgressive systems tract”

Figure 8: Key surfaces are added to the interpretation and the majority architectural elements of the delta is defined. Sequence boundaries are in orange, maximum flooding surfaces in green
4. Chronostratigraphic parasequences and numbering: Based upon law of superposition within stacked sequences, each parasequence is numbered in chronological order with #1 starting as the base/oldest. Parasequence boundaries are based on internal seismic reflectors, with suggested consistency when picking peaks or troughs.

Figure 9: Parasequences and ordered clinoform growth is added to give a more detailed interpretation of the delta model.
5. Systems Tracts: Owing to the predetermined sequence and surface boundaries, the systems tracts are more of a colouring exercise to aesthetically highlight and emphasize the different phases of delta growth. This becomes particularly useful in step 6.

Figure 10: The completed structural/architectural and systems tract model of the delta, based strongly on observations, highlighting stacking patterns and negating interpretation of the geological system i.e. sea-level change

6. Chronostratigraphic Chart Construction: Using equally spaced time-units (due to lack of dating) to show the relative age (i.e. chronological order; step 4), apply chronostratigraphic reconstruction and flattening of each numbered parasequence and surface.

Figure 11: Idealized structural model from Exxon Mobil workbook
Figure 12: Chronostratigraphic representation of idealized structural model
Figure 13: Practical application of methodology outlined in Figure 12 with real data and interpretations through hero-line section A
4.5 Stacking Pattern Analysis

Figure 14: Key-line Section A seismic sections. Section A was chosen mainly based on the duration of the seismic line in the landward direction. This is the only line that allowed full capture of the delta architecture compared to other lines which terminated just beyond the delta front. Although other seismic lines could have been used with superior quality or where Potoroo-1 exploration was present, the lines ran at an oblique angle in the direction of progradation. The quality of the seismic section is reasonable, with clear downlap terminations visible in the mid-section. Problems arise with the relationships of reflector geometries truncated by sequence boundaries. These truncations have limited clarity made worse by the low amplitude seismic facies of the internal structure. Truncations are better visualized in the apparent polarity section. The section furthest landward (NE) as well as the section directly underneath the high amplitude B1 bryozoan reef mound (SW) also lose seismic resolve and become difficult to interpret. These sections also show much lateral amplitude variation along reflectors. The internal seismic facies mostly consists of low-medium amplitude wavy reflector geometries with a relatively shallow slope angles (~8°). This decreases further basinward (~5°), although reflector amplitude increases. Individual parasequences vary in their amplitude characteristics, and lateral lithological–seismic facies changes are difficult to interpret without speculation.
Figure 15: Section A terminations. The most simplistic termination points are grouped as downlaps in the middle of the delta structure (green). These are pertinent above a strong high amplitude and continuous low frequency reflector downlaps to the base of the delta and unequivocally represents a maximum flooding surface. Other obvious terminations are bunched onlaps (yellow) onto a medium amplitude reflector, which designates a sequence boundary (yellow) with the same parasequences downlapping basinward. Termination interpretation becomes more difficult with regards to toplap truncations on the underside of this sequence boundary. To keep with model consistency, a sequence boundary has been used (erosion) to explain the terminations. Apparent polarity helps to deduce the truncations where the amplitude seismic section shows washed-out transparent facies.

Figure 16: Section A surfaces and system tracts. Parasequence interpretation provides much greater clarity, and visually aids the positioning of major boundaries. Parasequences were mostly picked using peak reflector events and interpretation confidence improved using the apparent polarity section. Issues are present with parasequences #4 and #5 which appear to onlap onto the MFS further landward. This could be an effect of seismic resolution, and it is plausible for a downward shift on the MFS in that section to accommodation a full sequence (albeit thin). Parasequences #20 and #21 proved the most challenging and almost appear retrogradational. To fit into the pre-defined model, this had to be explained by the use of a sequence boundary and part of a HST. The seismic facies sub-posed behind the transparent systems tracts is variable but roughly fits expected trends, with sandy sections bearing higher amplitudes and muddy sections bearing lower amplitude (i.e. lateral variation). The only exception is the high amplitude parasequence #22 which is anomalously high and interpreted as a basin-floor fan/sand.
Figure 17: Section A stacking pattern (black arrows) model with interpreted best-fit clinoform breakpoints (yellow triangles).

Figure 18: Section A sequence stratigraphic model.

By removing the interpreted systems tracts and boundary type, one is left with an architectural skeleton defined by multiple terminations and parasequence stacking patterns (top). Yellow inverted triangles are the interpreted clinoform roll-over points of individual parasequences. Unfortunately, owing to the nature of the erosional contact (sequence boundary) above most of the HST, it is not possible to see the true break-points. However, it is possible to speculate the stacking trend by deduction and analysis of parasequence slope angle within an eroded system tract. The stacking pattern analysis shows an overall trend analogous to the expected theoretical model in the accommodation stacking methodology. The proverbial “S” shape of the stacking pattern trend is fully engaged over the delta architecture from Retrogradation – Aggradation – Progradation – Aggradation – Retrogradation. The stacking pattern analysis brings into question the validity of the thin sliver of HST prior to the LST and the applicability of the methodology to real data. Generally, sequence boundaries show wavy and curved geometries with a variable amplitude on seismic sections. Maximum flooding surfaces are marked by curved to planar geometries and a generally high and persistent amplitude. Incised valleys (red) are interpreted as part of the erosion of the HST systems tract but the interpretations are speculative, and more a function of poor data quality and expected model predictability.
Figure 19: Section B key-line seismic sections. Section B (Figure 2) was chosen for similar reasons akin to section A. The seismic line extends landward enough to cover the entire depositional context of the delta, and has a relatively clean seismic signature. Problems in this seismic section which make interpretation difficult stem threefold: a.) Delta thickness is very limited, making reflector geometries subtle and not obviously apparent b.) A large fault runs through the entire section (post delta deposition) and offsets the entire structure by an estimated 50 m and c.) reflector amplitude varies significantly laterally. The apparent polarity section is not as useful towards internal architecture but does allow for easier tracking along reflectors with varying amplitude (as the amplitude level variation is negated). Mostly the internal seismic facies constitutes oblique prograding, medium amplitude reflectors and stacked parallel reflectors. There is a regular element of pinch-out towards lateral extremes. The delta is too thin to make seismic facies–lithological deductions.
Figure 20: Section B terminations. Reflector terminations are challenging in both amplitude TWT and apparent polarity. Subtle retrogradational onlaps can be observed in the landward oldest and youngest units (blue) and in the thickest section a group of downlaps (green). A large degree of post-depositional tilt coupled with low angle reflector terminations makes picking difficult and sparse.

Figure 21: Section B surfaces and system tracts. The most obvious and simple surface to define was the only maximum flooding surface in the section. The MFS shows a curved to planar geometry and is delineated well by downlap terminations. Similar to section A, a sequence boundary has been used to define a section of difficulty, post-deposition of the initial HST. As in section A, this was created and interpreted to “fit” the proposed model. The structural model is dominated by the TST in this much thinner delta section compared to section A with significantly thicker HSTs and LSTs. Two internal sequence boundaries have been interpreted to explain the oblique parasequences #10 & #11.
Figure 22: Section B stacking pattern (black arrows) model with interpreted best-fit clinoform breakpoints (yellow triangles).

Figure 23: Section B sequence stratigraphic model

As in section A the stacking pattern succession shows classic Exxon-style idealised structure with an almost full sequence of Retrogradation – Aggradation – Progradation – Aggradation – Retrogradation. Confidence is high within the retrogradationally stacked sections where reflector geometries and terminations are more clear. The major sequence boundary however, which lies above the highstand system tracts creates an issue, by eroding the top sets almost entirely and blinding the interpreter of true clinoform breakpoint geometries. Also, like section A, there exists difficulties following the initial HST, with a thin sliver of HST appearing again after a very thin LST episode. The basin floor fan has been interpreted based on an increase in seismic amplitude within the lowstand facies. The general appearance, seismic facies, reflector geometries and system tract architecture of section B suggests it is genetically linked to the delta in section A, although probably away from the main depocentre towards the fringes of the delta system.
Figure 24: Key-line Section C seismic sections. Section C (Figure 2) was chosen as a transect most representative of the D1 and D2 lobes, both of which show the same structural architecture and depositional style. This particular section also exhibits the thickest section of the D1 lobe and one of the most prolific examples of bryozoan reef mounds. Incidentally, this mound leaves a large noise train vertically beneath it, hampering interpretation. Fortunately, the delta is thinning significantly and not too much detail is lost. The frequency of the seismic amplitude section is variable and reflector geometries are best revealed by apparent polarity. The section appears deceptively simplistic but has several ambiguous points of interpretation. The seismic facies is more uniform than sections A and B with low-medium amplitude for parasequences (and lateral variation) and higher amplitude for major surfaces.
**Figure 25: Section C terminations.** Section C terminations are comparatively easier and abundant. The reflector geometries are regular and cyclic, exaggerated by the significant thicknesses. "Text-book" prograding clinoform geometries are pervasive throughout the section. Interpretation becomes difficult in proximity of the bryozoan reef complex (red). The onlap terminations landward are easy to spot, but there also appears to be downlap between chronologically younger parasequences i.e. retrogradational stacking. This could be a result of differential compaction or loss of seismic resolution near the bryozoan complex, as given the cyclic LST-HST units, and the TST seems geologically odd. The youngest topsets appear to be layered and stacked, unfortunately these are completely blocked by the reef mound at the critical break-point.

**Figure 26: Section C surfaces and systems tracts.** Bounding surfaces are relatively simple for the majority of the section owing to clear and numerous terminations. In keeping with strict observations, a TST has been interpreted following the 3rd HST, however confidence in this is low, with consideration of the cyclic repetition of LST, HST, LST,HST, LST, HST prior to this. Section A provided ample true clinoform breakpoints to be utilized and observed. A single basin floor fan has been also interpreted in the second LST where a sudden increase to high amplitude was observed. More heuristically prone interpreters may chose to link several of the basal high amplitude reflectors into fans. The mound basinward of the delta is not interpreted to be genetically linked, nor fits in the model (i.e. erosional deposit). It is likely linked to the reef mound and is documented in Chapter 3.
Figure 27: Section C stacking pattern (black arrows) model with interpreted best-fit clinoform breakpoints (yellow triangles).

Figure 28: Section C sequence stratigraphic model.

Section C stacking patterns are significantly different from those observed in sections A and B. The stacking patterns here show long-term cycles between Progradation–Aggradation (LST) – Aggradation–Progradation–Degradation (HST) stacking. The delta lobes D1 and D2 are clearly a different style of delta to D3 in terms of sediment supply, accommodation space and structural architecture. LSTs show thicker deposition but the HSTs extend further basinward. The second HST appears to extend clinoform sets far into the basin and is heavily eroded by the sequence boundary above. However, reflector geometries extended beneath the bryozoan reef mound are interpolated. The angle of clinoforms through section A are on average 10 degrees steeper than section B and C equivalents. Unlike D3 there is no observed localized incised valleys in the D1 lobe, only mass wasting at sequence boundaries. The absence of significant or influential TST through section A raises important questions regarding the timing and conditions that all delta lobes were subjected to.
4.6. Chronostratigraphic Analysis

Section A:

As in the structural model, the chronostratigraphic representation of section A fulfils the idealised section with a simple to follow "S" shaped stacking pattern trend. The proverbial "S" shape follows the stacking patterns from R–APD–PA– R. The chart clearly highlights the phases and extents of non-deposition and erosion. The chart can however be misleading in that the erosion of the first highstand systems tract takes up the vast amount of the chart. It leads to the impression that this erosive event capped by the first sequence boundary is a large one. However, the dating units are relative to one another and thus the parasequences within that HST may represent geologically rapid pulses of sedimentation (imagine only 1/10th of the vertical thickness on the chronostratigraphic chart). Hence, what appears to be a significant event may in fact be relatively short-lived. The chart also highlights the areas of issue #20 and #21 and the need for higher resolution data and/or further understanding as these remain the most ambiguous parts of the section leaving a difficult geological explanation.
Figure 29: Chronostratigraphic chart produced from section A. All geological time units are relative.
Section B

The section B chronostratigraphic chart also fits well with idealised Exxon style models. Individual surfaces vary from its counterpart in section A, but ultimately very similar styles are observed. The erosion from sequence boundaries is almost identical to that of section A with the exception of 'localised' sequence boundaries that are mostly likely due to significantly thinner delta structure. The same issue of ambiguity following the highstand phase is also observed. As in section A, the issue can be worked to fit with the Exxon model, but is difficult to explain geologically. What is contextually important is that the two sections appear genetically linked, and share the same events even though the section lines are some 100 km apart. Ideally, several interpretations would to be made, with higher resolution data, inclusive of hero-lines in the strike direction to tie sections and major bounding surfaces.
Figure 30: Chronostratigraphic chart produced from section B. All geological time units are relative.
Section C

The chronostratigraphic chart of section C shows a significantly different stacking pattern sequence to that of section A and B. The delta is units are clearly dominated by cyclic repetitions of PA–APD–PA–APD i.e. lowstand and highstand system tracts. As in sections A and B however, significant erosional hiatuses are observed in the HST units. Dating of parasequences would be necessary to genetically link the erosional events as ultimate proof of margin-wide erosion, but one can speculate it is no coincidence that all lobes exhibiting the same event surfaces were subjected to the same conditions. As with sections A and B, the construction of a chronostratigraphic chart raises questions of structural interpretation. Here, the 3rd LST–HST sequence raises a question of if the HST unit is actually an extension of the LST given the reasonable continuity and has actually been mis-interpreted. Terminations can be found to support the current interpretation, but this may not be the case under the ruling of a different seismic interpreter. The retrogradational package works with the model but as stated in the seismic observations this could alternatively be another LST cycle. To answer this requires imaging beneath the bryozoan mound complex or alternatively, other adjacent seismic sections may provide the answer (beyond the time-frame of this study).
Figure 31: Chronostratigraphic chart produced from section C. All geological time units are relative.
4.7. Discussion

The accommodation stacking methodology has several advantages; mainly practical simplicity, observation based bias, predictive quality independent of time-scale or sea-level terminological complexities, flexible for all scales of data and subsequent data-resolution improvement and allows for important first principles of delta style, architecture and chronostratigraphic significance. However, the identification of the conformable units and reflector geometries are governed by data resolution and seismic interpretation “skill” which should be considered in the heuristic sense. This is especially true when considering real datasets often contain sets of obscure and complicated reflector geometries. The Wobbegong Supersequence contains spectacular idealised real delta seismic sections, yet still produces a variety of conundrums. As discussed, several issues were encountered regarding the erosional nature of sequence boundaries above HSTs and the methodology provides no clear action/pathway to deal with such difficulties. Hence, one must stick with observation supported evidence rather than speculation to avoid bias and misguided speculation. This can be partially remedied with several differing models/theories being put forward.

With prolonged use of the methodology, one observation which came to light was that structural and architectural models have the ability to disguise errors/issues. This may be a function of aesthetic distraction or of data resolution. However; some errors of interpretation were highlighted only by the chronostratigraphic chart, and a return to seismic first principles had to be made. The chronostratigraphic charts provided a greater events-based comparison between delta lobes, however one must take care in their interpretation. A structural model shows the structure and the components as they are, however, the chronostratigraphic chart (in this case) are constructed with relative geological age. What appears to be a large and prolonged erosive event that takes up much of the chart, may actually only be a relatively small hiatus owing to short and rapid sedimentation pulses. Obviously the best option is to use the structural model and chronostratigraphic chart together.

Geological mapping of the Wobbegong delta lobes across the dataset coupled with sequence stratigraphic modelling met aims to further understand the nature of the final siliciclastic input into the GAB and describe in detail an important stratigraphic package of the Cenozoic GAB (in relation to chapter 3). Moreover, knowledge into this final siliciclastic
directly compliments work undertaken on bryozoan reef mounds (discussed in Chapter 5) which geographically locate with respect to varying underlying delta substrate and structure. Sequence stratigraphic results suggest a hierarchy of one margin-wide Supersequence/episode of deltaic input, split into at least three individual components; two genetically linked lobes (D1 and D2) and one shoreface front (D3).

This may change as and when new seismic coverage becomes available. D1 and D2 show significantly greater thicknesses, average angles of clinoform slope (calculated from a flattened perspective, compensatory for post-depositional tilt) and sequence stratigraphic models that are suggestive of 'deeper' (unknown; owing to lack of core data and inability to calculate compaction for back-stripping, although based on the angle of clinoforms and thickness of the deposit similar style deltas on the northeast American margin shown water depths of 50–100 m) water setting with a greater level of sediment supply. The D3 geometry coupled with significantly lesser thicknesses over a much greater area does not necessarily dictate a much lesser sediment supply, but based on the wide-spread deposition and internally oblique prograding highstand sequence, it does suggest limited accommodation. It is likely that sediment supply was also lower in this region, and cutting samples from Potoroo-1 show distal quartz grained of well rounded, well sorted, mature and reworked nature. XRD analysis of dark black grains found between the BRM and top Wobbegong surface show results concordant with glauconite (See Chapter 5 Appendix; Figure 3) – a mineral indicative of slow rates of accumulation and weathering strength. Such settings at the top surface of the Wobbegong fit well with the concept of a sedimentation cessation and the growth of mounded features.

Mapping of the Ceduna terrace and base tertiary unconformity beneath the Wobbegong, supports a limited accommodation space model as well as a shallower water setting than compared to D1 and D2 lobes. Seismic stratigraphic mapping of the entire Wobbegong Supersequence suggests coeval deposition of the Wobbegong Supersequence delta lobes based on reflector downlaps on the H1a unconformity. This raises serious questions when explaining the two very different delta styles and locations and especially towards provenance and sedimentation cause. Coeval growth between all delta lobes would have to account for provenance of the D1 and D2 lobes from the north, and the D3 delta shoreface front from the east/northeast. This is made more difficult owing to the Wobbegong Supersequence based on a
large Cretaceous–Tertiary unconformity; the hiatus of which is unknown but supposed to be within 5–7 Ma.

Two genetically separate delta systems forming within the hiatus of the base tertiary unconformity closely spaced overlapping lifespans is more likely than one system sourced from the same north-north eastern province but worked differently owing to basinal processes. Most likely, is the supposition that the deltas were subjected to margin wide events (as suggested by the erosional events post-dating highstand system tracts in all sections) and that margin-wide cessation was synchronous or very closely spaced. This would be necessary for the formation and systematic location of the giant bryozoan reef mounds which followed, and the cessation is backed up by cutting samples rich with glauconite. Owing to differences in structural style as a function of sediment supply, accommodation and basinal processes, the delta lobes provided different bryozoan reef mound growth thresholds.

The sequence stratigraphy and mapping of the entire Supersequence has provided unique insight into an important interval in the geological evolution of the GAB, at a critical point prior to the Lutetian Gap and onset of the world’s largest Cenozoic cool-water carbonate platform and structural home to the world’s largest bryozoan reef mounds. Furthermore, the Exxon methodology has proved overall reliable, practical and efficient. Inconsistencies have been highlighted and effectively the scene has been set for integration of subsequent higher resolution data and/or a more detailed sequence stratigraphic study.

4.8. Acknowledgements

Thanks to Vitor Abreu for his teaching and tuition of the ExxonMobile sequence stratigraphic method, over a three day course at the University of Manchester. Thanks to Rachel Harding for a series of thought provoking discussions.

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5.1. Abstract

Giant middle Eocene bryozoan reef mounds in the Great Australian Bight

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This paper reports the discovery of extensive middle Eocene bryozoan reef complexes along the paleoshelf edge of the Great Australian Bight (GAB). The complexes form the earliest carbonate deposit in the GAB, which is the largest Cenozoic cool-water carbonate province on Earth. The bryozoan reef mounds, previously misidentified as volcanic bodies, were deposited parallel to the shelf margin for more than 500 km along strike. Individual reef mound complexes are 60–150 km long, as wide as 15 km, and as thick as 200 m, and dwarf all previously described examples. Superimposed on the distal margin of an underlying Paleocene to mid-Eocene siliciclastic delta complex, the reef mounds provide a critical insight into changing paleoenvironments of the Australo-Antarctic Gulf ca. 43 Ma, coinciding with global and continent-wide climatic and tectonic events. The rapid growth and demise of reef mound–building bryozoans raises new questions regarding the interplay of Southern Ocean opening, ocean currents, and biosphere interactions.
5.2. Introduction

The most significant long-term climatic change during the Cenozoic was the middle to late Eocene climatic cooling and the change from greenhouse to icehouse conditions. This change, and the associated development of continent-scale ice sheets across Antarctica, has been closely linked with the opening of the Southern Ocean and the Tasman Gateway (Lear et al., 2000; McGowran et al., 2004; Miller et al., 2005). This study focuses on the transition between siliciclastic and carbonate deposition, and documents the earliest phase of carbonate deposition represented by a set of newly discovered bryozoan reef mound complexes located on the distal edge of the ultimate siliciclastic wedge in the Great Australian Bight (GAB). These reef mound complexes formed simultaneously with a number of regionally and globally important tectonic and oceanographic events, including the northward tilt of Australia (DiCaprio et al., 2009; Heine et al., 2010), accelerated Southern Ocean opening (Exon et al., 2002), onset of warm-water currents sweeping the GAB (McGowran et al., 1997; Li et al., 2003), mid-Eocene global sea-level fall (Miller et al., 2005), and regional sea level rise due to enhanced subsidence associated with acceleration in seafloor spreading and transition of the GAB from rift to drift domain (Li et al., 2003).

5.3. Data and Methods

This study is based on interpretation of a regionally extensive database of open-file high- and medium-quality, poststack time-migrated, multichannel two-dimensional (2-D) seismic reflection profiles, including a set of high-resolution, multichannel 2-D seismic lines (Fig. 1). Line spacing is highly variable, from <1 km to >40 km. Vertical resolution of the data sets ranges from 5–10 m to 15–20 m. The seismic data were integrated with well logs and cutting descriptions from Shell Development (Australia) exploration wells (Potoroo-1, 33.385733°S, 130.7700301°E; Jerboa-1, 33.502787°S, 127.60221301°E) and Ocean Drilling Program (ODP) Leg 182 boreholes (Fig. 1). Seismic observations in two-way travel time (TWT) were converted to depth using an interval velocity of 2200 m/s, based on sonic velocities recorded in the Potoroo-1 well. Washed and dried cuttings from 10 m intervals within Potoroo-1 were sampled and mounted on polished thin sections (Fig. 2).
Figure 1. Location map showing mid-Eocene bryozoan reef mound locations, two-dimensional seismic data set, boreholes (Ocean Drilling Program Leg 182), and exploration wells in Eucla Basin, Great Australian Bight. Dashed lines show underlying Mesozoic basins.
5.4. Geological Setting

The GAB is located on the passive continental margin offshore southern Australia. It is underlain by two vertically stacked basins: the Middle Jurassic–Late Cretaceous Bight Basin, and the unconformably overlying Cenozoic Eucla Basin. The reef mound complexes occur within the Eucla Basin succession where it overlies the Eyre sub basin and the margins of the Ceduna subbasin of the Bight Basin (Fig. 1). Following the deposition of the siliciclastic Bight Basin succession, post-rift sedimentation includes early siliciclastic deltaic and slope deposits followed by extensive cool-water carbonate deposition from the mid Eocene to the present (Fig. 1) (McGowran et al., 1997; Feary and James, 1998; Totterdell et al., 2000). Of particular interest to this study is sequence 7 (Feary and James, 1998; Shipboard Scientific Party, 2000), which forms part of the late Paleocene–early Eocene Wobbegong supersequence (Totterdell et al., 2000). This deltaic wedge represents the final phase of siliciclastic input to the GAB, ending ca. 43 Ma (Li et al., 2003). A lack of age-diagnostic fossils makes it difficult to constrain the hiatus between siliciclastic- and carbonate-dominated deposition, although a best estimate suggests a hiatus of <1 m.y. (Li et al., 2003). In the mid-Eocene, the GAB underwent extensive igneous activity linked with accelerated seafloor spreading between Australia and Antarctica (Schofield and Totterdell, 2008). From the mid-Eocene onward, the GAB became host to the world’s largest Cenozoic cool-water carbonate province as Australia drifted northward during progressive global
climatic cooling (James and von der Borch, 1991; Feary and James, 1998; Li et al., 2003; James et al., 2004).

5.5. Depositional Architecture and Mound Facies

Seismic stratigraphic analysis based on reflection continuity, downlap, toplap, and onlap geometries, coupled with limited biostratigraphic data (Li et al., 2003), suggests that the Wobbegong delta progradation was broadly synchronous across the margin. The delta supersequence comprises three distinct lobes (D1, D2, and D3) that are clearly defined from TWT thickness maps. D1 and D2 exhibit well-developed (to 400 m thick), highly progradational clinoform geometries (Figs. 3 and 4), and D3 is much thinner (to 200 m). The topsets of the deltaic sequences are perfectly preserved with no evidence of significant reworking or incision, and thus assumed to represent fair-weather wave base during delta deposition. Distinctly mounded deposits are observed immediately basinward of the final clinoform break point of D1, on the break point of D2, and at the clinoform toe of D3. Each mound complex has been interpreted with regard to geological and paleophysiographic setting, seismic facies, and architecture. The complexes exhibit convex-upward positive relief with onlap of overlying strata observed in seismic sections, and are thus considered mounded relative to the surrounding stratigraphy (Fig. 3). The mounds downlap onto the uppermost delta clinoform and have been mapped for ~500 km along the basin margin (Fig. 1). The acoustic responses of the mound tops are similar in amplitude to those of the seafloor and basement, suggesting that they are acoustically hard events. Mound geometry can be divided into three separate physical components: a basinward flank, a central core, and a landward flank, each with a characteristic range of dimensions. The maximum thickness of the reef mounds is ~200 m, and the average thickness is 75 m, although average thicknesses vary across the complexes, especially in the core. The B1 mound complexes are ~5 km wide in the dip direction and range from 60 km to 150 km in length parallel to the slope margin. The B2 mound complexes show a greater average width of 13 km. The most pronounced cross sectional mounded geometries occur in the Eucla Basin section overlying the western Eyre subbasin, where relatively simple mounds are observed.
5.6. Internal Mound Architecture

Nine closely spaced high-resolution seismic lines provide insight to the internal structure of the reef mound complexes (Fig. DR1 in the GSA Data Repository.). Convex-upward internal reflections show distinct aggradational geometries easily distinguishable against the onlapping parallel seismic reflections of the succeeding sequences. The internal aggradation of multi-crested smaller mound geometries forms a thick reef mound body with a variably rugose top consisting of peaks and troughs. This facies is distinct from the lower-amplitude appearance of the B2 mounds compared to B1. Basinward flank angles range from 8° to 30°, and landward flank angles are 5°–15°, corrected for postdepositional tilt, assuming originally horizontal delta topsets (Fig. DR1).
Figure 3. Annotated seismic cross section showing B1 bryozoan reef mound complex on the final clinoform breakpoint of the underlying siliciclastic delta in Eucla Basin, Great Australian Bight. TWT two-way traveltime. Inset: B1, B2—reef mound complexes; J1—Jerboa-1 exploration well; other circles—boreholes.
Figure 4. Combined two-way traveltime (TWT; 2-D—two dimensional) thicknesses of the siliciclastic delta sequence (grayscale) and overlying bryozoan reef mound complexes (B1 in red, B2 in blue) showing clear correlation between delta depocenters D1 and D2 and mound nucleation. J1—Jerboa-1 exploration well; P1 Potoroo-1 exploration well. Section views A–C are based on seismic lines have been back rotated ~5° to compensate for postdepositional subsidence. Note progressively basinward location of B1 and B2 toward the east where underlying clinoforms are shallower.
5.7. Mound Composition and Age

Evidence of mound composition and age comes from the Potoroo-1 exploration well (Taylor, 1975), which penetrates the eastern part of the B1 complex in the eastern Eucla Basin (Fig. 5). The depths of cuttings samples from Potoroo-1 were correlated to seismic traveltimes using check-shot data, allowing calibration of the seismically defined mound complexes to a 60 m interval (860–920 m below sea level) of bryozoan boundstone. The cuttings sampled contain abundant bryozoans (Figs. 2 and 5; ~80%–95%; Figs. DR2 and DR3 in the Data Repository) throughout the interpreted reef mound interval, with a mixed selection of taxa including at least eight genera of cheilostomes (*Porina, Cellaria, Puellina, Chondriovelum, Foveolaria, ?Reteporella, Nudicella, and Exechonella*) and eight of cyclostomes (*Patinella, Nevianipora, Hornera, ‘Entalophora,’ Idmidronea, Crisia, Platonea, and Diaperoecia*). Depositional units above and below the B1 complex show overall bryozoan contents of 5%–10%, sharply defining the top and base of the reef mound complex (Fig. 5). Foraminifera found within the reef mound interval include *Truncorotaloides (Acarinina) primitivus, T. collacteus, T. pseudotopilensis, Globigerinatheka ? index* or *G. senni, Pseudohastigerinamicra*, and *Tentuitella aculeata*. Such faunas are indicative of a mid Eocene age (ca. 43 Ma) (Taylor, 1975). ODP Leg 182 boreholes cored the siliciclastic carbonate transition and yielded a similar age (Li et al., 2003).
Figure 5. Seismic cross section (top) and interpreted section (bottom) showing Potoroo-1 exploration well penetration through bryozoan reef mound complex B1 located over margin of northeastern Ceduna subbasin, Great Australian Bight. CWCs—cool-water carbonates. Gamma ray log (left; GAPI—American Petroleum Institute gamma ray units) and estimated percentage log of bryozoan fragments (% Bry) within cutting sample bags (Fig. DR3; see footnote 1) correlated to depth are shown over interpreted seismic section. Star shows approximate location of Figure 2 photographs in seismic section.
5.8. Discussion

A previous study (Feary and James, 1995), focusing on substantially younger bryozoan mounds, referred to the mounds documented here as volcanic bodies, presumably due to the penecontemporaneous igneous activity (Schofield and Totterdell, 2008). A link between volcanism, ocean fertilization, and bryozoan reef mound growth can be speculated upon but lacks evidence. The systematic location and extreme elongation along strike of the paleoshelf edge, the internal configuration, and most important the Potoroo-1 cutting samples prove that the mounded complexes discussed herein are bryozoan reef mound complexes. The bryozoan reef mound complexes preferentially nucleated around the paleobathymetric threshold provided by the paleoshelf edge of the late Paleocene–early Eocene Wobbegong delta (Fig. 4). The chronostratigraphic resolution of most bryozoans is poor and age determination for the mounds thus relies on associated foraminifera found in Potoroo-1 as well as seismic stratigraphic work calibrated by ODP Leg 182 borehole data. Both methods suggest the age of the mounds to be ca. 43 Ma, coinciding with the 43 Ma event (Li et al., 2003), which is linked with several major geological events of regional to global significance.

Based on the seismic stratigraphic and biostratigraphic constraints, it appears that cessation of siliciclastic progradation in the Wobbegong delta sequence was near synchronous in the GAB and the 43 Ma event represents a geologically abrupt switch from siliciclastic to carbonate deposition (Li et al., 2003). Accelerated seafloor spreading (more than doubling of spreading rates) in the Australo-Antarctic Gulf may be responsible for the mid-Eocene regional sea-level rise on the northern margin of the gulf at a time of global sea-level fall (Veevers, 1987; Li et al., 2003). The acceleration in spreading rates was penecontemporaneous with northeastward tectonic tilting of Australia (DiCaprio et al., 2009; Heine et al., 2010) and reorganization of the southern margin drainage network. Together, the tectonic processes created accommodation and a siliciclastic-free environment conducive to carbonate sediment production.

Nucleation and growth of the B1 complexes was apparently nearly synchronous and rapid across the margin, with only a brief hiatus between the underlying clastic sediments and bryozoan mound growth. Bryozoans exist across a range of water depths (Taylor and James, 2013); however, given the steep, multi-crested aggradational geometries and proximity to the ultimate Wobbegong delta clinoform, we infer that this paleobathymetric threshold was of key
importance to bryozoan mound growth. As bryozoans are suspension feeders and not directly dependent on specific photic conditions, mound growth at the shelf edge would conventionally suggest an increased nutrient supply due to current interactions with bathymetric gradients (James, 1997). In the GAB, the present-day Leeuwin Current is nutrient deficient, but James et al. (2000) interpreted growth and stacking of bryozoan mounds in the Quaternary to be linked with current downtime and ocean upwelling during glacial lowstands. Anderskouv et al. (2010) rejected this theory, suggesting that the Pleistocene mounds originated as sediment waves. An origin as sediment waves is incompatible with the steep (to 30°) flanks and internal geometries observed for the mid-Eocene reef mound complexes.

Mound nucleation and growth controlled by nutrient supply, water depth, and ocean currents in the Australo-Antarctic Gulf for the B1 and B2 mounds seems likely, although it will remain speculative until further sampling. Seismic stratigraphic observations suggest coeval B1 mound nucleation between individual complexes followed by coeval B2 mound nucleation between individual complexes. However, mound physiographic nucleation differs between each delta lobe (Fig. 4). We therefore interpret mound nucleation to be linked to a combination of a paleobathymetric threshold, water depth, subsidence rate, and ocean currents. Initially, B1 reef mound complexes grew in accordance with rising local sea level, and developed prominent basinward flank angles. They were eventually outpaced by the rapidly increasing water depth on the steeper sections of the pre-existing delta. The younger B2 complexes are consistently located up dip and landward of the B1 complexes. Hence, the entire reef mound system shifted landward onto the flatter paleo-topset section of the Wobbegong delta and was eventually buried by the onlapping carbonate apron.

5.9. Summary

Large-scale bryozoan reef mound complexes have been discovered along a 500-km-long section of the mid-Eocene (43 Ma) paleoshelf edge of the GAB, along the northern margin of the Southern Ocean. The positions of the reef mounds were controlled by the bathymetric relief along the paleoshelf break of underlying siliciclastic delta lobes. North-eastward tilt of Australia from the mid-Eocene onward contributed to continent-scale reorganization of drainage patterns on the southern margin and shut-down of siliciclastic input into the Australo-Antarctic Gulf in the mid-Eocene. Accelerated tectonic subsidence along the continental margin, associated with
increased rate of separation between Australia and Antarctica, at a time of global climate change
allowed reef mound growth to be accommodated along the mid-Eocene paleoshelf break during
a fall in global sea level. Bryozoans exploited the shut-down in siliciclastic sediment supply and
became the dominant benthic organisms, thriving on the relic shelf break during rising regional
sea level with a nutrient supply sufficient to power their prolific growth. Mound growth was
prominent, but seemingly short lived, and the build-ups were onlapped and eventually buried by
the Wilson Bluff Formation carbonate apron.

5.10. Acknowledgements and References

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reef on a predominantly cool-water carbonate continental margin—Eucla basin, western Great
CBMABM>2.3.CO;2.


5.11. Supplementary Figures:

Figure DR 1: Seismic cross-section and interpreted section showing high-resolution and detailed internal structure of bryozoan reef complex (B1) located over the Eyre Sub-basin.
Figure DR. 2 A selection of representative microscope photographs of cutting samples and polished-thin sections at stated depths taken from Potoroo-1 exploration well through the B1 reef mound interval. Star at 890–900 m relates cutting sample depth to star in Figure 5 seismic section (TWT).
**Cutting Samples Analysis (2012)**

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<th>Analyst</th>
<th>Alexander Sharles</th>
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<tr>
<td>Exploration Well</td>
<td>Potoroo-1 (1975)</td>
</tr>
<tr>
<td>Cutting Samples</td>
<td>Washed &amp; Dried</td>
</tr>
<tr>
<td>10 m Intervals</td>
<td>800-1000m TVD (KB)</td>
</tr>
<tr>
<td>Location</td>
<td>Geoscience Australia Data Repository, Canberra, Australia</td>
</tr>
<tr>
<td>Method</td>
<td>Potoroo-intersected one of the identified mound complexes. Nine representative samples, each comprising 20 g of raw cuttings, were taken from 10 m cuttings bags over the interval 810–960 m (KB), fully covering the interpreted mound facies. Bags were analysed under the microscope for a calculated overall bryozoan % recorded and illustrated in Figure 3.</td>
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**Polished Thin Section Mounting: (2013)**

<table>
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<th>Analyst</th>
<th>Cathy Hollis</th>
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<tbody>
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<td>Potoroo-1 Cutting Samples Mounted</td>
<td>840-850 m</td>
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<tr>
<td></td>
<td>850-860 m</td>
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<td>890-900 m</td>
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<td>Details</td>
<td>Standard 40 micron thickness</td>
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<tr>
<td>Method</td>
<td>Standard binocular microscopic interpretation, illustrated in Fig DR 2</td>
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**Figure DR 3: Table of sampled cuttings and analysis methods**
CHAPTER 6: PUBLICATION (TO BE SUBMITTED): ORIGIN AND SIGNIFICANCE OF ENIGMATIC MOUND STRUCTURES IN THE GREAT AUSTRALIAN BIGHT

Origin and significance of enigmatic mound structures in The Great Australian Bight

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6.1. Abstract

Exploration of seismic reflection surveys often result in the discovery of a variety of ambiguous mounded phenomena. The temporal and spatial changes in morphology, internal architecture, seismic facies and relationship between mounds can be used to determine the origin and growth mechanisms. Here we used an extensive grid of 2D seismic reflection data and high resolution 3D seismic data integrated with dredge surveys and borehole calibrations to provide additional results on previously interpreted mounds in the Great Australian Bight and suggest a relationship between a volcanic and carbonate mounded province. In total, 61 mounds have been identified and geometrically separated. The mounds have been grouped into four categories based on distinct observations between seismic facies (principally amplitude) and geometry. Isolated mounds are up to 500 ms TWT thick and tens of kilometers width and length. Genetically linked mound complexes are up to 15 km wide and 75 km in length. Two distinct mound domains have been interpreted between carbonate mounds and volcanic mounds with seismic stratigraphic calibration suggesting both formed at approximately the same geological time. We interpret an initial magmatic eruption phase which produced several high amplitude conical volcanoes. This was followed by diminished magmatic pulses which powered the growth
an emplacement of a series of low amplitude volcani-clastic and hydrothermal mounds. It is speculated the volcanics played a key role in ocean fertilization in the Bight owing to the synchronous growth of bryozoan carbonate mounds in the same area. Our work highlights how constraining mound types provides significant input into the understanding of the geological system and the link to larger tectonic events. Mound analysis also allows for the deduction of palaeobathymetry, palaeoecological and palaeoenvironmental controls.

6.2. Introduction

The post-rift evolution of many continental margins is often associated with episodic and/or localized igneous activity and punctuated by unconformities. Such features often represent important changes in the tectonic evolution of the margin, inter-acting with changes in sediment supply and regional to global oceanographic and climatic effects (Ziegler, 1989; White et al. 2003; Allen & Allen, 2005). The Great Australian Bight (GAB) is a frontier deepwater continental margin with only a handful of exploration boreholes and is largely covered by widely spaced 2D seismic grids. The GAB underwent a protracted rifting history before initiation of seafloor spreading in the late Santonian (~83 Ma) leading to full oceanic conditions in the middle Eocene.

The earliest Cenozoic evolution of the GAB is represented by a series of unconformities, dramatic changes in sedimentation regime, from siliciclastics to cool-water carbonates, and a plethora of enigmatic large-scale mounded structures (Feary and James, 2000; James et al., 2000; Schofield and Totterdell, 2008; Anderskouv et al., 2011; Jackson, 2012; Magee et al., 2013). This paper presents a whole-GAB analysis of the geological context and detailed character of mound structures located on the mid-Eocene unconformity. It identifies a spectrum of volcanic, hyaloclastite and possibly hydrothermal mounds, plus carbonate build ups, raising several key questions on mound origin, growth and interplay. The mound characteristics and distribution are used to deduce the palaeo-water depth of the earliest Australo-Antarctic Gulf. The study highlights the need for a detailed assessment of mound origin when undertaking frontier basin analysis as one model may not fit all observed mound features. More specifically, the study highlights the use of non-clinoformal seismic architectures in palaeo-bathymetric reconstructions in early post-rift settings.
6.3. Data and Methods

This study is based on interpretation of a regionally extensive database of open-file high and medium-quality, post-stack time-migrated multi-channel 2D seismic reflection profiles including a set of high-resolution multi-channel 2D seismic lines (Figure 1). Line spacing is highly variable, from less than 1 km to more than 40 km. Total line length is approximately 22,000 km. Vertical resolution of the data sets range from 5–10 m to 15–20 m. The seismic data were integrated with well logs and cuttings descriptions from exploration wells (Potoroo-1, 33.3857°S, 130.7700°E and Jerboa-1 33.5027°S, 127.6022°E) and ODP Leg 182 boreholes (Figure 1). Seismic observations in Two-Way Time (TWT) were converted to depth using an interval velocity of 2200 m/s in the sub-sea section, 1525 m/s in the water column; based on sonic velocities recorded in the Potoroo-1 well. Two 3D seismic surveys were available for study including the open-file Trim 3D and the proprietary Ceduna 3D survey. The 3D Ceduna survey covers approximately 12,000 km². The version used for interpretation was a 32 bit zero-phase processed near-offset shallow hazards volume with a dominant frequency of 75 Hz. The volume was hard-drive intensive and had to be split into three swaths, virtually cropped at the 2 second mark and decimated by a factor of 1. No resolution or detail was lost in this process and all geology from the present day seafloor to the Paleocene sequences below the mounds was well imaged.
Figure 1: Data map across the project area. All 2D seismic lines were explored for mounded features.
6.4. Geological Setting

The Great Australian Bight is located on the passive continental margin offshore southern Australia. It is underlain by two vertically stacked basins – the Middle Jurassic – Late Cretaceous Bight Basin and the unconformably overlying Cenozoic Eucla Basin. The Bight Basin is split into several sub-basins of which the Eyre and Ceduna Sub-basins are key to this study. These Mesozoic to Cenozoic depo-centres developed during extension and rifting in the Jurassic, followed by Cretaceous to recent thermal subsidence and the syn-rift basin sediments comprise thick (> 3 km) siliciclastic deposits of early Jurassic to mid Albian age (Totterdell et al., 2000). Subsequent post-rift sedimentation (mid Albian to the present day) includes early post rift siliciclastic deltaic and slope deposits (Wobbegong Supersequence, Totterdell et al., 2000) followed by extensive carbonate deposition from mid-Eocene to the present day (Fig. 2) (McGowran et al., 1997; Feary & James, 1998; Totterdell et al., 2000). During the mid-Eocene, the GAB was located at approximately 60 degrees south, (Figure 2) at the transition between a tropical warm water and temperate cool water climate. The Middle Eocene was a time of global climatic change and in the GAB marks the stratigraphic transition from siliciclastic to carbonate dominated regime. This unconformable change has been referred to as the “Lutetian Gap” (McGowran et al., 2004) proposed because of an apparent biostratigraphic hiatus across the margin and the resulting surface unconformity hosts the mounded succession (Figure 3).
Figure 2: Palaeogeographic map modified to represent the 45-43 Ma mark in the Australo-Antarctic Gulf (Veevers et al., 1991; Norvick and Smith, 2001; Li et al., 2003).

Figure 3: Schematic dip section through Ceduna Sub-basin showing thick underlying Bight Basin siliciclastic sediments and thin overlying unconformable Eucla Basin cool-water carbonate sediments. Schematically located are examples of observed mounds types.
However, palynological studies suggest the hiatus varies in duration across the GAB (Li et al, 2003). This is true between near-shore vs. offshore (Shipboard Scientific Crew, 2000) and it is within the approximate age range of the Lutetian gap that mound growth exploded in the GAB. Mound growth was prominent in the Ceduna Sub-basin and is associated with the Bight Basin Igneous Province (BBIP sensu~ Schofield and Totterdell, 2008). The BBIC comprises a variety of large sills, dykes and submarine shield volcanoes, mounds, (Schofield and Totterdell, 2008; Jackson, 2012; Magee et al, 2013) and hyloclastites, as proven by dredge survey sampling (Clarke and Alley, 1993). This volcanic episode occurred during the early middle Eocene. Many of the mounds and their relationships to underlying sills have been reported further by Jackson 2013 and have been reinterpreted and reported here.

The Lutetian gap unconformity separates post-rift siliciclastic deltaic sedimentation (Pidinga Fm aka Wobbegong Supersequence) from extensive cool-water carbonate sedimentation (Wilson Bluff Fm aka Dugong Supersequence) and is dated as mid-Eocene (43 Ma) in shelfal sections (McGowran et al., 1997; Feary & James, 1998; Totterdell et al., 2000; Li et al., 2003). This significant change post-hiatus can be correlated to several geological events and hence it is inferred that a constellation of tectonic and palaeoenvironmental changes including; 1. tectonic back-tilting of the Australian continent, 2. initiation of final separation between Australia and Antarctica, 3. shut-off of siliciclastic supply, 4. basin subsidence and increased seafloor spreading, 5. volcanic sill emplacement and 6. rising sea-level at a time of global eustatic fall allowed the drop in sedimentation rate, the change from siliciclastic to cool-water carbonate setting but as discussed here; the rise and growth of mounded geobodies across the Great Australian Bight.

6.5. Mound Characterisation

Here we define a mound as a 3-dimensional geometrical body constituting positive relief and angular morphology with respect to surrounding stratigraphy (Figures 4). In total 65 mounds have been documented (Figure 5). The identification of mounds in seismic section is somewhat trivial in its most basic form, however, there are many observations to be taken further to fully characterize a mound in detail (Table 1). Each observation provides evidence towards the geological interpretation and must be evaluated according to its confidence and significance. It is
essential that objective observations are distinguished from more subjective inferences. For example, size is objective, whilst seismic reflection terminations and patterns are often affected by interference/tuning effects, and subject to interpretation with regards to their stratal significance. Also, mound characterization is not only based on and restricted to the cross section, but is equally as important in the map-view. Where 3D data are available they have boosted observations and results for both domains. Where 2D data is available it has been used mainly in conjunction with the cross section and has been used with care in the map-view (see Figure 7).

Cross-sectional Observations

Figure 4 demonstrates the basic 2-dimensional mounded ‘styles’ observed in the GAB and the relationship to surrounding strata. This was determined using basic seismic stratigraphic principles guided by onlaps, downlaps, toplaps and truncation in seismic cross section (Mitchum et al., 1977). Further observations in seismic section include symmetry, flank angle calculation, level of rugosity, structural components, relationship to faulting, relationship to igneous intrusions and internal stacking patterns. Mound geometry in cross section has been cross-correlated with map-view observations, and several of the mounds have been mapped with linear trends and associated with linear features i.e. fault planes.

Map-view observations

The mounds in the GAB have been mapped mostly using 2D seismic lines with variable spacing in the order of 10 km (Figure 5). As such, interpolation between seismic lines only gives a general portrait of mound geometry, and 3D geometry cannot be realistically reconstructed without 3D data (Figure 7). However, 2D mapping shows lineation trends (B1 & B2 reef mound complexes and LA mounds) and geographical location. Where 3D data were available, true mound geometries have been documented leading to much more complex and often unexpected geometries. In both 2D and 3D areas, map-view observations and trends can be correlated with geological settings and features, albeit with different levels of confidence and detail. These observations can then be fed into the overall geological evolution of the mounds.

Previous works by Sharples have interpreted a series of bryozoan reef mounds (Figure 1: B1 and B2) and work by Schofield & Totterdell, 2008; Jackson & Schofield, 2012; Magee et al., 2013; have documented abundant volcanics in the eastern Ceduna Basin. However, the volcanics
have not been selectively sampled via borehole, and calibration is via proximal dredge survey. The dredge survey reports, show results of porphyritic basalt and hyaloclastites (Clarke and Alley, 1993). The bryozoan reef mounds and the volcanic sea mounts appear distinct in seismic section and in perspective of each other. Thus, using these two calibrations and the previously discussed cross sectional and map-view properties we can compare and contrast all mounds, categorize them and interpret their geological significant into a regional geological perspective.
Figure 4: A simplified schematic cartoon showing the variety of mounded structures seen in seismic cross section through the GAB. 1 = Standard mound applicable to B1 and B2 reef mounds, high amplitude mounds, low amplitude mounds. 2 = Apparent ‘constructive’ mound with vertical stacking which can also be migratory, applicable to Quaternary bryozoan mounds (James et al., 2000) aka. sediment waves with bryozoan content (Anderskouv et al., 2010, Huuse and Feary, 2005). 3 = Mounded feature with associated velocity pull-up, applicable to B1 reef mounds, high amplitude mounds, shield volcanoes. 4 = Mounded geometry with accretion/progradational internal geometries directly above fault plane, applicable to all mounds except bryozoan reef mounds. 5 = Mound with surrounding depression or moat (erosion or differential compaction), applicable to low amplitude mounds, and high amplitude mounds but only at later stages ~mid Miocene onwards. 6 = Symmetrical constructive aggradational mound, often comparatively small and without visibly obvious structural control, applicable to low amplitude mounds only. 7 = Mound growth syn/post deposition of overlying strata, applicable to high amplitude mounds and shield volcanoes. 8 = Elongated mound structure with variable rugosity. Internal aggradation is applicable to B2 reef mound complexes, if internal progradation is visible, then style is applicable to low amplitude mounds.
Figure 5: Mound map of all mounds documented across entire dataset (3D Ceduna not shown for clarity purposes). Mound geometries are interpreted based on most likely geometrical configurations. In the BBIC much mounded "facies" is seen (blue) which cannot be successfully linked to an individual mound or mound group.
**Table 1**: Mound observations leading to classification of all mounded features recorded in the GAB at the mid-Eocene (43 Ma).

<table>
<thead>
<tr>
<th>Mound</th>
<th>Symmetry</th>
<th>Rugosity</th>
<th>Shape</th>
<th>Linearity</th>
<th>Average Dimensions (km)</th>
<th>Flank Angles</th>
<th>Internal Structure</th>
<th>Miscellaneous</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Length</td>
<td>Width</td>
<td>Thickness</td>
<td></td>
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<tr>
<td>B1</td>
<td>Asymmetrical</td>
<td>Med-High</td>
<td>Elongated</td>
<td>High</td>
<td>60</td>
<td>5</td>
<td>50-175</td>
<td>1-30°</td>
</tr>
<tr>
<td>B2</td>
<td>Asymmetrical (greater)</td>
<td>High</td>
<td>Elongated</td>
<td>High</td>
<td>60</td>
<td>13</td>
<td>50-200</td>
<td>1-30°</td>
</tr>
<tr>
<td>Low Amp</td>
<td>Asymmetrical</td>
<td>Medium</td>
<td>Elongated</td>
<td>High</td>
<td>&lt;1-20?</td>
<td>&lt;1-5</td>
<td>50-150</td>
<td>5-15°</td>
</tr>
<tr>
<td>High Amp</td>
<td>Asymmetrical</td>
<td>Med-High</td>
<td>Circular</td>
<td>Low</td>
<td>2–10</td>
<td>1–8</td>
<td>100-500</td>
<td>5-20°</td>
</tr>
<tr>
<td>2D Shield Volc</td>
<td>Asymmetrical (lesser)</td>
<td>Very Low</td>
<td>Circular</td>
<td>Low</td>
<td>5–10</td>
<td>5–10</td>
<td>200-600</td>
<td>1-10°</td>
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<tr>
<td>3D High Amp</td>
<td>Symmetrical peaks</td>
<td>Low</td>
<td>Circular</td>
<td>Low</td>
<td>11</td>
<td>8.5</td>
<td>50-400</td>
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</tr>
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<td>Medium</td>
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<td>High</td>
<td>10</td>
<td>4.5</td>
<td>50-200</td>
<td>5-15°</td>
</tr>
</tbody>
</table>
6.6. Mound Classification

6.6.1. Bryozoan Reefs

Setting & Grouping: A prominent set of margin parallel bryozoan reefs of mid-Eocene (43 Ma) age have been documented locating directly on top of the siliciclastic–carbonate unconformity in the GAB. They are present in seismic cross-section as prolific mounds and are visible throughout the Eucla Basin where it overlaps the underlying Eyre and Ceduna Sub-basins (Fig 1). The reef-mounds have been documented and described by Sharples et al, (2014) (B1 and B2 bryozoan reef-mound complexes) however, for the purposes of contrast and comparison between other mounded features (Figures 2; 5) will be documented in further detail here. The bryozoan reef mound complexes are located on the palaeo-shelfbreak of the siliciclastic-carbonate unconformity and are not present in over the Ceduna Terrace section in the BBIC. However, seismic data is sparse landward of the BBIC and it is not apparent if the bryozoan reef mound complexes are present landward. Near the Eyre Sub-basin, occasional shield volcanoes and other high amplitude candidates are in close proximity to the reef mound. The nature of the siliciclastic-carbonate unconformity is poorly constrained and complex. However, seismic stratigraphic relationships based on downlaps and onlaps suggest that the reef mound complexes are co-eval, or slightly younger than other mounds in the GAB. Based on superposition of wedging sequence below the volcanic mounds which are succeeded by the Wobbegong delta clinoform packages it can be ruled out that the BRM complexes are older than VMs.

Characteristics & Geometry: The reef mound complexes cover in total a length of 550 km, showing a palimpsest topography above the underlying deltaic substrate. In seismic section, mound positioning varies between delta lobes (see Figure 4, Sharples et al., 2014). Over the Eyre Sub-basin, mounds are positioned just basinward of the final clinoform breakpoint (D1), this is also true over the northern margin of the Ceduna Sub-basin (D2), however, north east mound complexes are at the toe of the delta slope (D3) Although mounded in cross-section the complexes clearly form elongated structures which for geometrical purposes possess more “reef-like” characteristics. The definition of “reef” remains a point of debate to the present day, with various authors (Wood (2002), Riding (2002), Flugel and Kiessling, 2002) more recently accepting the close relationships between reefs and mound. More orthodox and older definitions strictly limit the definition of reefs as applicable only to warm water coral build-ups in shallow
water whereby a sheltered back lagoon system is created. In this case we employ the term reef mound principally because of the elongated nature, and base results on cutting samples with ca. av. 75% of bryozoan cuttings reported as fenestrae, which in accordance with post-mortem charts from Taylor & James (2013) is indicative of 'reef-builders'.

Geometry between B1 and B2 complexes vary, (represented by Figure 4 style 1 and 9) which can always be split into a core component and two flank components. Each is then characterized individually in terms of symmetry, rugosity and angularity. Correlation between increased mound width and increased rugosity is positive; however, a constructive internal fabric is pertinent in both set complexes. The palaeoecological connotations of this are not yet understood. In total, two sets of reef mound complex growth are observed, (B1 and B2) each set containing 3 individual complexes which are linked/separated by 2D seismic interpretation, and continuity/absence of reef mound facies. B1 reef mound complexes grew first, and B2 are always found immediately landward, representing a transgression and shift onto the higher sections of the paleo-delta front. An average length of 60 km, height of 175 m and width of 6 km is common between the B1 complexes, compared to an average length of 40 km, height of 200 m and width of 10 km between the B2 complexes.

The most simplistic mounds (B1) are found in the west over the Eyre Sub-basin. Mounds here are generally more symmetrical with a single peaked core and two flanks; landward and basinward. Complexes become more rugose eastwardly, showing multi-crested cores with numerous peaks and troughs. B2 mounds are more rugose with shallower flank angles and greater widths (Fig. 3). All mounds appear to show a constant ratio between basinward and landward flanks angles, whereby, basinward flanks exhibit a steeper inclination averaging 8-10 degrees, while landward flanks average 3-5 degrees. The multi-crested and rugose mound cores show angles between peaks and trough of up to 35 degrees, although this is rare.

Seismic Facies: Geophysically the mound tops are ‘hard kick’ events, and show significant acoustic impedance to the overburden stratigraphy of the cool-water carbonate Wilson Bluff Fm (2225 ms velocity according to Leg 182 boreholes). Mound tops are generally continuous with a bright and strong amplitude. Exact pinch-out of the mound tops as they reach the flank endpoint is limited by seismic resolution, and a best estimate has to be taken. High resolution lines however, show distinct downlap onto the mid Eocene unconformity. Seismic
data quality below the mounds is variable and a clear basal surface is not always obvious. This is exaggerated where mounds generate a multiple artefact and significant velocity pull-up. Not all mounds have this; the reason is not entirely clear, geological i.e. diagenesis? or synthetic i.e. processing and noise cancellation?

Where better clarity beneath mounds exists, it can be seen that the base of the mounds is conformable with the underlying delta substrate. There are no initial internal downlapping reflectors owing to the constructive aggradational basal facies. Latter stages of mound internal structure do show internal downlap on occasion. B1 and B2 mound internal facies have a distinctive character, it is not chaotic, nor continuous, but regular and wavy which pinches-out at both landward and basinward flanks. Internal amplitudes vary; again, indicative of diagenesis or hard grounds as suggested by the apparent randomness of sharply terminating high amplitude reflectors. Alternatively some of the randomly terminating high amplitude internal reflections may be a function of 2D side-swiipe (Sharples et al., 2014; Fig DR 1).

Surrounding Stratigraphy: Sequentially the bryozoan reef mounds lie above the Wobbegong Supersequence, which is represented by an early Paleocene to mid-Eocene siliciclastic delta. The delta is split into three separate lobes within the project area, with the south eastern-most limits undetermined due to lack of data. It appears reef mounds are conformable (under the central core) with the delta top surface, and if any downlap is present it is below the resolution of 2D seismic data. Onlapping the B1 and B2 reef mounds is a deep water (cool) carbonate ramp which is part of the Wilson Bluff Fm. The base of the Wilson Bluff Fm is a predominantly cherty clastic thin sandstone veneer (Hampton SST). Until further reef mound sampling takes place it is not yet known if the reef mound growth precedes this, or is syn-depositional.

All mounds are associated at the same time interval in seismic sections of between 1.1-0.8 seconds TWT, regardless of their varying geological positioning in relation to the underlying siliciclastic delta. The exact placement and configuration of mounds above the delta lobes is complex and does slightly vary. However, overall Figure 4 by Sharples et al., 2014, shows a correlation between delta thickness and mound growth, whereby the thickest points of the delta (area which coincides with final prograding clinoforms and rollover point) provides the substrate and structural base for the reef-mounds. Geographically this trend also follows that of margin
palaeobathymetric contours. Although a correlative boundary can be picked to tie all lobes, each
delta lobe has a different sequence stratigraphic architecture, ergo; sediment supply regime,
environment of deposition, underlying basal structure, and hence split into the separate lobes.
The age of the delta top-sets upon which the reef-mounds lie is \textit{ca.} 43 ma as interpreted by ODP
Leg 182 boreholes and foraminifera samples from the nearby Potoroo-1 exploration well.

Limited documentation in the well completion report and poor core recovery in the ODP
expedition limits the resolution of the age between the top of the delta and the onlapping deep-
water carbonate apron. There is no faulting observed in association with the bryozoan reef
mounds, albeit B1 mounds located on the northern margin of the Ceduna Sub-basin have been
observed to locate within erosional scar depressions of the delta slope. This may be considered
fault associated, if the erosional scars are low-angle thrust fault initiated. Even so, this is more
likely coincidental, as opposed to fault slip determined by paleoecological reef mound growth,
and appears only on a local scale above the D2 lobe. Laterally, bryozoan mound facies shows no
observed changes. There are no apparent signs of debris aprons which are so often associated
with structural carbonate build-ups. One observed case which may be interpreted as a 'toe slope
slump deposit' does exist to the west of the Eyre Sub-basin (to be discussed).
Figure 6: Seismic cross sections (far and near) highlighting examples of B1 and B2 (Sharples et al., 2014) bryozoan reef mounds. Top left shows B1 mound emplaced on final clinoform breakpoint of underlying siliciclastic delta. Top right close section shows high resolution 2D seismic (~5 m vertical resolution, dominant frequency 100 Hz) through the B1 mound adjacent to the seismic line in the top left. Bottom left shows both B1 and B2 complexes, their overlapping nature and the clear transgression of B2 landward behind B1 in the Eucla Basin over the margin of the northern Ceduna Sub-basin. The B1 mound appears to be located in an erosional slump/scar of the pre-existing siliciclastic delta final clinoform breakpoint. Bottom right shows a seismic section in the south western Eucla Basin and the elongated rugose nature of the B2 reef mound complex.
6.6.2. Isolated Bryozoan mounds

Alongside the bryozoan reef-mound complexes there are numerous examples of what are interpreted as isolated bryozoan mounds; that is; mounds which do not correlate between seismic lines at all. Isolated bryozoan mounds have been documented previously by James et al., (2000), James et al., (2004) and mostly reside within younger Miocene strata. The isolated mounds do not share the linear properties of their B1 and B2 relatives and cannot be classified as reefs or reef mounds. Isolated mounds are not calibrated by borehole coring or cutting samples, hence the exact composition of the mounds is unknown, but given the geological setting and characteristics, the most likely and sound interpretation is a bryozoan-based composition. Isolated mounds possess a slightly different seismic facies to the main reef-mound complexes. Owing to the calibration of the bryozoan reef mound complexes it is safe to rule out igneous (in?) composition for all isolated mounds found landward of the B1 and B2 reef mound complexes.

The isolated mounds appear to be mainly located in the western sections of the Eucla basin, in particular over the margin of the Eyre Sub-basin. It remains to be seen how many isolated examples of mounds lie between seismic line spacing, but given the average spacing of 10 km between seismic lines it likely there may be many. Here we will discuss 3 cases of isolated bryozoan mounds which are observed in cross section both basinward and landward of the initial B1 and B2 reef mound complexes.

Landward Isolated Bryozoan Mound Example:

The mound is one of 4 similar mounds seen in the west of the project area where the Eucla basin overlies the margin of the Eyre Sub-basin. The mound is located at X: 411622, Y: 6328576 and is cross-cut from north to south by 2D seismic line #27 (Japan National Oil Company, JNOC). The present day burial depth is 0.6 s TWT and the mound is akin to Figure 4, style 1. Like all mounds in this study it is located on the same major unconformity and delta topsets, (D1 lobe) some 15 km landward of the final clinof orm break-point and basinward B1 reef mound complex.

Mound geometry is roughly asymmetrical, although the basinward flank is more rugose and thicker than the landward flank. The core of the mound appears to be symmetrical (taking
into consideration only 1 seismic line intersects the mound). Flank angles are approximately 8–10 degrees for the basinward and 1–3 degrees for the landward flank and the mound is approximately 75 m thick (assuming 2215 ms velocity). Geophysically the mound is a 'hard-kick' event represented by a positive acoustic impedance change on the upper mound surface. However, this outer surface amplitude is significantly weaker in comparison to the B1 and B2 reef-mounds, and in-fact only just has higher amplitude than the overburden. The internal seismic facies also perpetuates a low amplitude but with the same convex-up constructive structure. No geophysical anomalies are associated below the mound and it appears concordant with the underlying delta. The isolated mound is also onlapped by the younger Wilson Bluff Fm with scours and moat-like features around the base of each flank with no evidence for faulting, folding or source conduits observed.

**Basinward Isolated Bryozoan Mound Example:**

The mound is located at X: 411922, Y: 6298812 and is cross-cut from north to south by 2D seismic line JA90_27 (Japan National Oil Company, JNOC). The present day burial depth is 1.35 s TWT and the mound is not like others seen elsewhere in the entire dataset. The isolated mound is located in a depression (slump?) in the siliciclastic–carbonate unconformity approximately 8 km south of the B1 complex. The geometry is roughly symmetrical with shallow flank angles of 3–6° and an estimated thickness of 100 m. This estimate is rough-handed as the composition of this mound is speculative. The seismic facies is similar to that of B1 reef mounds (within the same seismic section) and the multiple noise effect is also present. Internal fabric is not obviously apparent, and more so, the geological setting showing a paleo-ecological configuration similar to that of B1 is not obviously apparent if the mound was to be considered to be bryozoan based. Links to volcanism are also speculative as there is no obvious or apparent signs in underburden. Most likely the mound is genetically connected to the B1 reef mounds as in some sections of the B1 western- most complex there appears to be wasting; hence, this could be a downslope collection of reef mound debris, but with only 1 seismic line, the origin and composition of this mound remains speculative.
6.7. Volcanic Mounds

The southern Australia margin is by definition classed as a "non-volcanic" rifted margin owing to absence of significant volcanism during break-up of Gondawana land in the Mesozoic (Teasdale et al., 2003). However, several previous works (Fraser and Tilbury, 1979; Stagg et al., 1990; Clarke and Alley, 1993; Lanyon et al., 1995; Totterdell et al., 2000; Sayers et al., 2001; Teasdale et al., 2003; Totterdell and Bradshaw, 2004; Schofield and Totterdell, 2008; Jackson, 2012; 2013; Holford et al., 2012; Magee et al., 2013) have reported and documented in detail various igneous features in 2D seismic data; this includes sills, dykes, lava flows and conical volcanic extrusions (mounds) and volcanoes. The first detailed reports of Bight Basin volcanism came with acquisition of the Flinders 2D seismic survey became available. A report by Schofield and Totterdell (2008) referred to a cluster of interpreted igneous features in the southeastern Ceduna Sub-basin (Fig 1) as the Bight Basin Igneous Complex BBIC, including dykes, sills and extrusive volcanic mounds. Although no direct sampling or isotopic dating has been undertaken there is reasonable confidence to date the volcanic episode as mid-Eocene, based on the seismic stratigraphic framework.

With recent work by Sharples et al (2014) constraining bryozoan reef mound growth on the 43 Ma Palaeo-shelf break and new sequence understanding from the 3D Ceduna survey (BP) the volcanism can now be correlated to regional geological events at the mid-Eocene ~43 ma, such as doubled sea floor spreading rates, and mantle upwelling beneath the thinned crust. This episode of volcanism is not only present in the GAB but is present across the entire southern margin. The vast majority of volcanism is centred around the south-eastern margins of the Ceduna Sub-basin and the overlying Eucla Basin. Volcanics have also been observed on the margins of the Eyre Sub-basin and the Duntroon basin making the total area of the BBIC approximately 50,000 km squared. Forced folding events are associated with this volcanic episode and sill emplacement mechanisms have been discussed by Jackson et al., 2012; 2013; Holford et al., 2012.

Previous work (Magee et al., 2013) grouped the volcanic mounds in the BBIC into two distinct groups; each with its own internal structure composed of several sets of seismic facies. These interpreted seismic facies varied their presence with respect to group 1 and group 2 mounds. Here, we re-interpret and document the BBIC mounds and add new observations from
the 3D Ceduna survey to provide a more detailed analysis where 2D seismic data lacks detail. We prefer to promote mound grouping based upon seismic facies and especially amplitude variation given its direct relationship to velocity changes reflecting rock properties. We also utilize a mix of geometrical characteristics from all mounded features in the area including the newly discovered mounds in the Ceduna 3D survey which allows us to create an extensive database by which to compare and contrast. This grouping style allows for greater clarity when comparing mound types and is more observationally based allowing for revisions should further data become available.

Since the introduction of the 3D Ceduna survey it also became apparent that significant geometrical detail was missing from the 2D seismic coverage alone. Figure 7 illustrates the proposed Hansen (2008) 3D geometrical reconstruction via 2D seismic lines which have been employed by Jackson, 2012; Magee et al., 2013, in the Great Australian Bight and others elsewhere. We take serious issue with the methodology which is geological mapping at its most basic, and not a new or fundamental methodology at all. Inaccuracy is highlighted when overlapped with the 3D mound geometries in the GAB. Scientific detail is missed and furthermore, there is the potential to compound mistakes which can be fed into interpretation. Using both 3D and 2D seismic data we propose categorization of the BBIC mounds into i.) high amplitude mounds, ii.) low amplitude mounds and iii.) giant low amplitude mounds. Two examples selected from the 3D Ceduna are also provided to illustrate key seismic facies and geometries.

6.7.1. High Amplitude Mounds (HA)

High amplitude mounds are characterised by significantly higher seismic amplitude facies than surrounding mounds. Their volumes and dimensions are difficult to constrain due to their tendency to be linked with extrusive tabular flows and forced folding from associated shallow sills (Jackson, 2012)

Setting & Grouping: They coincide with giant low amplitude mounds often partly sharing some of the seismic facies (Magee et al., 2013) and were initially interpreted as a sub-seismic facies of the giant mounds. However, isolated high amplitude mounds have also been discovered and mapped without any apparent genetic connection to giant lower amplitude mounds; thus,
they have been grouped separately. Figure 8 illustrates the high amplitude nature of the mounds in comparison to all others seen, however, it is in combination with several other factors that make the HA mounds deserving of separate grouping.

**Characteristics and Geometry:** HA mound geometry is roughly asymmetrical in the form of central sharp-tipped conical mounds that link into tabular flows. This is unlike the flat topped smooth giant low amplitude mounds or the linear low-amplitude mounds. Small normal fault fracture sets are present above the conical tops of high amplitude mounds.

![Figure 7: "2D mound mapping" methodology as proposed by Hansen et al., (2008) and employed by Magee et al., (2013), to decipher 3D geometry. Actual 3D geometry of mound shown, using 3D Ceduna survey. Shows the apparent degree of error and critical observations missed.](image)
Seismic Facies: HA mounds show a chaotic internal fabric in the central mounds. This is linked physically with intrusive sill complexes below, and tabular flow units at the mound base (strongly indicative of lava flows Figure 11; 3D Ceduna volcanic mounds). The facies of the high-amplitude mounds reported here similar to the SF1 reported by Magee et al., 2013, and is suggestive of an initial basaltic flow and/or episode of low viscosity volcanism, hence, we can consider HA mounds as volcanoes. This flow facies is often vertically stacked with flows emanating from the central conical vents. The central vents bodies are mostly lower-amplitude with a washed out transparent facies destitute of internal structure. This is likely a limitation of seismic data and the inability to resolve near vertical stratigraphy plus a degree of velocity pull-up.

Surrounding Stratigraphy: HA mounds are often located near to large shield volcanics and downlap relationships above, suggest they are the initial phase of volcanism with the larger giant mounds following deposition owing to observed downlaps onto the HA mound surfaces. The high amplitude nature of the mounds often leaves significant seismic noise below the central vents, however, on several seismic sections it can be interpreted that major faults exist directly underneath the central vent. This is deduced by regular fault spacing and deep 'fault tells' shown by offset reflectors. These offsets are approximately 5 seconds TWT below the mound surface. Unlike their giant low amplitude counterparts, the HA mounds do not show moats or bottom current features. They are onlapped by the cool-water carbonates and show little evidence of folding. The HA mounds do not appear to influence the overburden carbonate sequences.
Figure 8: Seismic cross sections (far and close) showing examples of high amplitude mound (HA) candidates. High amplitude mounds occur across the Bight Basin, and are often associated with major faulting below, sill complexes and tabular flows. High amplitude mounds are also in close proximity to giant mounds although do not share the same characteristics and based off seismic stratigraphic observations appear to pre-date the giant mounds.
6.7.2. Low Amplitude Mounds (LA)

The low amplitude of this mound group corresponds to both the external reflector and internal facies. These mounds are arguably the most interesting in the Bight Basin for their range of characteristics across carbonate, volcanic and sedimentary precipices. Here we suggest they are not carbonate (bryozoan) based, but are more likely to be a genetically linked phenomena to the volcanic system in the BBIC, with arguments existing for mixed volcani-clastic and hydrothermal compositions.

Setting & Grouping: The low amplitude mounds occur only within the margins of the Ceduna Sub-basin. Initially, their interpretation over 2D seismic data were classed as 'flows', however 3D geometries in the Ceduna show the low amplitude mounds to have mostly linear geometries; distinct from other BBIC mounds that correlate strongly to faulting presence (Figure 9). The low amplitude mounds tend to form away from high amplitude or giant mounds and are not associated with shallow igneous intrusions. As documented by Jackson (2012) and Magee et al., (2013), small, conical, smooth "vents" are present and sometimes directly above a fault or apparent conduit. Here, we group these into the "low amplitude" category alongside their much larger, linear and possibly genetically larger counterparts.

Characteristics & Geometry: The low amplitude mounds have mostly linear features, are largely asymmetrically, (with respect to the length dimension) and are ridge-like along their axis where fully resolved in 3D data. Notably the mounds appear to be steep sided on one flank and less so on the other (Figure 11, 3D Ceduna; large linear mound). A variety of sizes have been observed, from small 'vent-like' candidates in the order of hundreds of meters wide and tens of meters thick all the way to giant ridge-like candidates, tens of kilometres long, 3–4 km wide and up to 300 m thick.

Seismic Facies: LA mounds are named for their significantly lower amplitude compared to all other mounded features in the project area, with the exception of B2 bryozoan reef mounds. Their velocity is assumed to be similar to that of the overlying cool-water carbonate (2215 m/s), however unlike the giant low amplitude mounds (interpreted shield volcanoes Schofield and Totterdell, 2008; Magee et al., 2013) there is a pristine, well imaged, and preserved prograding internal fabric. The progradation is not just on upper portions of the mound (as can be seen on GLA mounds) but is pertinent throughout the entire mound. It is this prograding facies and
accretion which drives the mound growth into the steep sided and linear ridge-like trends in the larger candidates. In smaller LA candidates (i.e. interpreted 'vents') the prograding facies is not always present but appears more aggradational (see Magee et al., 2013; Figure 8B)

Surrounding Stratigraphy: The LA mounds show a variety of interactions and no persistent geological setting. LA mounds in the 3D Ceduna survey show 3 candidates with growth parallel to the strike major faulting, (SENW) and 3 other candidates perpendicular to the strike of major faulting. The largest of the LA mounds are persistently genetically linked to major faulting. This is confusing and difficult to relate geologically. This may be a product of 2D 'mirage' as exemplified by Figure 7 where trends vs. underlying structure cannot be well resolved. Small isolated mounds (not connected by adjacent seismic lines) do not always appear to be linked to faulting, albeit it may not be shown in that particular seismic section. The vast majority of LA mounds do not appear to be linked to shallow intrusive sills, this is especially true further northwest over the 3D Ceduna coverage. However, candidates for deep sills (up to 4 S TWT) have been observed juxtaposed against major fault planes within close correlation to the LA mounds.
Figure 9: Seismic cross sections (far and near) demonstrating low amplitude mound (LA) candidates. Top left shows LA mound in close proximity to HA mound with clearly distinct geometry and no physical connection within that seismic line. Top right shows the close section with well-defined internal prograding facies. Bottom left and bottom right show isolated low amplitude mounds without any major faulting or igneous complexes in section or adjacent. The same internal facies persists across all LA mounds in the area.
6.7.3. Giant Low Amplitude Mounds (GLA)

Giant mounds have been interpreted as shield volcanoes (Schofield and Totterdell, 2008; Magee et al., 2013) and can without doubt be linked to shallow intrusive sills (Jackson, 2012; Magee et al., 2013) which clearly exploit the major fault network as discussed by Jackson (2012).

Setting and Grouping: The giant mounds commonly occur in close proximity to high amplitude mounds and on occasion share the high amplitude mound facies on their flanks. They are the largest type of mound seen in the GAB with volumes on the order of 0.06 to 57.21 km$^3$ (Magee et al., 2013) based from 2D seismic mapping, but again drawing attention to Figure 7, these volume will have large associated errors. Grouping the GLA mounds and linkage between seismic lines is no meagre task. Magee et al., (2013), reported in total 48 "group 1" mounds, (HA and GA mounds mostly here) and also stated the expectancy of more. On the contrary, until closer line spacing or 3D data can fully resolve mound geometry (Fig 7) there could also be less. This is also applicable to the grouping used here.

Characteristics & Geometry: The size and dimensions of the GLA mounds is the most defining factor separating them from other mounded features in the area. Flank angles average approximately 13° and the 2D seismic line mapping suggest a sub-circular mound outline with basal diameters of 2-19 km and central core thicknesses of up to 300 m (assuming 2215 m/s velocity). GLA mounds range from flat-top to smooth cones, and are roughly symmetrical in cross section. Most GLA mounds show parasitic vent-like structures and secondary phases of mound growth.

Seismic Facies: The GLA mounds are acoustically hard events sharing the same kick as the seafloor. Particular sections of the flanks and the outer-most reflectors change to soft events; possibly owing to a genuine change in velocity, or poorly resolved seismic data on steeply inclined beds. The internal fabric of the GLA mounds is mostly low-medium amplitude, and several examples show well defined stacked, flow-like reflectors with significant internal boundaries dividing the entire structure into 'sets'. Beneath the central cones or cores, a velocity pull-up effect is persistent and has been calculated to represent an interval velocity of approximately 3000 m/s (Jackson, 2012). In Magee et al., (2013), the internal velocity ranged between 2365–6739 m/s, with an average of 4000 m/s assumed to calculate cone height. Our
suggestion is much lower owing to the separation and categorization of HA mounds vs. GLA mounds; the crux of the argument being, amplitude correlates greater acoustic impedance contrast, and therefore velocity changes, ergo; the most important seismic facies characteristic to differentiate mound types. It is then no coincidence other important factors i.e. internal structure, geometry, trends etc are also distinct between HA, LA and GLA mounds. GLA mounds show evidence for horizontal oblique progradation in the upper sections of their cores and geometries not dissimilar from hyaloclastite mounds documented at the western Indian margin (Calves et al., 2011)

Surrounding Stratigraphy: Similar to the HA mounds the GLA mounds are also often found above major fault trends. Juxtaposed against the some of the faults are deep, high amplitude, low frequency reflectors; likely igneous sills. More often however, the GLA mounds are genetically linked to shallow intrusive igneous sill complexes. This is not always true, however, Jackson (2012) showed a general correlation between shallow saucer shaped sill complexes and mounded geobodies. Where the majority of sills are located, so are GLA mounds. The GLA mounds appear to have stacked or mono-layered tabular flow units sometimes located on their flanks. The overlying cool-water carbonate sequences of Oligocene (Wilson Bluff Fm) appear to show onlap and curvature towards the base of the mounds suggesting either syn-deposition or more likely differential compaction. Interestingly, where the early Miocene cool-water carbonate sequences meet the GLA mounds there are regularly moat-like features i.e. depressions against the mound flanks.
Figure 10: Seismic cross sections (far and near) demonstrating giant low amplitude mounds (GLA) candidates. Top left shows the interaction of the giant mound with nearby intrusive sills and dykes as well as tabular flows. Clearly demonstrated is the flat topped and smooth surface of the mound - strikingly different from HA and LA mounds. Top right highlights the internal oblique prograding fabric in which 2 visible "sets" are present. Bottom left and bottom right highlight a large giant mound which falls into the shield volcano interpretation categories as in Schofield and Totterdell, 2008 and Magee et al., 2013.
6.7.4. 3D Ceduna Mounds

The 3D Ceduna survey was undertaken in 2011 with initial processed swaths available by 2012 for interpretation by British Major Oil Company BP. BP and partner StatoilHydro own all rights to the 3D Ceduna survey and it is classed as confidential. Hence, we are limited to only two seismic sections showing the different mound styles. The first author partook in two in-house internships with BP with access to the 3D Ceduna where study and interpretation of mounded features was undertaken. In total, eight individual mound candidates are interpreted. Of which one classifies as a volcanic mound, and the other seven as LA mounds; each has their own set of detailed observations and characteristics. No mounds have been calibrated physically and are considered geohazards, hence, future sampling is unlikely. The 3D Ceduna survey allows for a more educated interpretation of mound growth, volcanism, structural control and overlying sequences than ever previously documented. For the purposes of mound grouping in this study and 3D Ceduna confidentiality, we discuss only two of the eight mounds discovered, which we deem key examples to illustrate mound types throughout the area.

3D Ceduna: Mound 1#: “Volcanic Mound”

The extreme conical, high amplitude, elevated above the present day seafloor drape, steeply inclined geometries of these two mounds, coupled with the well-developed basinward gravity-driven high amplitude tabular flows (seen on 3D amplitude extractions (for thesis version of this paper see Chapter 3 Appendix; Figures 1, 2, 3 Mounds #1–8)) make for a confident interpretation of these mounds as volcanoes. There are no other reasonable candidates or explanations. Unlike their flat-topped counterparts documented in 2D to the east these are not shield volcanoes, and their high amplitude sharp conical tops, linking to underlying sills and tabular flows provide further confidence to group other similar HA mounds into a separate category (Figure 11). The volcanoes are approximately 5 km width by 10 km length with maximum peak heights of approximately 500 m (estimated velocity 5550 m/s, according to Hansen and Cartwright, 2007).

Both peaks are onlapped and exist at seabed as the most significant high amplitude features in the entire 3D survey. Figure 11 shows both volcanic bodies are host to smaller
parasitic cones mid way down the flanks in the order of 50 m thick (from top of volcano surface). Between the two vents, 400 ms deeper, a large, winged sill is observed and appears to genetically connect the two cones. The tabular flows associated with the volcanoes are often stacked and terminate sharply without apparent erosion. Their high amplitude from the soft overburden suggests velocities representative of pure igneous lithologies of which basalt is the most fitting for the geological setting. It fits well with nearby dredge survey results (Clarke and Alley, 1993). Internal cone structure is beyond seismic resolve; probably due to an exceptionally high internal velocity. A significant amount of pull-up is present under the volcanoes and as outlined in the methodology by Jackson (2013) would suggest velocities on the order of 5000 ms/6000 ms which is concordant with basalt. Interestingly, there appears to be no major faulting in direct conjunction with the emplacement of these volcanoes. Such faulting would not be missed laterally around the volcanoes by the 3D Ceduna survey. Other interesting features observed in nearby proximity are deep sinuous channels (also in the same propagation direction as the lava flows) and a large scallop-shaped mass transport complex which was sided by another large linear LA mound. However, for the purposes of this study and within the constraints of data confidentiality these will not be analysed here.

3D Ceduna Mounds #2: “Large Linear Low Amplitude”

The large linear LA mound has been chosen as the key representation of LA mounds based on its identical seismic facies and geometrical character. The LLLA mound is linear overall but appears to form a dog-leg trending both in the down-dip basinward SW direction as well as fault-strike and margin parallel NWSE. The latter is only observed along 2D lines and is not covered by 3D data (Figure 7). This trend and geometry is not akin to any other mound category; B1, B2 reef mounds; HA mounds; GLA mounds or the 3D Ceduna Volcanoes. The large linear mound is representative of several other LA mounds in the 3D Ceduna and fits well with interpreted LA mounds seen in 2D sections over the BBIC. The mound is located above several major fault planes and its basal surface is regularly offset in mini-depressions. The top surface is undulating in cross-section, yet, in 3D dimensional geometry is actually ridge-like. The ridge is steeper on the SE flank and more gentle on the NW flank even though overall the mound geometry is lineated basinward. This raises questions regarding gravity-driven propagation of mound growth vs. lateral accretion. Internally the mound structure is distinctly progradational.
There are no observed shallow sills at least within the 3D component of the mound, although the possibility remains of shallow sills between 2D line spacing. One candidate exists for a deep sill (high amplitude fault-offset feature) some 5 seconds (TWT) beneath the mound on an adjacent 2D seismic line, however the physical connectivity of the fault and the mound is unknown. There are no tabular flows associated with the mound, and more significantly there are no high amplitude features associated with this mound. Hence, owing to the combination of geometrical trend, seismic facies and 3D structure; this mound is the ideal candidate for why the LA mounds have been categorized separately.
Figure 11: Seismic sections and accompanying TWT structure maps of two key mounds discovered within the 3D Ceduna. Top left shows shallow seismic section intersecting two well defined volcanoes, the obvious peak of one on the right, the magma-flow flank on the left. Note the similarity between these features and HA mounds with clear-cut differences between LA mounds and GLA mounds. Top right shows the true 3-Dimensional structure in TWT of the two volcanoes with associated tabular high amplitude flows basinward. Bottom left shows shallow seismic section through a large linear LA mound and its pristine preserved internal structure. Bottom right shows the true 3-Dimensional structure map in TWT of the large linear mound and the inclined steeper eastern flank compared to the shallowly dipping and wider western flank. This mound continues beyond the 3D data coverage and changes azimuth as interpreted by 2D seismic line mapping (see Figure 7).
6.8. Discussion

Mound Interpretation:

The large coverage of 2D seismic data gives a substantial degree of confidence that the purported mounds represent the major of potential styles within the project area. Naturally, we expect there to be many new mounded features between 2D seismic coverage, as we also expect there to be extensions of already defined mounds. Documentation of the bryozoan reef mounds at the 43 Ma mark (Sharples et al., 2014) coupled with the introduction of the 3D Ceduna mega survey gives new and improved understanding of volcanic mound styles in the BBIC. The extensive mapping of mounded features allowed for a well-founded set of observations to compare and contrast mound types. Figure 7 highlights the extent of how much 3D geometry can be missed with 2D contouring techniques, and why seismic facies should be utilized equally if not decisively in defining mound groups, as opposed to geometry and structural observations.

Mound Grouping:

The Bryozoan reef mounds are well documented by Sharples et al, 2014 and fall into a category of their own, based on their linearity, sampling and systematic elongation along strike. Evidence across 2D and 3D seismic datasets has shown that volcanic mounds across the GAB fall into distinct categories based on seismic facies (mostly amplitude) alone. After being grouped principally using seismic facies, mound groups are given further confidence owing to correlation of structural/geometrical observations (Figure 12). Giant Low Amplitude mounds show flat-topped or smooth geometries and similar dimensions. High Amplitude mounds show rugose, sharp and conical geometries with similar dimensions and are almost always associated with tabular flow units. Low Amplitude mounds show linear geometries with progradational internal accretion and appear to be fault controlled without presence of igneous intrusives.

A variety of isolated mounds exist and the grouping system is most effective in such examples. Complications in grouping mounds correctly only arise where mounds are in close proximity to each other. The GLA mounds are not covered by 3D seismic and details of their true morphologies and integration with other mounds are still uncertain. Seismic sections show HA mound facies associated with the lower sections of the GLA mounds. The observation that both mound types share sometimes share the same underlying sills and a genetic link suggests
they are part of the same overall igneous mound forming process, albeit at different phases. Magee et al., 2013; interpreted mixed seismic facies within a single mound group, which we agree with but feel a more complex group breakdown can be made owing to isolated mounds with distinct properties and characteristics.

Mound Synthesis:

Based on the observation that the HA mounds are sometimes associated with the lower flanks and basal reflections of the GLA mounds, we infer the GLA mounds to be younger. Given the difference in seismic expression, internal facies and geometry, we also interpret them to be of a different composition. Internal seismic velocity can be estimated through the mounds by back-calculating the pull-up effect and reached calculations of ~3500 m/s concordant with mixed volcani-clastic material (Jackson, 2012). We agree with this conclusion given the 3D Ceduna clearly highlights the very different nature (with a significantly larger pull-up) of what we interpret as a basaltic volcanic mound. We also agree with the interpretation of Magee et al., 2013 that the mounds are consistent with shield volcanoes, however, our observations suggest more of an emphasis on the hyaloclastite mode of formation owing to the flat-tops and prograding flanks.

The most confident of our mound groupings are the larger LA mounds. They are very well imaged in the 3D Ceduna volume and stand out from all other mounds with a distinct seismic facies, internal structure and morphometric profile. This suggests a different control mechanism on growth and formation. There is no clear-cut evidence of interaction with HA mounds, but based on the similarity to GLA mounds we assume that the LA mounds are also younger than the initial episode of volcanism which created the HA mounds. The nutrient supply regime of the bryozoan mounds will remain speculative until further mound sampling has been undertaken. Recent reports from the NE pacific suggest volcanic ash and eruptions linked with surface ocean fertilization (Langman et al., 2010). Given the timing and layout of the bryozoan reefs in comparison to the BBIC it is possible that there could have been a contribution to nutrient supply and growth of bryozoan reef mound complexes derived from growth and presence of nearby volcanics. Note that, this is not to suggest that bryozoans are directly dependent on nutrients released by volcanics but that a more nutritious ocean would lead to increased levels of phytoplankton which would in-turn would lead to increased growth of
bryozoan colonies. The coincidental timing of volcanics and bryozoans may explain why BRMs grew and perpetuated to such great heights and were not abundant again until ~2 Ma, albeit on a much smaller scale and coupled with sediment waves (Huuse and Feary, 2005; Anderskov et al., 2011).

Timing and origin:

Magmatism in the Bight correlates with doubling of seafloor spreading rates (Tikku and Cande, 1999) and a set of global tectonic events (Veevers, 2000; Teasdale et al., 2003). Onset of bryozoan reef mounds also correlates with these same events and raises questions regarding the interplay of all mound types. This time has been referred to as “the 43 Ma event” (Li et al., 2003), and is an amalgamation of global tectonic events (Veevers, 2000; Teasdale et al., 2003). Sharples et al., 2014 linked the growth of formation of the bryozoan reef mound complexes to sea-level rise, owing to seafloor spreading and basin subsidence outpacing the falling global sea-level at the time, the back-tilting of Australia to the then north-east (DiCaprio et al., 2009) (contributing to the final shutoff of siliciclastic supply in the GAB providing optimal condition for bryozoan mound growth. Schofield and Totterdell, 2008, outlined the potential causes for mantle-derived igneous activity including mantle decompression, fluxing and anomalous temperatures.
Figure 12: Palaeogeographic map with interpreted mound locations drawn onto map at the ~43 Ma mark. TWT (white) maximum thicknesses representative of each mound.
Bryozoan reef mounds have been dated as ~43 Ma and are backed by biostratigraphic
dating of foraminifera found throughout the reef interval. Volcanics have been dated mid-
Eocene based on their formation alongside the basal surface of the Dugong Supersequence
and apparent emplacement above the distal section of the Wobbegong Supersequence
(Schofield and Totterdell, 2008). The majority of the basal Dugong units drape the extrusive
mounds and forced folds from the nearby sills. Above some of the LA mounds in the 3D
Ceduna, early oligocene (interpreted and correlated from stratigraphic framework, calibrated
from ODP Leg 182 boreholes) carbonate sequences can be seen onlapping the mounds,
suggesting mound growth may have been active up until the late Eocene/earliest Oligocene.

The timing of the mounds lays the foundations for the environment of deposition.
The Wobbegong and Dugong Supersequences are both marine based sequences and the
Dugong further landward shows initial sequences sampled and interpreted as a deep water
carbonate apron. The onlapping of this early sequence coupled with the presence of
interpreted “moats” or negative depression, around the basal circumference of some mounds,
defines them as submarine. We suggest a submarine environment is accountable for such
well-preserved mound structure negating wave or tide erosion. Ocean bottom currents
forming the scours were not of sufficient strength to erode the mounds entirely, (only the
sediment at the bases). Such interpretations are synonymous with those of Jackson, 2012.
HA, LA and GLA mounds appear to have been fed and sourced by relatively small intrusions
which exploited the pre-existing fault and fracture network. This would also account for why
mounds have not been subject to magma withdrawal and collapse.

Interpreted model:

Figures 12 and 13 shows that the grouping of the GAB mounds fall into trends.
Bryozoan reef mounds are clearly separate and follow the palaeoshelf edge, parallel to the
margin. GLA mounds are mostly clustered and located in the eastern BBIC, around which are
located HA mounds in close proximity. LA mounds however, appear to form away from
GLA, HA or bryozoan reef mounds and follow linear trends in association more with
structural faulting and fracture patterns. We propose that following the cessation of paleocene
sedimentation (Wobbegong Supersequence) into the GAB, magmatism was introduced (the
exact reasons why are still unclear) and the initiation of volcanic extrusives begin. Most
extrusive mounds are linked to shallow intrusive features, but not all. All intrusive and
extrusive features are linked however, to the pre-existing faulting and fracture network
(Figure 13). Note, not all faults could be interpreted owing to seismic noise below mound complexes, however, given the large frequency of Mulgara growth faults and overall NWSE trending strike of all faults in the area, their regular spacing and offsets, it is safe to assume such fault systems underlie the volcanic extrusive mounds. We suggest an initial phase of intrusive emplacement (responsible for forced folding) was active at least until mid-Eocene. Eruption and formation of extrusive features followed and the first sub-phase of which was the formation of HA mounds and what can be considered “true” volcanics with steep, conical peaks and sinuous lava flows in the down-dip direction.

We suggest this was followed by growth and formation of the GLA and LA mounds, both being driven by the underlying intrusions. The GLA mound which is associated with the highest concentration of intrusive features, the LA mounds which must also be volcanogenic, but are not dominated or genetically linked to the same shallow intrusive features. The measured effect of the presence of extrusive volcanogenic mounds into the AAG cannot be determined; however growth of the giant bryozoan reef mounds with the growth of LA and GLA mounds appears penecontemporaneous. By the earliest Oligocene the final onlaps of the Dugong Supersequence deep water carbonate apron onlapped both B1 and B2 bryozoan reef mound complexes and entire mid-Eocene mounded succession in the GAB was buried. Mantle stabilization and equilibrium following seafloor spreading rate increases must have been reached and hence so had volcanogenic mounds growth.
Figure 13: Map to show underlying fault systems with overlying mounds. Mulgara fault system consists of listric growth faults which propagate up to (mostly) the mid-Eocene base mound surface. Other faults represent basement faults are not associated directly with mound growth but shown for discussion.
6.9. Summary

Existing mounded features previously interpreted have been re-interpreted using a more extensive database with 3D seismic reflection data shedding new light where 2D seismic lines left ambiguity. Several new mounds have been discovered and all mounds in the area have been grouped into new categories based on seismic facies and geometry observations. Volcanic mounds have been confirmed to be linked to intrusive sill complexes, however the new group of low amplitude mounds have been reallocated as fault controlled, not intrusion controlled. Inter-mound genetic relationships have been interpreted on the basis of observed seismic stratigraphic reflector geometries. HA mounds appear to represent an initial episode and original mounded features into the GAB. Following this (downlapping) GLA mounds and LA mounds form with vastly differing seismic facies and geometries. GLA mound appear to be in close correlation with the presence of intrusive igneous sills. LA mounds do not, although appear heavily fault controlled. It is speculated that the volcanic system powering HA, GLA and LA mounds is the same but with episodic and diminishing pulses with later on included a mixture of volcanic-clastic material.

The volcanic episode appears to form in association with doubled seafloor spreading rates and mantle upwelling owing to the coincidental timing. Such tectonic processes also contributed to the palaeoenvironmental shift at the ~43 Ma mark and to origin and placement of giant bryozoan reef mounds. It is speculated that the volcanic input into the closed Australo-Antarctic Gulf may have contributed to ocean fertilization and leading to the giant proportions of the bryozoan reef mound complexes. Despite a lack of sedimentation into the GAB at the 43 Ma mark, the explosion of enigmatic mounded features, their analysis, interplay, origin and timings can be used to reconstruction palaeoenvironments and categorize differences between volcanic and carbonate mounds.

6.10. Acknowledgements

We thank BP exploration Australia for providing access to the 3D Ceduna survey over the course of two internships. We thanks Geoscience Australia for providing access to the 2D seismic database and exploration well reports. We thank ODP Leg 182 and the Galathea-3 Danish expedition for access to the 2D high resolution seismic data over the Eyre Sub-basin.
6.11. References


Norvick, M. S., Smith, M. A., 2001, Mapping the plate tectonic reconstruction of southern and southeastern Australia and implications for petroleum systems, APPEA Journal, v. 15, p 15–34


CHAPTER 7: SYNTHESIS AND DISCUSSION

7.1. Introduction

Understanding the relationship between sediment deposition, tectonics, unconformable hiatuses, palaeoenvironmental change and the growth and origin of associated mounded features plays a key role in the evolution of sedimentary basins worldwide. More so, the exploration of new areas with 2D and 3D seismic reflection data and methods and techniques provides critical insight when testing geological models from a chronostratigraphic and laterally extension perspective. Here, we used sequence results from an multidisciplinary integrated borehole and 2D seismic reflection study (ODP Leg 182) and extended it across a linked and further extensive database of 2D and 3D seismic reflection lines. Seismic stratigraphic interpretation and methodology provided observational evidence of new sequences and a variety of palaeoenvironmental indicators such as MTC complexes, igneous intrusions and extrusions, bryozoan reef mounds and sediment waves. Results yielded new interpretations and discoveries which gave new perspective on geological evolution in the GAB but also linked regional events to the global scale events/changes. This chapter presents a synthesis of results from previous chapters and how they compile to not only shed new light on the local areas geological evolution but also how they were limited and to be refined further beyond the scope of this Ph.D.

7.2. Aims

The extensive suite of 2D and 3D seismic data across the western GAB was used in its entirety to map and observe each defined sequence from the Leg 182 ODP over the Eyre Sub-basin. This aim was two-fold, either to produce an equally detailed sequence framework across the entire dataset or the latter and also discover and introduce new sequences and eliminate others by testing lateral extent. Sequences bound within frameworks reflect large scale depositional trends and interplay of geological processes that are so often responsible for the formation of anomalous geological features. Such frameworks if based on observational and clear data importantly provide a foundation for the introduction of higher resolution data and integrated studies at later dates. Owing to the planar and often “calmly” stacked nature of cool-water carbonates, special attention was given to document geological features within sequences in hope of gathering critical information, which is not otherwise obvious.
Bryozoan reef mounds are prevalent throughout much of the shelf and palaeoshelf of
the CWC Cenozoic GAB but in no place are they larger, more regular and arguably more
important to palaeoenvironmental interpretation than at the mid-Eocene palaeoshelf-break.
The aim was to document BRMs in meticulous detailed regarding their morphology and
dimensions, lateral extent across the GAB and superposition above the Wobbegong
Superequence and constrain their timing and origin relative to the tectonic sequence
framework.

Further mound-mapping across the entire dataset was undertaken to expand upon and
detail the BRM documentation. The aim was to group and categorize all mounds as a
manifestation of their seismic facies, morphometric geometry, dimensions and connectivity.
Mound growth and emplacement could then be linked to tectonic sequences and surfaces to
detail the geological evolution of the GAB and palaeoenvironment at the ~43 ma mark.
Given the anomalous nature of mounds in seismic cross-section it was to be tested if the
comparison of mounds local to the GAB could be used as a case study for mounds elsewhere.

Sequence stratigraphic mapping and modeling of the Wobbegong Supersequence was
undertaken with the aim to further increase the resolution of understanding on this entire
supersequence of uniformity throughout the Cenozoic succession. Also, in an attempt to
understand the systematic emplacement of BRMs above the delta sequence and the major
palaeoenvironmental shift that occurred in conjunction with global and regional tectonics to
der end major SC input into the GAB at the ~43 ma mark.

7.3. Results

Detailed mapping and extension of Leg 182 sequences in the Cenozoic CWC section
over the Eyre Sub-basin resulted in the interpretation of a regionally applicable revised
sequence stratigraphic framework. Three new sequences were interpreted in the basinal
sections of the Ceduna Sub-basin and the truncation or pinch-out of four of the seven Leg 182
sequences beyond the deep-water (> 1km water depth) mark. An array of new features
including mass transport debris aprons (stacked), growth-fault gravity based erosion lobes,
semi-polygons faulting, seafloor canyoning, ocean bottom-current sediment waves and
erosional margin parallel present-day seafloor erosion (and contourite production) have been
discovered.
BRM although only accounting for a comparatively small succession yielded interesting results applicable to global geology. BRM were mapped into two complexes (B1 and B2) each with a set of individual characteristics but always persisting to the same trend. The trend was bound that of the underlying SC Wobbegong delta sequence although it was found that the exact positioning of the BRM differed between lobes D1 and D2 to lobe D3. Reef mounds were up to 200 m thick, 10 km wide and tracked over 500 km parallel to the margin. Results of cutting sample identification yielded several cheilostome and cyclostome bryozoan components, possibly some of which have not been identified before. The BRM were found to be the corresponding geological product of a series of tectonic changes in the GAB at ~43 Ma including siliciclastic shut-off in combination with 1.) Tectonic back-tilting of the Australian continent to the northeast and reorganization of drainage networks. 2. A large marine transgression in association with doubling of seafloor spreading rates and basin subsidence 3.) CWC production and flourishing of BRMs owing to the initiation of final separation of Australia and Antarctica and global climatic change.

Extrapolation of the BRM mapping to all mounds in the GAB provided a significant expansion of mound observations, moving the study into the volcanic realm. Three new mound types were interpreted all of which reflected either true volcanism or volcano-sedimentary lithologies. Two of these were observed in the 3D Ceduna seismic survey at very high resolution. The first was a mound categorized as pure volcanic lithology (likely basaltic based on nearby dredge results) associated with tabular flow units, steep angular conical geometries and heights of up to 500 ms TWT. Giant mounds interpreted as volcani-clastic composition were also mapped and grouped separately. They are noticeably lower amplitude, flat topped and smoother in comparison to all other mounds in the area forming local highs of up to 500 ms TWT but with significantly greater volumes. They are interpreted as shield volcanoes but also exhibit hyaloclastite architectures on upper flanks indicative of lateral progradation in line palaeosea-level.

Both of these mounds are genetically linked to a series of intrusive igneous sills. Finally, a new style of mound was interpreted similar in seismic amplitude to the giant mounds but with a constructing linear and fault-controlled geometry and structurally bias progradational internal structure. These low amplitude mounds are the most mysterious and share components suggestive of volcanic, sedimentary and hydrothermal origins. Compilation of mound origin and placement suggests a genetic link between mounds, igneous intrusions and control of the pre-existing fault and fracture network. Their timing at
the ~43 Ma mark also puts forward the potential for a link between volcanic ocean fertilization and BRM growth.

Sequence stratigraphic modeling and sequential break-down of the Wobbegong Supersequence allowed significant extraction of delta growth and deposition concepts on a margin-wide basis. Several key differences including thickness, slope gradient, water depth and system tracts (based on stacking patterns) were interpreted between Wobbegong delta lobes. Lobe boundaries have been confirmed as outlined in the BRM study owing to difference in delta architecture. Two northern lobes mostly located over the Eyre and Eucla basin show significantly thicker deposition (up to 500 m) and steeper clinoform slope angles of up to 8 degrees. The D1 and D2 are geometrically lobate and likely sourced from the North. Delta structure is predominantly lowstand with very limited transgressive tracts. The D3 lobe is significantly thinner and reflects an entirely different style of deposition as an effect of basal platform structure and likely sediment supply. The deltas appear mostly coeval within the resolution of the dataset.

7.4. Limitations

Mostly, limitations in each of the study topics fall into the category of data or time. As extensive an area as the 2D seismic array covers, the average spacing of the lines is of the order 10–20 km. This was with exception to the 2D Flinders which had an average of 5 km spacing between seismic lines. Overall, the quality and resolution of the 2D data was sufficient for the mapping of sequences however suffered towards the shelf with no removal of heavily obstructive seafloor multiples. The spacing of the 2D seismic grid is apt to show 2D mound geometries in cross-section and their general geographic location, however, when overlapped with 3D data it is noted that 2D seismic grid spacing is not sufficient to purport and reconstruct 3D geometries missing important details of scientific value.

Where the 3D Trim volume was available, the resolution of the data was relatively poor and poor processing hindered seismic quality. The 3D Ceduna volume was excellently processed and covered a large area. The downfall of this was the entire volume came to 3.5 terra bytes of data and had to be cropped, converted to 16-bit and halved in its inline/ xline spacing. Only an approximate time of 4 months was given to interpret the 3D volume in-house at BP. The tectonic sequences evaluation was made especially challenging and difficult by a set of large seafloor and palaeo-canyon systems characterized by their
truncation and incision as far as mid-Eocene strata. Above the Eyre Sub-basin steep gradients following the palaeo-shelf resulted in localized unit debris flow (interpreted on basis of chaotic internal structure) and the confidence of sequence boundaries is less in this area.

All chapter studies suffered from the lack of well/borehole data and lithostratigraphic data. More so, dating methods relied solely on seismic stratigraphic observation which is limited directly by the resolution of the data and cannot be cross-referenced. Although well documented and forming strong correlation between various geometries and seismic facies, mound grouping is limited by lack of sampling. Even in the BRMs the bryozoan fragments are incomplete representations of poorly documented and understood bryozoans of that period and fail to add explanations to the series of large and important palaeoecological questions arising from the discovery of the BRMs. The same case is true for the volcanic mounds, with grouping based solely on seismic data and dredge results being out of situ. The lack of dating however, is perhaps most limiting to the sequence stratigraphy of the Wobbegong delta sequences. Sampling of even the uppermost topsets would provide a wealth of information towards the onset of events at the ~43 ma mark and effectively test the accommodation succession methodology based on seismic observations alone.

7.5. Compilation of results

The results of each section of work strongly compliment the overall Cenozoic evolution of the GAB, with a variety of interpreted features providing critical insight into the palaeoenvironment through the epoch. Prior to the results from the various chapters, very little was known about the unconformity that bounds SC from CWC domain in the GAB. 2D and 3D mapping of that surface has significantly enhanced this with a range of features documented to constrain palaeoenvironment and ecosystems in correlation with major geological events. Sediment waves visualized in 3D attribute sections (Chapter 3 Appendix; Figures 24, 25) show potential for palaeobathymetrical ocean bottom current indicators in the 3D Ceduna wedge sequence. Mapping of mounds shows a variety of volcanic inputs and interplay between intrusive sills, extrusive mounds, phases of magma eruption and exploitation of fault and fracture networks.

Detailed mapping of the fault network and sequence divisions allow for timing and constraints of fault timing, as well as fault associated erosional lobes and gouges suggesting gravity-driven fault movement was still in effect in the early Cenozoic. Sequence stratigraphy of the Wobbegong Supersequence shows cyclic repetitions between lowstand and highstand.
systems tracts in the thicker lobes, with significant marine flooding events represented as maximum flooding surfaces. Such transgressions may account for the sediment waves observed in the wedge sequence further basinward. More importantly, the final transgression appears to be major indicating a significant rise in relative sea-level and formation of the bryozoan mounds. The coincidental timing of the volcanic mounds in the system may link volcanism with ocean fertilization and explain the seemingly short-lived yet rapid growth of the BRMs perpetuating to such large proportions. The flat topped nature and interpreted hyaloclastic flanks of some volcanic mounds can possibly be used to initiate a relative palaeobathymetry estimate at that relative geological interval. Coupled with the sequence stratigraphic results and transgressions in the Wobbegong Supersequence the framework is set for a sea-level reconstruction in the GAB around this period. The onset of basin subsidence penecontemporaneous with doubling of seafloor spreading rates at ~43 Ma mark is likely no coincidence. More so coupled with the explosion of mounds in the GAB, the exact mechanics and geothermal gradients are beyond the scope of this study however, documentation of the mounds has shown how linkage of tectonic events to palaeoenvironment can be important and accomplished without actual sampling and emphasizes the potential for interpretation with seismic reflection data.

The 2D seismic dataset is extensive and allows the Cenozoic sequence framework to be extensively tracked from near shelf to deepwater basin margins. Most surfaces are constant, but importantly, packages of each sequence change significantly laterally. Where 1D studies fail to draw distinctions between chronologically separate units, lithological approaches inaccurately group major units together (i.e. biostratigraphy and grouping of Wobbegong Supersequence into the Bight Basin) seismic stratigraphic studies provide the important initial framework based on regionally correlative observations.

7.6. Suggested Further Work

The framework for the Cenozoic section of the GAB is now not only well defined but extensive across the western and central GAB. It is set for the integration of higher resolution data and more detailed investigation with the presently available data. With major exploration underway, it is likely further data acquisition will arrive in the near future. Ideally, this will include borehole and physical sampling, and logging suites for integration with seismic reflection data. Future ODP legs in the GAB are already under discussion with a date aiming
for 2017, albeit the scientific proposals are still being drafted. Significant work which could be undertaken with the present available data includes:

- A variety of features although found can be further investigated to benefit the overall understanding of the tectonostratigraphic framework and the palaeoenvironmental implications. With access to the 3D Ceduna survey, detailed 3D attribute extraction analysis along mapped surfaces from the base Mesozoic Hammerhead to the present day seafloor would further highlight geological features and compliment the overall understanding of the framework. In particular:

  - Quantitative and qualitative documentation of sediment waves should to understand and palaeobathymetry
  - Internal structure and time-slice mapping of mounds to understand growth rates
  - Volumetric calculations of hanging wall erosion lobes to better understand erosion rates and sedimentation rates.
  - The mid–late Miocene stacked MTC complex should be internally mapped to help understand and delineate flow patterns. Such data may help answer the fundamental question of the trigger.
  - Further work could be undertaken to constrain BRM mound intervals landward of the B2 sections. However, a degree of processing and seafloor multiple removals would be necessary prior to this.
  - Mapping and documentation of seafloor canyons and palaeocanyons east of the Eyre Sub-basin would significantly help tracking Leg 182 sequences across the margin. Furthermore, such documentation within the 3D Ceduna and in particular of the Nullabor canyon may suggest causes for mass transport trigger mechanisms applicable to the MTC sequence and other MTCs around the database. Further sequence stratigraphic studies within the Wobbegong and 3D modeling in such software as OpenDtech may provide enough detail for the reconstruction of a local GAB sea-level curve.
  - Sequences of lower confidence include: The Pleistocene base where it intersects Potoroo-1 and just basinward above the Ceduna Terrace. Here, it is observed that large seafloor margin parallel mass wasting is in effect. The product of which appear to be a set of contourites left over in the truncation of the Pleistocene. Further...
investigation will aid the sequence framework and improve understanding of present
day/modern geological interactions in the GAB.

- With regards to the Wobbegong Supersequence, internal seismic facies and lateral
  change along parasequences linked to lithological change can be integrated and
  further key-lines analysed. This would ideally provide a greater framework ready for
  lithological sampling integration in the future.

Australia’s Southern margin is under-explored on both an academic and industrial basis. Serious capital and real investment has only being focused heavily in the last two years. With commitment to 5 exploration wells and a 3D mega-survey BP and partner StatoilHydro are due to drill in 2014/2015, and have already acquired targets. Oil giant Chevron has also invested into the GAB and attained license blocks to the east of BP. Potential for a new iODP project and the return of the JOIDES rig to the GAB has also been scheduled for 2017. With climate change one of the hottest topics in present day science much focus now shifts towards the GAB and the knowledge to be discovered. If further data was to be included:

- Well data is sparse and significantly lacking within the shallow section. Ideally to
  better constrain the major tectonic events logging and coring for dating purposes
  should be taken within a short interval to the H1a unconformity. Such information
  would significantly improve understanding of tectonics interplay and basin evolution;
  feed into deeper hydrocarbon understanding and quality-check the products of this
  thesis.

- Well data integration with seismic frameworks is the most important next step for
  GAB understanding. Dredge sampling and dating of the igneous mounds that
  penetrate the seafloor for the purpose of proof-checking interpretation

- Further sampling of BRM intervals along the mound flanks may provide significant
  information to answer outstanding palaeoecological questions and feedback into the
  global climate change debate at the mid-Eocene.

7.7. Conclusions

Where large scale global events are present, small scale regional events will also
occur and can be recorded as relatively small scale geographically limited features. This
thesis shows that even with a relatively thin sedimentary cover representing a large proportion of time, small and isolated features can be documented and analysed to provide a wealth of information that would not be otherwise apparent or obvious. Results shown here naturally fit with results and interpretations from pre-existing literature and over a variety of disciplines and scales without bias.

This thesis has taken the sequence framework provided by Leg 182 ODP and extended it across the GAB to meet the lateral extensity of studies by Totterdell et al., 2000 of the Mesozoic GAB framework to provide a much more detailed and fully developed regional framework and geological context. Results have already been utilized and applied, adding significant industry value with an important risking and geohazard decision based on the likelihood of encountering significant quantities of H₂S gas over the Ceduna Sub-basin. Extension of the Leg 182 sequences also meets the original requirement of the Leg 182 proposal – to further develop understanding of the CWCs. Structural mapping and attribute extractions have resulted in the discovery of several geological features within the CWCs which raise new questions such as MTC triggers, palaeocanyons system sources and submarine density flows and erosion lobes. Each features discovered here can go on to be analysed in further detail to build an extensive profile of the CWCs in the GAB.

The most prolific features discovered are the mid-Eocene BRMs that record the initial transition from SC to CWC sedimentation in the GAB. The BRMs are the third installment of such features in the GAB, with the original interpretation made by James et al., 2000, which was then rejected and reinterpreted as sediment wave features by Anderskouv et al., 2010. Once again BRMs are back in the GAB but on a significantly larger scale and with a brand new model. Bryozoans still remain the most under-documented carbonate fauna with the main examples until now being Danian mounds in the Danish Basin (Surlyk, 1997; Surlyk et al., 2006) and it is hoped the discovery ignites future interest with a proposal for a new ODP Leg to drill the mound flanks already made.

The central surface to the entire study is without question the H1a unconformity and transition between SC and CWC lithologies in the GAB. The unconformity has never been well represented and now has a visible structure across the GAB with some of the complexity unraveling owing to meticulous mapping within the 3D Ceduna. Until now, documentation and detail of the nature of the unconformity and its relationship to surrounding sequences has been vague or missing. BRM studies at the palaeoshelf edge have not only constrained the
hiatus but have linked several tectonic events on the global and regional scale complimenting large scale regional studies based on gravity and magnetics, structure, basin modeling, tectonic plate modeling and basin evolution (Veevers, 1987; Stagg et al., 1990; Veevers et al., 1991; Teasdale et al., 2003; McGowran et al., 2004; Norvick and Smith, 2005; Muller et al., 2008).

Lack of sampling never allowed in-depth palaeoecological questions to be answered, however the presence of the BRM raises new questions regarding the biosphere interplay, palaeoenvironment, nutrient supply, sea-level and palaeobathymetric in the AAG at the ~43 Ma mark. Mound mapping in the 3D Ceduna added new and beneficial information to previous volcanic studies in the GAB (Schofield and Totterdell, 2008; Jackson, 2012; Jackson et al; 2013; Magee et al., 2013) and complimented many existing observations while refining others and reconfirming the ever present global link between volcanic and carbonate provinces.

The thesis has taken the next step in a more complex and intricate hierarchical understanding of the Cenozoic GAB from which it is hoped further work will be undertaken and based upon.
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Mound #3: Twin Volcanoes

Mound #4: Large Linear

Mound #5: Small Linear

Mound #6: MTC Mound

Mound #7: Twin Mounds

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<td>Source</td>
<td>32 airguns</td>
<td>64 sleeve airguns</td>
<td>3 (6) GI airguns</td>
</tr>
<tr>
<td>Volume</td>
<td>1450 cu. in.</td>
<td>2180 cu. in.</td>
<td>450 (900) cu. in.</td>
</tr>
<tr>
<td>Shot Interval</td>
<td>25 m</td>
<td>25 m</td>
<td>12.5 (25) m</td>
</tr>
<tr>
<td>Sample Rate</td>
<td>4 ms</td>
<td>4 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>Record Length</td>
<td>6 sec</td>
<td>6 sec</td>
<td>3.5 (8.5) scs</td>
</tr>
<tr>
<td>Cable Length</td>
<td>2400 m</td>
<td>3000 m</td>
<td>1000 m</td>
</tr>
<tr>
<td>Cable Offset</td>
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<td>200 m</td>
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<tr>
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<td>240</td>
<td>80</td>
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<tr>
<td>Group Interval</td>
<td>50 m</td>
<td>12.5 m</td>
<td>12.5 (25) m</td>
</tr>
<tr>
<td>CDP Interval</td>
<td>25 m</td>
<td>6.25 m</td>
<td>6.25 (12.5) m</td>
</tr>
<tr>
<td>Fold Coverage</td>
<td>48</td>
<td>60</td>
<td>40 (20)</td>
</tr>
</tbody>
</table>

**Figure 1:** General Seismic Data Properties Table LEG 182

**Figure 2:** Amplitude spectrum chart from Galathea Expedition survey
Figure 3: Amplitude spectrum chart from Australian Geological Survey Organisation multichannel 2D seismic survey 1995

Figure 4: Amplitude spectrum chart from Japan National Oil Company 2D seismic lines 1990/1991
Figure 5: Amplitude spectrum chart from ESSO 2D seismic lines 1979

Figure 6: Amplitude spectrum chart from Woodside Flinders 2D seismic survey 2000/2001
Figure 7: 3D Trim Seismic Survey details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>No of streamers</td>
<td>10</td>
</tr>
<tr>
<td>Streamer length</td>
<td>4,595 m</td>
</tr>
<tr>
<td>Streamer depth</td>
<td>9 m</td>
</tr>
<tr>
<td>Number of source arrays</td>
<td>2</td>
</tr>
<tr>
<td>Source array total volume</td>
<td>0.051 m$^3$ (0.99 ft$^3$)</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>13,789 kPa (2,000 psi)</td>
</tr>
<tr>
<td>Source array depth</td>
<td>7 m</td>
</tr>
<tr>
<td>Shotpoint interval</td>
<td>25 m (~7.5 seconds)</td>
</tr>
<tr>
<td>Peak source sound pulse</td>
<td>220-240 dB re 1μPa·m</td>
</tr>
<tr>
<td>Frequency range</td>
<td>10 to 110 Hz</td>
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</table>

1.3 Key parameters
Source: 2 x 4130 in$^2$
Source depth: 7 m
Streamers: 12 X 8100 m
Streamer spacing: 120 m
Streamer depth: 9 m
Near trace offset: 245 m (see details on offset diagram sect 6.2)

1.4 Systems
Source type: Bolt LLXT 1900 guns
Streamer type: RDH-Solid
Recording system: PGS gAS system, NTRS
Navigation: SkyFix.XP Orbit & Clock Corrected GPS
            StarFix.HP High Performance DGPS
Float positioning: Seatrack RGPS
Acoustic ranging: DigiCOURSE DigiRANGE DRII

1.5 Production
<table>
<thead>
<tr>
<th></th>
<th>Sail line km</th>
<th>CDP km</th>
<th>Sq km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prime chargeable</td>
<td>16,725.98</td>
<td>400,984.00</td>
<td>12,029.52</td>
</tr>
<tr>
<td>Prime run out</td>
<td>538.65</td>
<td>12,903.30</td>
<td>387.10</td>
</tr>
<tr>
<td>Infill</td>
<td>2,317.45</td>
<td>54,188.52</td>
<td>1,625.66</td>
</tr>
<tr>
<td>Infill run out</td>
<td>56.70</td>
<td>1,360.80</td>
<td>40.82</td>
</tr>
<tr>
<td>Infill percentage (of preplot prime)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>19,638.78</td>
<td>469,436.62</td>
<td>14,083.10</td>
</tr>
</tbody>
</table>

Figure 8: 3D Ceduna Seismic Survey details
Figure 9: Screenshot from SMT Kingdom 8.6 showing converted and applied ASCII logs in ODP Leg 182 boreholes 1130 and 1132 and calibration of LEG 182 sequences to seismic sections. Digital logs not available for Potoroo-1.

Figure 10: ODP (Leg 182) transect map taken from Feary, 2000 ODP proposal report to Geoscience Australia
<table>
<thead>
<tr>
<th>Water depth (m)</th>
<th>Hole 113D</th>
<th>Hole 113E</th>
<th>Hole 114D</th>
<th>Hole 113F</th>
<th>Hole 113G</th>
<th>Hole 113H</th>
<th>Hole 113I</th>
<th>Hole 113J</th>
<th>Hole 113K</th>
<th>Hole 113L</th>
<th>Hole 113M</th>
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</thead>
<tbody>
<tr>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Depositional Environment**

- Shelf margin
- Upper slope
- Lower slope
- Outer shelf slope
- Upper foreslope
- Lower foreslope
- Upper slope break

**Principal Lithologies**

- Holocene, Eocene, Oligocene, Pleistocene, Pliocene, Miocene,
- Pliocene, Pleistocene, Oligocene, Eocene

<table>
<thead>
<tr>
<th>Tool strings</th>
<th>Hole 113D</th>
<th>Hole 113E</th>
<th>Hole 114D</th>
<th>Hole 113F</th>
<th>Hole 113G</th>
<th>Hole 113H</th>
<th>Hole 113I</th>
<th>Hole 113J</th>
<th>Hole 113K</th>
<th>Hole 113L</th>
<th>Hole 113M</th>
</tr>
</thead>
</table>

**Intervals Logged**

<table>
<thead>
<tr>
<th>Interval</th>
<th>Hole 113D</th>
<th>Hole 113E</th>
<th>Hole 114D</th>
<th>Hole 113F</th>
<th>Hole 113G</th>
<th>Hole 113H</th>
<th>Hole 113I</th>
<th>Hole 113J</th>
<th>Hole 113K</th>
<th>Hole 113L</th>
<th>Hole 113M</th>
</tr>
</thead>
</table>

**Figure 11: Leg 182 hole Summary (taken from 182 initial reports Summary, Figure 1)**
1.3 Key parameters

Source : 2 x 4130 in³
Source depth : 7 m
Streamers : 12 X 8100 m
Streamer spacing : 120 m
Streamer depth : 9 m
Near trace offset : 245 m (see details on offset diagram sect 6.2)

1.4 Systems

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Streamer type : RDH-Solid
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 : StarFix,HP High Performance DGPS
Float positioning : Seatrack RGPS
Acoustic ranging : DigiCOURSE DigiRANGE DRII

1.5 Production

<table>
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<td>1,360.80</td>
<td>40.82</td>
</tr>
<tr>
<td>Infill percentage</td>
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</tr>
<tr>
<td>(of preplot prime)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>19,638.78</td>
<td>469,436.62</td>
<td>14,083.10</td>
</tr>
</tbody>
</table>

---

Figure 12: 3D Ceduna Seismic table of key parameters:
Figure 13: Overlay used to extract Gamma Ray log at Potoroo-1 and calibrate Wobbegong Supersequence. Provided by Geoscience Australia
CHAPTER 3 SEQUENCE FRAMEWORK APPENDIX:

Figure 1: Picking extent of base Tertiary across the 2D seismic dataset

Sparse data masks continuity of D3 lobe making sequence stratigraphic studies challenging

Figure 2: Picking extent of base Wobbegong Supersequence across the 2D seismic dataset
Figure 3: Picking extent of top Wobbegong Supersequence across the 2D seismic dataset

Figure 4: Picking extent of interpreted sequence 6 (early Oligocene) across the 2D seismic dataset
Figure 5: Picking extent of base sequence 5 (early-mid Miocene) across the 2D seismic dataset

Figure 6: Picking extent of base sequence 4 (mid-late Miocene) across the 2D seismic dataset
Figure 7: Picking extent of base Sequence 3 (Pliocene) across the 2D seismic dataset

Figure 8: Picking extent of base Pleistocene across the 2D seismic dataset
Figure 9: Picking extent of seafloor across the 2D seismic dataset

Figure 10: extent of H1b base wedge pick in 3D Ceduna
Figure 11: Extent of H1a unconformity pick in 3D Ceduna – North swath picked entirely with autotrack and not shown here

Figure 12: Extent of H2 / Sequence 6a base pick in 3D Ceduna. Note patches of challenging geometry countered with finer interpretation gridding
Figure 13: Autotracking and picking extent of H3 / Sequence 3 base in 3D Ceduna. Interpretation grid is not shown owing to Petrel issue and conversion. Surface picked by Gayle Hough – BP.
Figure 14: extent of seafloor pick across 3D Ceduna. Note the relatively large interpretation grid spacing owing to strong continuity of seafloor reflector.
3D Ceduna amplitude extractions:

Each surface constructed has a high and low resolution version. High resolution surfaces were picked on a tight (10x10) gridding interval and then autotracked and quality checked. The surface was then gridded using convergent interpolation algorithm, 1 pre and post-processing smoothing function and a 10x10 gridding interval (incredibly detailed). These surfaces, although incredibly detailed significant slowed computer processing and visualisation. Hence, low resolution counterparts were also constructed, with a higher (5X pre and post-processing iterations) smoothing value and used for thickness mapping purposes.

Each high resolution surface (with exception to H1b and the southern swath of H1a owing to catastrophic autotracking attempts) was used for 3D seismic attributes extraction. Attributes included: Max Amplitude, Variance and RMS Amplitude. Each attribute was repeated using a different window above or below the surface. 10 ms, 20 ms, 40 ms, 50 ms and finally a window of interpreters choice reflecting geological knowledge and input. Dip and azimuth was also calculated along each surface in each swath and has been shown here as well as high resolution TWT structure maps. Owing to the large size of the surfaces, they can only be shown per individual 3D Ceduna swath (north, central and south). Colour scales do vary (shown) and have been chosen to best highlight specific features.

With some extras and test and shallow gas extraction windows in total approximately 200 surface attributes were extracted. Obviously, not all the work in the project can be shown here, but a selection of the “best” or most geologically significant/interesting have been chosen and annotated. These extractions ARE classed as confidential and not to be shown beyond this thesis without permission of BP. Confidentiality is also the principal reason why the geological features observed have not been written in a publication style chapter but bound to the appendix.

Please refer to Chapter 3; Figure 3 megasequence diagram to understand relative sequence positioning. These attribute extraction are quite spectacular and detailed and are best viewed on the electronic version of this appendix/or accompanying DVD, and will be visually limited in their paper printing resolution.

*Not all shown surfaces are continuous i.e. H1a TWT structure shown in north, but not central or south owing to artefacts or other issues, the following images are “best of”*
Figure 15: H1b: North (Wedge Sequence Base) – Variance: 0 ms.

The only significant set of faults in the north 3D swath

Unknown NS striation (subtle)

Tips of major fault visible in close contact to imprint of mound
Figure 16: H1b: Central (Wedge Sequence Base) – Variance: 0 ms.

Main listric growth faults of Mulgara fault family. Genetic minor faults within hanging walls.

Change in fault strike orientation to NEE-SWW.

Faint sediment wave patterns.
Figure 17: H1b: North (Wedge Sequence Base) – Max Amplitude: 50 ms above window

NS Lineation also present in amplitude extraction

Sediment waves
Note, positioning and size of sediment waves in lower wedge sequence compared to Figure 25 over the same area but with much larger waveforms.

Smaller sediment waves with (200-300 m wavelength), same NNE-SSW orientation

Surface truncation near hinge point and major faulting

Waveforms link-up through the faults and are not controlled by the faults
Figure 19: H1a: North (Wedge Sequence Top) – Two-way travel time of surface

Mound #2 (See Appendix Chapter 5)

Genuine sediment wave structure visualised better using lighting tool
Large horizontal artefact persistent throughout all attribute extractions as a result of processing issue and streamer line

Angular prograding internal fabric of mound #2 shown well with variance

Figure 20: H1a: North (Wedge Sequence Top) – Variance: 20 ms above & below window
Figure 21: H1a: Central (Wedge Sequence Top) – Variance: 0 ms window

- Surface artefact
- Nullarbor canyon erosion striations
- Erosion lobe structures
- Large, genuine erosional lobe structures, following the strike of fault planes
- Large Linear Mound #4
- Small Linear Mound #5
- Twin mounds #7
Figure 22: H1a: South (Wedge Sequence Top) – Variance: 40 ms above and below window

- Circular faulted structure
- Twin volcanoes (mound #3) and basalt flows
- Scallop-shaped MTC, associated with growth faulting and polarity reversals indicative of trapped gas
- Increase in frequency and arc of fault planes indicative of hinge zone prior to abyssal slope
- Polygonal faulting pattern
Figure 23: H1a: South (Wedge Sequence Top) – Variance: 100 ms below window

Increased growth faulting and polygonal faulting
Figure 24: H1a: North (Wedge Sequence Top) – Max Amplitude: 40 ms below window

E-W curved and mysterious lineation

Large sediment waves, 500 m wavelength, NE-SW orientation
The largest sediment waveforms, with 1 km wavelengths and length of up to 10 km. These are not visible on H1b extractions and lie above sets of smaller waveforms.

Miniature sediment waveforms - see DVD for zoomed in resolution.

Waveforms distorted, possibly owing to closely spaced faulting.
Figure 26: H1a: South (Wedge Sequence Top) – Max Amplitude: 50 ms above and below window

Circular structure with bounding faults landward. Possibly failed scallop shaped MTC

Large (500 m wide), downslope channels with the same orientation as lava flows
Figure 27: H2: North (Sequence 6 Base/Middle Apron Top) – Two way travel time surface

Subtle imprint of downslope processes
Figure 28: H2: Central (Sequence 6 Base/Middle Apron Top) – Two way travel time surface

Imprinted surface features prevalent throughout H2. Possibly pseudo-polygonal faulting

Erosion Lobes

Large, fault parallel mini-basins
Figure 29: H2: South (Sequence 6 Base/Middle Apron Top) – Two way travel time surface

- En-echelon style fractures

- Deep canyoning of surface towards southern extent of 3D survey
Figure 30: H2: North (Sequence 6 Base/Middle Apron Top) – Structural dip

Dip map confirms lower angle, less faulted surface beyond "hinge point" seen in central and southern swaths.
Figure 31: H2: Central (Sequence 6 Base/Middle Apron Top) – Structural dip

- Downslope imprints amplified
- Steep flanks of mini-basin well imaged
- Large Liner Mound #4
Notable increase in frequency and angle of surface downslope features and general surface
Figure 33: H2: North (Sequence 6 Base/Middle Apron Top) – Variance: 0 ms window

- Linear "forks" of mound #2 clearly shown. Perhaps linked to faulting below resolution in seismic
- Well imaged downslope surface features and gouges
- Downslope MTC scours (subtle)
Figure 34: H2: Central (Sequence 6 Base/Middle Apron Top) – Variance: 0 ms window

Extensive Mulgara growth fault network with major faults, minor hanging wall faults, relay ramps and fault linkage detailed.

- Fault/Trim Mound #1, fault parallel
- Large Linear mound #4, fault perpendicular
- Small Linear mound #5
- Steep flanks of fault parallel mini-basin with concentric fill "rings"
- MTC Mound #6
- Twin mounds #7, fault parallel
Figure 35: H2: South (Sequence 6 Base/Middle Apron Top) – Variance: 0 ms window

- Polygonal faulting
- Circular structure?
- Large erosive seafloor canyons truncating surface
Figure 36: H2: South (Sequence 6 Base/Middle Apron Top) – Max Amplitude: 20 ms above and below window

- High amplitude igneous twin volcanoes
- Seafloor cutting into section
- Surface artefact
Figure 37: H3: North (Sequence 3 Base/Base MTC Sequence) – TWT

- Large "high" which diverts MTC flow patterns
- Fault appears to affect MTC
- Change in MTC scour azimuth - NNE-SSW
- Divergent MTC scours
- Deepest scours with increased gradient
Deeper set of scours overlying thinner set? Perhaps explaining the observed "stacked" nature seen in seismic sections.

MTC sequence truncated by Nullarbor canyon.

Shallow offset faulting.
Shallow (~75-100 m) but wide and extensive seafloor canyons

Deep (~200 m) seafloor canyons

Extensive downslope MTC scours
Figure 40: H3: North (Sequence 3 Base/Base MTC Sequence) – Structural dip

Steep sided 'V' shaped MTC scours highlighted with dip attribute
Figure 41: H3: North (Sequence 3 Base/Base MTC Sequence) – Structural dip

- Deep (~25-50 m) scours
- Unknown lineation, oblique to faulting and downslope MTC scours
Figure 42: H3: South (Sequence 3 Base/Base MTC Sequence) – Structural dip

Significant increase in dip of southern swath H2 surface
Figure 43: H3: North (Sequence 3 Base/Base MTC Sequence) – Max Amplitude: 40 ms above and below window

- Blocks within MTC complex located on flanks?
- Higher amplitude structural remnant with diverging MTC flow around it
- Basinward scarp surface of remnant block
Figure 44: H3: Central (Sequence 3 Base/Base MTC Sequence) – Max Amplitude: MTC–Seafloor (bugged Petrel folder – broken link to extractions along surface)

Cross-cutting oblique (to fault strike and downslope MTC scours) lineation

Unknown "patterns"
Figure 45: H3: Seafoor (Sequence 3 Base/Base MTC Sequence) – Max Amplitude: 40 ms above and below window

Twin Volcanoes propagating through MTC surface (mound #3)

High amplitude owing to seafloor reflector cutting through into extraction
Figure 46: H3: North (Sequence 3 Base/Base MTC Sequence) – Variance: 40 ms above and below window

Variety of MTC scours with thicker (100 m wide) and thinner (50 m wide) channel-forms. Various divergent orientations also visible, likely owing to tacked nature of several MTC complexes.
Figure 47: H3: Central (Sequence 3 Base/Base MTC Sequence) – Variance: 40 ms above and below window

Large ‘V’ shaped scour

Continuation of blocky pattern from northern swath
Figure 48: H3: South (Sequence 3 Base/Base MTC Sequence) – Variance: 40 ms above and below window

Set of deep large scours extensive across the basin. Similar features seen in present day Nullarbor canyon

Twin Volcanoes

Headwall scarp

Palaeocanyon or MTC collapse?
Figure 49: H4: North (Seafloor) – Structural dip

Spur between two canyon systems

Canyons also present outside fo 3D Ceduna imaged with 2D seismic sections

Canyon sides steeper and narrow (~5 km). Canyon becomes wider (~15 km) in southern swaths

Surface artefact owing to processing
Figure 50: H4: Central (Seafloor) – Structural dip

Greater stability in the west with increased canyoning and dip in the east section of the swath

Initiation of transport complex owing to increased slope gradient

Large scarp and 'step-down' (200 m) in seafloor canyon surface owing to faulting
Significant erosion owing to Nullarbor canyon

Several steep downslope trending lineations with a greater continuity than other swaths

Seafloor canyon significantly wider than in northern swath and now with a strongly asymmetrical profile, steeper on the west
Figure 52: H4: North (Seafloor) – Max Amplitude: 0 ms window

- Subtle, regular, downslope oblique features
- Anomalous feature
Figure 53: H4: Central (Seafloor) – Max Amplitude: 0 ms window

Well imaged head scarps of seafloor slides

Fault parallel mini-scarps affecting downslope canyon scours. Final scarp results in collapse and step-down
Figure 54: H4: South (Seafloor) – Max Amplitude: 0 ms window

- Twin Volcano peaks penetrating through seafloor surface
- Significant increase in slope failure of southern swath
- Disproportional erosion
Figure 55: H4: North (Seafloor) – Variance: 0 ms window

Anomalous feature

Anomalous feature
Figure 56: H4: Central (Seafloor) – Variance: 0 ms window

Several 'V' shaped features, similar to slope failure head scarps.

Well imaged "step-down" canyon floor failure
Figure 57: H4: South (Seafloor) – Variance: 0 ms window

Significant increase in slope failure

Steep scarp, similar to that in the Nullarbor canyon seen in the central swath
Intern-Project: Potential for Hydrogen Sulphide in the Upper 500 mbsf of the Ceduna Sub-basin

Mid June - July 2012

(v.1)

Compiled By: Alexander Sharples

With Contributions From: Simon Shoulders, Mark Osborn, Christopher Veale, Bob Eatough, Ceduna Exploration Team.
Executive Summary:

Hydrogen sulphide was detected in boreholes in LEG 182 of the Ocean Drilling Program. LEG 182 drilled nine ODP wells in the western Great Australian Bight in the Eyre Sub-basin. ODP sites were drilled in correlation with a regionally spaced 2D seismic grid. Results show large quantities of H$_2$S (up to 158,000 ppm) in the upper 500 mbsf along an eastern transect (Sites 1127, 1129 & 1131) and a western transect (Sites 1130 & 1132). The presence of a hypersaline brine (106%) was also picked up in the same interval as the high H$_2$S shows.

The Eyre Sub-basin lies adjacent to the Ceduna Sub-basin (and subsequently BP license blocks) thus; an objective was established to correlate the H$_2$S shows and to test the potential for H$_2$S presence in the deep water Ceduna environment. ODP raw gas elements data were acquired, collated, plotted, interpreted and linked to a bacterial sulphate reduction (BSR) H$_2$S formation mechanism. This was to effectively cross-check LEG 182 scientific reports and to establish a model for correlation into the Ceduna Sub-basin.

Results showed high H$_2$S (15%), CH$_4$ (50%) and CO$_2$ (75%) correlation between high CH$_4$ and brine alkalinites and high H$_2$S intervals. However, some ODP Site results showed presence of brine and methane without H$_2$S. A migratory component of hydrocarbons into the H$_2$S bearing sequences in the Eyre Sub-basin has been interpreted in coordination with a localised specific paleoenvironment which acted to optimise H$_2$S production preferentially in the eastern section of the Eyre Sub-basin compared to other parts of the margin. Thus, we interpret the high H$_2$S shows here to be a localised phenomenon.

A correlation exercise was made to link Eyre Sub-basin H$_2$S formation mechanism components to the deep water Ceduna. Results show potential for all H$_2$S forming components to be present but with a high degree of uncertainty towards presence of a sulphate source. This is due to a lack available data for correlation of interpretations. We interpret the risk of H$_2$S in deep water Ceduna Pleistocene packages to be low risk. This may change as and when new data is collected and analysed.

Further work has been suggested including seafloor sampling for brines (Cl$^-$ concentrations), hydrocarbon shows & subsequent isotopic analysis, gross depositional environment mapping of potential H$_2$S bearing sequences and further understanding of H$_2$S chemistry and stoichiometry in subsurface reactions.
10. References ......................................................................................................................................................349
1. Document Rationale

This document aims to describe the potential for the presence of hydrogen sulphide (H₂S) gas in the upper 500 mbsf of the Ceduna sub-basin in preparation for drilling commitments to be initiated in 2014. It is intended to be an informative guide and risking tool used to aid the selection of H₂S specific drilling equipment purchases, inform geotechnical sampling surveys and furthermore to contribute to drilling time HSSE H₂S countermeasures and procedures. Preparation of this document has required multidisciplinary input and describes:

- The upper subsurface geological setting across the Great Australian Bight
- The known H₂S presence and formation mechanism in the Eyre Sub-basin
- The potential for similar and/or other H₂S formation mechanisms in the Ceduna Sub-basin
- An overall understanding of the likelihood of H₂S in the Ceduna Sub-basin

This description should give further understanding of the need to prepare and combat potential H₂S shows during drilling and ties into geohazards work in the shallow subsurface. Given a lack of data availability and pressing time, it is advised that this document is altered at a later stage as and when more data becomes available and is to be subject to review as and when experienced team members with shallow gas backgrounds are introduced.
2. Project Overview

**Introduction:** H$_2$S presence is often linked to reservoir souring within the realm of petroleum geoscience studies, appearing where sources of sulphate are reduced in anoxic environments via a few key mechanisms. H$_2$S is highly reactive and has been shown not to migrate far as it encounters oxides within the subsurface sediments (particularly siliciclastics) to form solids of pyrite and pyrrhotite. In the case of the Great Australian Bight (GAB) some of the highest H$_2$S gas concentrations previously seen were encountered in the Leg 182 Ocean Drilling Program (ODP) in the late 90's. These H$_2$S concentrations appear confined to a particular stratigraphic interval in the upper 500 mbsf Pleistocene cool water carbonate succession over the Eyre Sub-basin.

The Eyre Sub-basin (Fig 1) shares a similar post-rift deposition history and shallow section composition to that of the Ceduna Sub-basin where BP license blocks EPP 37-40 are located. This project documents H$_2$S shows in the Eyre Sub-basin and correlates and risks presence in the Ceduna Sub-basin as a summary of multidisciplinary results.

*Figure 1: General location plan, current tenements, restricted land and well locations, Great Australian Bight taken from PIRSA Vol 5, The Great Australian Bight, Petroleum History.*
Foreseen Implications of H$_2$S Presence in Ceduna:

- H$_2$S becomes *instantaneously lethal* at approximately 1000 ppm to human contact. The implications of H$_2$S bearing sequences being drilled and rig personnel safety are overwhelmingly obvious.

- The *corrosive nature* of H$_2$S means welds and joints and well head designs must be taken into consideration. In the case of H$_2$S is signifies whether well heads will be housed or not. This has several up scaled effects:
  1. Equipment must be ordered and logistically emplaced months in advance
  2. Grade of casing steel must be chosen. Typically, lower casing grade has to be chosen to mitigate against H$_2$S embrittlement – lower grade steels have lower burst, collapse and tensile values. These lower values have serious implications when drilling in extreme deepwater environments such as the Great Australian Bight.
  3. Wellhead connectors must be considered. A threaded connector might have to be chosen as opposed to a welded connector due to H$_2$S concerns on the weld. A threaded connector has a lower fatigue life, which again, could have a big impact or riser analysis and rig operability in a harsh environment such as the deepwater GAB.

Ocean Drilling Program Leg 182 Fundamentals:

LEG 182 of the ODP was to further understand the cool-water temperature carbonate depositional domain of the Great Australian Bight. Primary drilling objectives were to understand in more detail the paleoenvironmental changes that occurred in this region at mid-high latitudes and why at the mid Eocene a transition occurred from siliciclastic dominated to the onset of the world's largest cool-water carbonate complex.

Overburden Sequence Stratigraphy:

Nine ODP boreholes (Fig2) were drilled in the Eyre Sub-basin; 1127, 1129, 1131 (eastern transect - Figure 5), 1130, 1132 (western transect - Figure 6), 1126, 1128, 1133 & 1134 from which the following stratigraphic sequences were derived on account of biostratigraphy, isotopic dating and coring efforts:

**Sequence 7:** Early to middle Eocene progradational siliciclastic wedge (correlates to Wobbegong Supersequence Geoscience Australia)

**Sequence 6A:** Middle Eocene to late Oligocene multi-lobed deepwater carbonate apron with disconformable hiatuses between lobes

**Sequence 6B:** Middle Eocene to Oligocene cool-water carbonate ramp with biogenic bryozoan mounds in abundance

**Sequence 5:** Estimated middle Miocene aerially restricted sediment wedge (not cored)

**Sequence 4:** Early Miocene extensive aggradational deepwater carbonate ramp with three internal hiatus surfaces.
**Sequence 3**: Late Miocene to early Pliocene aggradational carbonate ramp sequence with a basal hiatus of 0.5 m.y duration.

**Sequence 2**: Pleistocene thick carbonate sigmoidal clinoform succession at shelf break-point forming the majority of the modern outer shelf. Large bryozoan isolated mounds are present throughout.

**Sequence 1**: A thin deepwater drape of latest Quaternary age.

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**Figure 2**: Locations of Leg 182 drill sites in the western Great Australian Bight relative to the Eucla Shelf edge and the Eyre Terrace. Red lines through Sites 1127, 1131, and 1129 (eastern transect) and Sites 1130 and 1132 (western transect) show locations of seismic reflection data presented in Figures 5 & 6. – Taken from Leg 182 Scientific Results
Figure 3: Stratigraphic column with cool-water carbonate sequences of interest highlighted in transparent green. Taken from http://www.pir.sa.gov.au/__data/assets/pdf_file/0007/27767/pgsas5_chapter4.pdf
Figure 4: Seismic reflection image (seismic line AGSO-16g/a5a) of the eastern drilling transect, showing the thick Pleistocene clinoform wedge underlying the modern outermost shelf and upper slope and the location of Sites 1127, 1129, and 1131. Bryozoan mounds are visible as individual mounds and as stacked mound complexes immediately below the seafloor seaward of the shelf edge and also buried within the sediment wedge. Taken from Leg 182 Scientific Results.
Figure 5: Seismic reflection image (seismic line AGSO-169/13a) of the western drilling transect, showing the thick Pleistocene clinoform wedge underlying the modern outermost shelf and upper slope and the location of Sites 1130 and 1132. Taken from Leg 182 Scientific Results.
Important ODP Gas Shows:

In the eastern transect H$_2$S levels higher than previously seen for an interpreted Bacterial Sulphate Reduction (BSR) mechanism (typically 100-10,000 ppm) were encountered with a maximum show of 158,000 ppm at Site 1127. Significant shows were also seen in the western transect (sites 1130 & 1131) but on an order of magnitude lower 4000-5000 ppm. High levels of CH$_4$ (50%), CO$_2$ (75%) and H$_2$S (15%) were also encountered at the same interval.

![Figure 6: Plot showing interstitial water sulfate, hydrogen sulfide, and methane from Site 1131 vs. depth. Note the co-occurrence of sulfate and methane. The presence of hydrogen sulfide, a by-product of sulfate reduction, indicates that active sulfate reduction and methanogenesis are occurring over the same depth interval (after Mitterer et al., 2001).](image)

Geochemistry, Diagenesis & Mechanism of Formation:

A significant discovery of a brine with up to 106% salinity was discovered in the upper slope sediments of the eastern transect. Initial Reports suggest the brine to be associated with the high H$_2$S whereby high sulphate concentrations within the brine provide source for extensive sulphate reduction and elevated production of H$_2$S and alkalinity. This would create a chemical environment in which extensive carbonate recrystallisation and thus dissolution of metastable High Magnesium Content and aragonite and precipitation of Low Magnesium Content and dolomite (Swart et al, 2000).

Leg 182 Scientific Results suggest the brine originated from a hypersaline lagoon environment, such as that which would occur at a sea level lowstand. The scale of the Eucla shelf supports the likelihood of subaerial exposure and the arid conditions that still reside in South Australia today could have caused extensive
evaporation in shallow marine lagoons which were recharged with seawater and salt/brine source. Brines formed, then potentially percolated into underlying sediments and came to be in present locations by force of hydrostatic head were they then diffused into newer sediments during cyclic sea level fluctuations.

Swart et al (2000) suggested gas hydrates as an explanation for high H$_2$S shows. This was put forward as a combination of H$_2$S and CH$_4$ substituting as guest gases in a crystalline structure. Hydrates form in the subsurface under particular gradients of temperature and depth. These conventional hydrate formation windows are not applicable to the shallow section seen here. However, argument has been made towards the compositional factor of H$_2$S as the guest gas in the hydrate lattice acting to potentially shift the hydrate formation window. By using measured temperatures and salinities provided by the Colorado School of Mines hydrate models, results do suggest that presence of H$_2$S-CH$_4$ gas hydrates would be theoretically possible. Dissemination of hydrates upon contact was then suggested as to why no presence of hydrate was seen in cores samples with the dissemination by-product being the high gas shows (Swart et al 2000).

Coincidentally methanogenesis and sulphate reduction are separate and exclusive geochemical reactions. Reduction of sulphates inhibits methanogenesis and CH$_4$ does not appear in significant amounts until most of the sulphate in the stratigraphic interval has been reduced. Here, Mitterer et al (2001) suggest non-competitive sources of organic material within the cool-water carbonates for the microbial populations to catalyze these two reactions. Feary et al (2000) also speculated a more causal relationship between bryozoan mounds present and H$_2$S formation based upon a brine body interaction with depth ranges corresponding to mound formation.

LEG 182 of the ODP provided key observations, interpretations, and results and set the scene for a H$_2$S correlation project to be run across the Eyre Sub-basin and into the BP Ceduna license blocks. All ODP data is available open-access in an online database, thus results published results could be quality checked, and a suitable data-feasible methodology could be planned to correlate into the Ceduna Sub-basin.
Figure 7: Contour plot showing Cl− concentrations at Sites 1127, 1131, and 1129 (the eastern transect) overlying an interpretation of the seismic line joining the three sites. Note that the lines of equal Cl− concentrations crosscut the seismic sequence and accordingly are consistent with the presence of a sub-horizontal brine (after Feary, Hine, Malone, et al., 2000).

Taken from Leg 182 Scientific Results
3. Methodology

Project Workflow:

Figure 8: The project workflow

Figure 8 demonstrates how the project initiated as a simplistic seismic stratigraphic correlation exercise and quickly developed into a multidisciplinary task with various inputs so as to meet integration standards to BP H₂S presence risking flowcharts. In terms of time this meant the project failed to meet initial deadlines regarding well head design and purchases. It is hoped results will boost confidence in technical and overall understanding of the H₂S risk and contribute to a further informed decision on well head housing design and HSSE H₂S safety mitigation approaches essentially making the extra time spent on the project worthwhile.
4. Results

The following geochemical gas elements results, seismic interpretation results and any other literature based ODP published results of relevance are presented for each an every ODP Leg 182 Site.

Gas Elements Database:

All ODP data used is open access and can be found at [http://iodp.ldeo.columbia.edu/DATA/](http://iodp.ldeo.columbia.edu/DATA/). A LEG 182 Gas Elements database was imported into Excel and split into counterpart ODP well tabs. Additional data columns of depth (s TWT) and gas ratios with depth (dryness, pro/eth, butane ratio) were added to this database – see personal working appendix – Alex_Sharples. The following Graphs were constructed to give clarity on \( \text{H}_2\text{S} \) presence & formation mechanism.

**Graphs Constructed include:** *Not all ODP sites contain gas shows, thus some Site charts are missing / blank*

1.) \( \text{H}_2\text{S} \) vs. Depth (mbsf) & \( \text{H}_2\text{S} \) vs. Depth (s TWT)

2.) \( \text{H}_2\text{S} \) & \( \text{CO}_2 \) (ppm) vs. Depth (mbsf)

3.) \( \text{C}_1-\text{C}_6 \) vs. Depth (mbsf)

4.) Gas Ratios vs. Depth (dryness, pro/eth, butane ratio)

Seismic Package Identification:

Borehole correlated picks of the exact \( \text{H}_2\text{S} \) bearing Pleistocene succession via seismic cross-section were too complex and erroneous to tie reliably from the Eyre to Ceduna Sub-basin alone. This was due to:

a.) Data quality:

- The presence of a Miocene reef in shelf sections causing severe noise trains in the shallow subsurface
- Sub-horizontal stratigraphy running parallel to a strong seafloor multiple in some shallow sections
- Spacing between 2D lines on the order of 10 km minimum (average of 40 km between hero-lines)

b.) Geological Phenomena:

- Distinct changes in lithology across sequence boundaries and thus seismic facies
- Large incision surfaces, erosion and hiatus surfaces
- Large canyon system bringing horizons to present day seafloor
c.) Lack of data:

- Lack of boreholes/well to correlate which include shallow subsurface data
- Wide 2D seismic data spacing and lack of intersections

To remedy the issue of reliability three surfaces were picked and one generated along a chosen hero-line grid pattern (to be discussed). This will was to ensure were difficulty arose with the $H_2S$ package; the lower lying package could indirectly give evidence for presence. A surface modelling seabed multiple was generated from the seabed pick to amend shallow picking ambiguities. Picks were ODP borehole correlated (when possible), but package and observational based for the majority of the exercise.

1. **Light Blue – Seafloor** + 2. **Red – Seafloor multiple** (Seafloor * 2)

3. **Green – Base Pleistocene/Pliocene**

4. **Purple - Base Miocene**
Figure 9: Base map showing 2D data (light blue lines), ODP sites (red circles), grid used for hero lines (coloured lines) and Figure positions (black lines).
ODP Site 1126:

**Background:** Site 1126 is located on the eastern Eyre terrace in approximately 800 m of water and was originally designed to intersect the Miocene carbonate ramp slump lobes with the aim to date hiatus between lobes and intersect as much Cretaceous section as permitted by drilling time.

**Gas Shows:** Only low concentration of methane and ethane were detected at Site 1126. Methane ranges from 2.2 to 13.6 ppm, and ethane ranges from 1.1 – 2.7 ppm between 186.5 – 236 mbsf but is not present at greater depths. No $\text{H}_2\text{S}$ is present in Site 1126.

**Misc:** Site 1126 shows a large increase in salinity that manifests itself as shallowly as 10 mbsf, reaching a maximum of 106% by 100 mbsf which gives interesting implications for the $\text{H}_2\text{S}$ formation mechanism across the Eyre Sub-basin.

**Picking Criteria & Package Identification:** Confident horizon picks correlated directly to ODP Site 1126 and subsequently into chosen hero line intersections.

**Pleistocene package observations:** Strike-line reflections showed an aggradational, discontinuous, high frequency and high amplitude character which terminated regularly upon a continuous high amplitude basal surface which could be picked out relative to ODP initial results.

**Miocene package observations:** Strike-line reflections show an extensively aggradational, low frequency, low-mid amplitude stacked facies with a basal reflector of high impedance contrast to a lower amplitude transparent facies in the Oligocene.
Figure 10: Seismic section (TWT) showing relation of ODP Site 1126 to horizon picks and associated seismic facies packages.
Figure 11: ODP Site 1126 various associated gas element plots charts
ODP Site 1128:

**Background:** Site 1128 is located on the upper continental rise in approximately 3900 meters of water. The primary goals were to recover pelagic ooze from upper continental rise to compile a paleoceanographic record of the Cenozoic opening of the Southern Ocean and development of the circum Antarctic current and to determine the history of Cenozoic and late Cretaceous CCD fluctuations and deep-water mass variations during the evolution of the southern ocean.

**Gas Shows:** Only low concentrations of methane were detected (max 6 ppm) with the greatest reading at depth appearing to be an anomaly / error of data collection. No H$_2$S is present in Site 1128.

**Misc:** Site 1128 appears to intersect the base Miocene / top Oligocene sequence boundary in a wedge shaped geometry with several internal unconformities. These unconformities show the same wedge shaped geometry when picking surfaces off the eastern Ceduna shelf-break - here the mid Eocene boundary meets the seafloor and to extend the surface would require picking along one of these unconformities. Due to the seafloor exposure it is unclear which unconformity to choose. Site 1128 may prove key by directly linking the base tertiary across hero lines to deep water Ceduna.

**Picking Criteria & Package Identification:** ODP results show poor core recovery and limited data/criteria for correlative picking. Picks had to be based upon vague seismic facies as no other seismic lines were available to tie. Confidence of reliability in this section is low.

**Pleistocene package observations:** ODP results show only the upper 25-50 m as Pleistocene (1-2 reflectors) thus no package observations exist. Horizon ties are not possible further shelfward due to erosion.

**Miocene package observations:** A Miocene package is present although based on vague package observations being a strong acoustic impedance reflector followed by a transparent Oligocene package as seen in other sections. Correlation attempts from this line to deep water Ceduna Sub-basin lines are low confidence as strike-lines exhibit severe seafloor scouring and horizon exposure.
Figure 12: Seismic section (TWT) showing relation of ODP Site 1128 to horizon picks and associated seismic facies packages.
Figure 13: ODP Site 1128 various associated gas element plots charts
ODP Site 1133:

Background: Site 1133 is located on the middle upper slope in 1037.2 m of water. It is one of the two paleoceanographic sites located to intersect pelagic sections that collectively span the entire Cenozoic succession and form the deeper water component of the shelf-to-basin transect.

Gas Shows: Relatively small methane shows averaging 10 ppm where seen in the upper 150 m. No H₂S is present in Site 1133.

Misc: Seven interstitial water chemistry samples were taken indicating as with other sites 1133 is underlain by a high salinity fluid, although the maximum salinity measured here was only 41% at 123 mbsf. Compared to other sites the sulphate reduction rate is substantially reduced and resulting maximum alkalinity values are <5.2 mM. This suggests carbonate diagensis at deeper water sites is lower than of shallow water sites.

Picking Criteria & Package Identification: Missing check-shot data resulted in the exclusion of time-depth curves for integration of Site 1133 into the BP database. However, strong ties and intersections along hero-lines from the eastern ODP transect and strong ties from the Potoroo-1 tied hero lines provided high confidence picks along distinct package boundaries.

Pleistocene package observations: Distinctly prominent Pleistocene sigmoidal prograding clinoforms to the west provided a continuous ODP well correlated base surface which extends the package basinward. Complications arise where the package resides above an extensive slump/mass transport complex but improves in clarity eastward with strong hero-line ties from Potoroo-1.

Miocene package observations: The Miocene package has strong ties from the eastern transect and interpretation suggests it forms part of an extensive slump/mass transport package that has moved off-shelf. Several lobes and associated hiatus can be seen within however, the package as a whole consists of chaotic, mid amplitude, disrupted flow-like reflections. The base pick can be made as per usual by the distinct high amplitude pick with separates the flow complex from the continuous, extensively aggradational Oligocene.
Figure 14: Seismic section (TWT) showing relation of ODP Site 1133 to horizon picks and associated seismic facies packages.
Figure 15: ODP Site 1133 various associated gas element plots charts
**ODP Sites 1127, 1129, 1131 (eastern transect):**

**Background:** Sites 1127, 1129 & 1131 are located on the shelf-margin in approximately 500 m of water. The sites were principally to collect detailed, high resolution information to construct profiles through the upper Neogene shelf edge (high energy) to upper slope (low energy) succession and the cool-water carbonate environment. This was to further determine the response of the depositional system to Pliocene-Quaternary sea-level fluctuations.

**Gas Shows:** The eastern transect possessed the highest gas shows overall and some of the highest subsurface H$_2$S gas shows on global record (certainly within the realm of BSR generation). Between the three sites, H$_2$S shows of 158,000 ppm, CH$_4$ shows of 500,000 ppm and CO$_2$ shows of 750,000 ppm were recorded. Compared to other Sites significant amounts of heavier C$_2$-C$_4$ hydrocarbons were also recorded, although the profile of hydrocarbons remains predominantly methane (dry).

**Misc:** Exhibition of inorganic geochemical features such as the presence of a hypersaline brine were common across all sites with exception to some pore water profile due to increased degradation i.e. Site 1131 showed an alkalinity of 137 mM compared to 106 mM at Site 1127. Site 1131 also showed considerable depletion in so$_4^{2-}$ measureable concentrations remained even in high alkalinity zones suggesting organic matter was the limiting factor in H$_2$S production, not sulphate source.

**Picking criteria & package identification:** Strong well correlative ties coupled with strong stratigraphic ties and package distinctions made for pinpoint accuracy of key horizon picks in the subsurface.

**Pleistocene package observations:** Correlated to ODP Sites, the Pleistocene package is readily identifiable and ties strongly between transects. The package exhibits notably thicker (compared to other sections) prograding sigmoidal carbonate clinoforms with an integrated deep water carbonate mound facies in higher shelf settings. Higher amplitude, sub-parallel reflections exists within the main body of the clinoform package but become distorted further shelf ward changing to a wavy “chewed” seismic facies.

**Miocene package observations:** The Miocene package as a whole shows 4-5 aggradational lobe packages, some of which are slumped with assumed hiatus between lobes. Smaller wedged geometries with more chaotic facies occur at the toe-slope section but is still identifiable as part of the overall package due to the clean, transparent, low frequency and extensively aggradational Oligocene package beneath.
Figure 16: Seismic section (TWT) showing relation of ODP Sites 1127, 1129, 1131 to horizon picks and associated seismic facies
Figure 17: ODP Sites 1127 various associated gas element plots charts
Figure 18: ODP Sites 1129 various associated gas element plots charts
Figure 19: ODP Site 1131 various associated gas element plots chart
Figure 20: Eastern Transect H2S Contours vs Seismic:

Pleistocene
Pliocene
M-L Miocene
M Eocene
Oligocene
E Miocene
H₂S concentrations overlain on seismic cross-sections (Figure 20) can be contoured into stratigraphy cross-cutting sections of very high, medium and lower (respectively) concentrations. Contouring is subjective and 3D relationships cannot be calibrated and accounted for. Contours of H₂S correlate with those of Cl⁻ from the LEG 182 initial results indicative of a hypersaline brine. Contouring with emphasis on stratigraphy and seismic profile was attempted but did not prove feasible. Note, H₂S zero's out in correlation with a stratigraphic base (base Pleistocene).

**ODP Site 1130, 1132 (western transect):**

**Background:** Sites 1130 & 1132 are located on the shelf margin in approximately 500 m of water. The sites principal objectives were to collect information on the siliciclastic wedge which progrades out from the mid Eocene (Wobegong Supersequence) and to evaluate the complex interaction among paleogene sea-level fluctuations, accommodation space and subsidence and also to determine facies characteristics, sea-level response and paleoceanographic history of the Neogene cool-water carbonate succession in the shelf-edge.

**Gas Shows:** High levels of H₂S on the order to 10000 ppm were recorded with corresponding high levels of CO₂ at 40000 ppm. Interestingly however, much lower concentrations of methane and heavier hydrocarbons were associated with the western transect H₂S shows. The western transect is almost of order of magnitude lower than that of the eastern transect in regards to H₂S shows.

**Misc:** Site 1130 is influenced by high-salinity pore fluids, as was the case at sites 1126 & 1127. The maximum rate of salinity increase, 5.7/m is the highest observed during Leg 182. The steep gradient down to ~32 mbsf and then the constant salinity concentration (83) suggest nonsteady-state conditions. In contrast to 1127 the SO₄²⁻ reduction zone is incomplete and confined to the upper part of the profile and the degree of SO₄²⁻ reduction is ~40% less than at site 1127. The Pleistocene package here is notably less thick and prominent compared to the eastern transect.

**Picking Criteria & Package Identification:** Strong well correlative ties coupled with strong stratigraphic ties and package distinctions made for pinpoint accuracy of key horizon picks in the subsurface.

**Pleistocene package observations:** The Pleistocene package comprises of the same clinoform geometries described in the eastern transect however, here the package is thinner and with less continuity along reflectors.

**Miocene package observations:** As with the Pleistocene package the Miocene section here is of similar character to that in the eastern transect only thinner and still strongly show up by the contrast in Oligocene seismic facies.
Figure 21: Seismic section (TWT) showing relation of ODP Sites 1130 & 1132 to horizon picks and associated seismic facies
Figure 22: ODP Site 1130 various associated gas element plots charts
Figure 23: ODP Site 1132 various associated gas element plots chart
Figure 24: Western Transect H₂S Contours vs. Seismic
$H_2S$ concentrations overlain on seismic cross-sections (Figure 24) can be contoured into stratigraphy crosscutting sections of high and low (respectively) concentrations. Contouring is subjective and 3D relationships cannot be calibrated and accounted for. Contours of $H_2S$ correlate with those of $Cl^-$ from the LEG 182 initial results indicative of a hypersaline brine. Contouring with emphasis on stratigraphy and seismic profile was attempted but did not prove feasible. Note, $H_2S$ zero's out in correlation with a stratigraphic base (base Pleistocene).

Figure 25: Basement structure map of Eyre and Ceduna Sub-basins with ODP well locations and associated gas elements.

A complied gas elements map (above) was created not only to give more simplistic summary of gas shows with location, but also to assess the potential for migration from deeper structures. As shown above the Eyre Sub-basin basement structure map supports (not proof) potential for generation of hydrocarbons within deep half graben structures followed by vertical migration of hydrocarbons along basement highs followed by up-dip lateral migration into the ODP sections.
Figure 26: Base map to illustrate presence of base Miocene horizon which acts as the base to the \( \text{H}_2\text{S} \) bearing package and outlines the chosen hero line grid pattern. All horizons discussed (base Pleistocene, base Miocene / Top Oligocene, Seafloor and Seafloor Multiple) were picked along the coloured grid format. Due to picking complications resulting from erosion and slumps, the Pleistocene proved too complicated to pick reliably in the given time frame. The four hero lines (black) follow correlate to the following seismic sections with purpose to demonstrate package characteristics and presence across shelf – shelf margin – slope environment.
**Figure 27: Strike-line JAg0_23:** A heavily shortened seismic section (TWT) linking directly ODP transect correlated horizon picks to Potoroo-1 across the Eyre and Eucla Sub-basins. Note the canyon feature located in the centre of the section which cuts out the Pleistocene package and causes poor quality data making the top Oligocene difficult to pick across. Note the apparent Oligocene package thickness increase to the east but maintenance of seismic facies and package characteristics. Although Potoroo-1 does not date a Pleistocene sequence boundary, it does penetrate into the Oligocene thus by package identification and deduction we can make a pick across the section with high confidence.
Figure 28: Strike-Line FDWoo83: A heavily shortened seismic cross section (TWT) showing picked package boundaries which can be directly tied to Potoroo-1 interpolated boundaries. With good fortune the section by and large contains reflections which prove highly continuous and distinct and prominent changes in seismic facies and acoustic impedances. This provides very high confidence as a start point from which to take hero dip-lines into the Ceduna 3D section and observe the package distribution in the off-shelf Ceduna.
Figure 29: Dip-Line W00FDw00: A heavily shortened seismic cross section (TWT) showing sub-parallel and relatively continuous reflections which can be used to pick the base Pleistocene and top Oligocene. The Oligocene package is particularly distinct with a change from mid-amplitude, wavy reflections in a wedge shaped geometry which pinches out further basin ward to a transparent, low frequency continuous facies marked at the base by the characteristically high amplitude mid Eocene horizon. Picks made along this dip line correlate (purple and green markers) almost perfectly with hero line grid ties.
Figure 30: Dip-Line DWGAB_02: A heavily shortened seismic cross section (TWT) illustrating an example of seafloor incision whereby a large section of Pleistocene is missing and speculation exists as to whether or not it appears again further basinward. Here the base Miocene / top Oligocene which separates the transparent extensively aggradational package below from the higher amplitude chaotic wedge provides a strong correlation to suggest that the Pleistocene is present further basinward an answer not obviously apparent due to complex slope Pleistocene reflections and package changes. This is confirmed by several strongly correlative picks (purple and green markers).
Key Observations & Interpretations

H₂S Presence:

- H₂S is present in large quantities in the eastern section of the Eyre Sub-basin, up to a maximum of 158,000 ppm in the eastern ODP transect and in lesser but still relatively high concentrations in the western ODP transect up to 4,000 ppm.
- No H₂S shows are associated with Jerboa-1, Potoroo-1, Gnarlyknots-1, Apollo-1 or other known offset wells in the area. However, this is due to no data being collected in the immediate shallow interval.
- H₂S only forms in the upper 500 mbsf within the Pleistocene cool-water carbonate succession.
- H₂S concentrations appear greater where thicker Pleistocene intervals are present.
- H₂S concentration has been interpreted to cut stratigraphic boundaries (similar to contours of the hyper-saline brine Figure 7 also found in this section) and this is assumed NOT to be an artefact of limited data. H₂S does appear to bottom out at the base of the Pleistocene and does NOT form in Miocene sediments or older to the extent of our knowledge.
- H₂S distributions do not appear to correlate to seismic signatures i.e. amplitude variations, wavelet polarities.
- There is no evidence on seismic to support presence of shallow H₂S hydrates.

H₂S Formation Mechanism:

- H₂S formation is via in-situ Bacterial Sulphate Reduction (BSR)
- Formation constituents have been interpreted as follows:
  - Bacteria Source - Cool-water carbonates + seawater influx & meteoric mixing zone
  - Sulphate Source - Hypersaline brine + biodegraded migratory methane and biogenic methane
  - Temperature – constant 15-20 Celsius (ODP data derived)
  - Anoxic environment
- A migrated thermogenic component of methane is suggested due to presence of heavier hydrocarbon compounds i.e. C₃ and n-C₄ which are only derived from thermogenic sources.
- Increased sedimentation rate and rapid burial over the eastern transect (and subsequent increased thickness of the package) may have promoted anoxic conditions and a further optimised H₂S formation environment.
- High salinity brines which cross cut stratigraphic are likely responsible for the extremely high BSR generated H₂S shows – we suggest this as a localised
phenomenon, not a basin-wide process. It is not clear how much of the sulphate
source the brines produced compared to biogenically derived methane.

**H₂S Interval Distribution:**

- Pleistocene packages with proven H₂S shows form a sigmoidal clinoform carbonate ramp geometry
  exhibiting low frequency, sub-parallel, variable amplitude (cyclicity?) seismic facies in shelf-margin
  sections. This is thickest in the eastern ODP transect (approx 500 m) and less so over the Eucla Sub-
  basin were it is intersected by Potoroo-1 (approx 300 m).

- Pleistocene packages in distal sections (basinward towards the Ceduna 3D area) lose their
  progradational character and become stacked layer-cake geometries. Continuity is good with
  exception to areas immediately off the shelf-break where seafloor incision and potential contourite
  interplay has resulted in truncation and distortion of reflections / data quality. Package distinction
  picks up again further basinward in water depths of approximately >1500 ms TWT.

- Where severe erosion has occurred of the Pleistocene package or where strike-line geometries of
  Pleistocene progradational geometries prove too complex (with a short time frame to pick reliably),
  an ODP correlated base Miocene horizon was picked to prove package presence. This was due to a.)
  The distinct associated seismic facies change between Miocene and Oligocene packages b.) The
  continuity of the bounding reflector c.) The greater interval depth which was significantly less
  incised/disrupted by erosion events (i.e. canyons) of this package.

- The sequence of Pleistocene bearing H₂S concentrations found in the Eyre Sub-basin eastern most
  ODP transect IS present across the Eucla and Ceduna Sub-basins shelf-break margins and DOES
  continue into the distal sections of the basin.
6. Risking \( \text{H}_2\text{S} \) Presence in Deepwater Ceduna & Conclusions:

**Key elements:**

- **Bacterial Presence** – Present/highly likely
- **Organic Facies** – Present/highly likely
- **Clean Non-Scrubbing Reservoir** – Present/highly likely
- **Anoxic Environment** – Present/likely
- **Sulphate Source** – Unknown, no brine data/sulphur bearing biogenic methane content data? No migration data/deemed unlikely

**Interpretation Conclusion:** Low Risk

**Eyre Sub-basin \( \text{H}_2\text{S} \) Formation Mechanism:**

1. **Sulphate source:** A hypersaline, sub-aerially exposed back-shelf environment (i.e. lagoon system) with marine water influx was subjected to high evaporation rates with the present day southern Australian climate. This acted to concentrate brines. The brines percolated into underlying sediments (possibly during a lowstand sea level fall) and diffused upwards into rapidly deposited Pleistocene carbonate successions which provided an anoxic environment. The brine has potentially been pushed down under hydrostatic head and provided a key source of sulphates for BSR \( \text{H}_2\text{S} \) generation.

2. **Organic Source:** A component of biogenic methane is likely to have provided an organic source and also a degree of sulphate. However, we suggest also that lateral migration of hydrocarbons from syn-rift deposits has contributed to this system (and effectively boosted \( \text{H}_2\text{S} \) production). This is based upon observational evidence of heavier \( \text{C}_3 \) and \( \text{n-C}_4 \) compounds and gas depth ratios present at all high \( \text{H}_2\text{S} \) show sections. The origin of methane/hydrocarbons cannot be proved without isotopic analysis – which is not available.

3. **Bacterial presence:** Temperature gradients support bacteria in the seawater mixing zone at shelf margin sections. Cool water carbonates are likely to be the source for bacteria and also provide an oxide-free low scrubbing potential reservoir.

4. **Anoxic Environment:** BSR has been interpreted to be optimal at shelf-margin sections which may be linked to sedimentation rates and creation of strongly anoxic environments. This is supported by rates of Pleistocene sedimentation in the eastern transect coupled with \( \text{H}_2\text{S} \) shows, then compared to the western transect.

**Ceduna Sub-basin \( \text{H}_2\text{S} \) Formation Mechanism:**
Lack of data inhibits conclusive interpretation regarding a potential Ceduna Sub-basin H₂S formation mechanism. Thus, we have to speculate a BSR mechanism and further speculate on missing elements and risk. With emphasis on localisation of the Eyre mechanism, we interpret the likelihood of BSR derived H₂S being present in distal Ceduna Pleistocene deposits as low risk. Missing elements or absent data include:

1.) Sulphate Source: The lower likelihood of a hypersaline brine being present as a source of sulphates and no data to correlate hydrocarbon presence. It is as yet unclear to what degree methane shows contribute to sulphate source due to off-shelf ODPs with brine & methane presence but no H₂S. Migration and percolation of a brine into distal Ceduna Pleistocene sediments is deemed unlikely but as yet unproven.

2.) Organic Source:

c.) Pleistocene H₂S intervals in deep water Ceduna show significantly thinner stratigraphy compared to shelf-margin sections. Temperatures and degree of oxidising conditions remains unclear.

**Guided Interpretation Conclusion:** Low Risk
The BP risking flowchart (Fig#) was kindly provided by Mark Osborn and Christopher Veale and is used principally for the risking of \( \text{H}_2\text{S} \) in reservoirs. In this scenario we have assumed our "reservoir" is the Pleistocene cool-water carbonate complex and applied various potential scenarios to the Ceduna Pleistocene sequence based on what we do know and alternatives were we are missing data (i.e. availability of sulphate).

The Eyre Sub-basin \( \text{H}_2\text{S} \) risk flow is represented as the sharp red line, correlating to a risk of \( \text{H}_2\text{S} \) on the order of 10,000 ppm.

The Ceduna Sub-basin \( \text{H}_2\text{S} \) risk flow is represented as the smooth blue line, with an intersection at the unknown parameter of sulphate source. This leaves two potential options for a low risk <10 ppm or a higher risk equal to that of the Eyre Sub-basin. Until further data is collected we cannot prove either scenario, however as a gathered summary of data we suggest is it more likely a sulphate source is not present and thus there is a low risk of \( \text{H}_2\text{S} \) generation on the order of <10 ppm.
7. Discussion

Methane Source: is a heavy point of debate arising from this study and could give implications as to why we see such high H₂S concentrations. Current interpretations suggest methanogenesis to be strictly biogenic within the cool-water carbonate domain. We contest this for the following reasons:

- Methanogenesis and H₂S sulphate reduction are mutually exclusive chemical processes with little methane being produced in-situ until the majority of the sulphate reduction potential has been used up. This has been accounted for in literature (Mitterer et al 2001) by a hypothesis for non-competitive organic sources within the carbonates backed up by outdated literature sources.

- Presence of heavy hydrocarbons such as C₃ and n-C₄ are indicative of thermogenic origin from thermal maturation of source rocks. Thus, we suggest hydrocarbon migration from deep sections and subsequent biodegradation upon contact of the Pleistocene sequence whereby heavier/more wet components of C₂-C₆ would be removed which would result in increased CO₂ and C₁ (supported by gas plots).

- Overall, hydrocarbon gases are very dry i.e. mainly methane with very minor C₂, C₃, C₄ and consistent with biodegradation. The temperatures are too cool for the thermogenic gas to be generated in-situ, so it must have migrated laterally (supported by the “bow-shaped” curves seen in the gas elements plots). Methane could also be produced from the biodegradation of a migrated thermogenic gas which would explain the very high concentrations seen. It is impossible to quantify how much thermogenic gas has migrated, but presence of n-C₄ does prove it was there originally.

- High H₂S shows in the eastern and western transect correlate with high methane shows and presence of a hypersaline brine. However, in ODP 1126 methane shows are present with the greatest concentration of brine (106) yet no H₂S shows. Question is therefore put forward to the degree of sulphur contained in the biogenic equation of methane compared to the interpreted migrated methane and why when all components necessary for a H₂S formation reaction are present in this instance none is detected. This may also reflect the value of the shelf-margin position of the H₂S shows and importance of paleoenvironment.

- Only isotopic analysis of the hydrocarbon gases would give a clear answer of origin, but all other evidence points towards at least some degree of migrated hydrocarbon presence. Isotope studies of gas elements have been missed in the ODP reports, skipped over in literature and passed as 100% biogenic hydrocarbon formation – a major oversight!

- Migration pathways are supported on seismic section with the most h₂s prominent section overlying tilted fault blocks and half grabens with scope on seismic cross-section for vertical migration followed by lateral along-slope migration into the Pleistocene succession. Data spacing and gridding and make this impossible to prove, but 2D sections suggest it is a readily available scenario. The only way to cement interpretation regarding methane migration and contribution to H₂S formation in the eastern transect is to incorporate isotopic analysis – of which unknown or unavailable at present.

Sediment thicknesses: is a point of debate regarding its potential contribution to elevated H₂S concentrations. Pleistocene thicknesses vary from western to eastern transects i.e. 62.5 cm / year at site 1127, compared to 26 cm / year and 8.8 cm /year in sites 1130 and 1132. The latter rates are much more typical of
Eucla basin sedimentation and thus we can deduce accelerated productivity and/or more vigorous off shelf transport has occurred preferentially in the area of the eastern transect compared to the rest of the margin. Interplay between sedimentation rate and rapid burial may have led to promotion of less oxic environment, boosting H$_2$S production. In contrast, the western transect’s slower rate of sedimentation may have allowed for more exposure to the oxic environment, lessening H$_2$S production.

**Potential for other H$_2$S mechanisms in Ceduna:** In regards to Pleistocene cool-water carbonates or other cool water carbonates in the seismic record we suggest is not feasible. The cool-water carbonates are too shallow even with highest applied Geotherms, to give potential to TSR derived H$_2$S and therefore the only potential mechanism is in-situ BSR.

**Potential for hypersaline brine in Ceduna:** this stands as the one key critical area which could make or break H$_2$S formation in the distal Ceduna Sub-basin. Unfortunately no relevant data is available aside seismic cross-sections, thus the potential for a hypersaline brine (in particular reference to the Eyre H$_2$S formation mechanism) or any sulphate source at all i.e. evaporates, is not known / understood. Sulphate source potential is the missing link to make a strong interpretation of Ceduna H$_2$S formation. In the eyes of the author, it is deemed very unlikely as there is no scope for a paleoenvironment in the offshore Ceduna which would produce a.) A hypersaline environment, b.) A lithological source of sulphates. The potential for brine percolation and hydrostatic head push is also deemed unlikely considering the section in focus is some 100 km further away from the shelf-margin mixing zone seen in the Eyre Sub-basin and in 5x the counterpart water depths.

**Scrubbing potential of Ceduna Pleistocene Sequences:** H$_2$S is an extremely reactive gas, often forming pyrite as soon as it contacts any oxidising element. Core data shows Eyre Sub-basin cool-water carbonates prove relatively clean in regards to oxides. Cool water-carbonate scrubbing potential in the Ceduna is simply not known, there is no data to calibrate against.

**H$_2$S migration in Ceduna:** This links back to the scrubbing potential. With no data present it is impossible to calibrate any interpretation however; globally H$_2$S does not migrate far due to its high reactivity. This is especially true in siliciclastic sequences which often contain a much greater degree of oxide elements than carbonates, thus we assume H$_2$S migration from deeper sections in the Ceduna (siliciclastic) is very unlikely.
8. Recommendations

- Seafloor sampling – A seafloor sampling program is currently in planning stage (July 2012), we suggest taking into account testing the deep water Ceduna shallow section for brine presence, the interstitial pore-water chemistry and hydrocarbon presence.

- Scrubbing minerals sampling – during the seafloor sampling program consider the possibility of sampling the sediments to a.) Prove composition b.) analyse scrubbing potential

- Brine migration & shelf margin map – Maximum H$_2$S shows occur at shelf margin (mixing zone?) in the Eyre Sub-basin. Scope may exist for brine not being present beyond the shelf margin as all ODP wells off-shelf margin do not show H$_2$S. Thus, a shelf margin zone GDE map may compliment risking.

- Cool-water carbonates GDE map & section back-stripping – a CWC Gross depositional environment would bolster confidence in potential for organic source / sulphate reducing bacteria presence.

- Pleistocene – Seafloor isopach maps, mid Eocene – Seafloor isopach maps – thickness maps may provide indication between sedimentation rate and/or trends with H$_2$S shows in the Eyre Sub-basin which can be correlated to the Ceduna Sub-basin.

- H$_2$S chemical equation stoichiometry fundamental research on input parameters – Background into chemistry fundamentals may give indication as to how / why the H$_2$S yields in the Eyre Sub-basin were so extraordinarily high.

- H$_2$S hydrates search on 3D / shallow hazards volume – given potential for H$_2$S hydrate presence in the Eyre Sub-basin, 3D data (or better high frequency geohazards volumes) should be explored bearing in mind potential for H$_2$S & CH$_4$ hydrates.

- Seep analysis & hydrocarbon migration – show hydrocarbons migrating through the shallow section which would give source of organic matter and sulphate, raising the chance of H$_2$S potential.
9. Acknowledgements

Simon Shoulders, Mark Osborn, Christopher Veale, Nick Goodwin, Bob Eatough, Mads Huuse & various BP Ceduna team members.

Special Acknowledgement: The ODP LEG 182 Cabin Crew, “Initial Results” & “Scientific Results” Hardcopy Volumes and Online Databases which make up and account for many of the observations, background information and correlations in the project.
10. References


- Swart, P. K et al, 2000, Hydrogen sulfide-hydrates and saline fluids in the continental margin of South Australia, Geology, v. 28, pgs. 1039-1042.


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CHAPTER 5: BRYOZOAN MOUNDS APPENDIX

Figure 1: High resolution photograph of sampled cuttings and selected bryozoan fragments
Figure 2: High resolution photograph of sampled cuttings mouted to polished thin section
Figure 3: XRD micrograph of selected dark grains from base of B1 reef and top D3 lobe. Originally speculated to be basalt, XRD pattern clearly shows a glauconitic result and hence the reefs do not sit on an older re-worked basalt layer. The XRD was performed with the intention to unravel inter-mound relationships between BRMs and VMs.

*Further photographs and documentation of the BRMs can be found on the attached DVD Appendix*
CHAPTER 6: 3D MOUNDS APPENDIX

3D mound interpretation took place mostly over the course of one BP internship working with the 3D Ceduna for the purpose of the Ph.D. Mounds were mapped with rigorous precision and a very fine grid spacing (down to 2; Figure 1). This was undertaken using Landmark Powerview and issues occurred with surface creation and exportation on mound #3. Hence, the surface of this mound contains artefacts.

The following is a very basic report of observations during the initial stages of mound mapping. Although basic, some of the observations set the key foundations for the documentation of mounds in the GAB which feed into Chapter 5.
Basic Report: Ceduna 3D ‘FaultMound(s)’ & Associated Horizons: Initial key picking
and package observations v.1

Complied by: Alexander Sharples
For: BP Ceduna Exploration & PhD Project "Great Australian Bight Mid-Eocene Mounds"
Seafloor: 16x16

- Seafloor is 100% continuous and simple to pick and to be used as a reference point for isopach mapping. Signature shows Strong Red, Stronger Black, Strong Red.

Oligocene?_top: 16x16

- **Amplitude:** mid-high
- **Continuity:** Discontinuous
- **Frequency:** Low frequency
- **Character:** sub-parallel with single high amplitude reflector in the southeast and a double high amplitude reflector pair in the northwest. Acts as a distinct break between two transparent seismic facies packages
- **Package:** Top Oligocene to Seafloor with Miocene and Pleistocene components. Distinct transparent facies with a layer-cake, discontinuous character and assumed unconformable hiatuses in-between. Miocene sections exhibit a higher amplitude chaotic facies which wedges and pinches out 5-6 reflections thick. This section appears to be broken by degrees of minor faulting. A distinct aggradational and laterally extensive profile.
- Shows minor offset from major faults which cut all other horizons, however by and large the majority of faults to not propagate this far into the overburden
Early Oligocene? wedge top(a): 16x16

- **Amplitude:** mid
- **Continuity:** continuous with exception to a.) faults, b.) directly over mounds (inconsistent)
- **Frequency:** Low – mid
- **Character:** Single reflector and package limit definition with varied drape-geometry basinward, and aggradational layered geometry landward
- **Package:** Laterally extensive aggradational package with similar transparency characteristics to the Pleistocene succession followed by a thinner landward onlapping wedge with internal transparent sections bound by mid amplitude prominent reflections. These onlap and appear to terminate as the top of the wedge thins onto the faultmound and becomes 1 reflector thick landward. Erosion or non-deposition?

Early Oligocene? wedge top (b): 32x32

- Attempt to see if lower trough made a more continuous pick and better showed mound relationship to wedge. This did not work proving less continuous and clearly part of the internal package.

[Image of seismic data with annotations]
- **Amplitude**: Strong
- **Continuity**: Strong in non-faulted / eroded sections.
- **Frequency**: Low
- **Character**: Complex boundary subject to a large unconformity with various wedges, facies changes and heavy faulting offsets. Strong amplitude and acoustic impedance marking a change from carbonates to siliciclastics.
- **Package**: No single package can be associated with the base tertiary due to the nature of the unconformity and lack of correlation points (wells). The boundary is basin-wide extensive and subject to several facies changes.
- Fixed and amended directly under mounded features
- Acts as base_mound in some cases
- Appears to form as the top of a wedge which is broken and offset by the faultmound and associated faults
- Complex to pick with regards to backmound – appears to jump down and cross-cut. Suggests backmound is older.
- Unclear / inconsistent relationship to F1 due to growth within fault packages and uncertainty towards unconformity hiatus / erosion.

Faulting & unconformity character make for complex picks. Surrounding basin picks (green_hussain) make for strong ties, however note amended section under the top mound (yellow). Top footwall of the fault also makes for difficult and inconsistent reflector interpretation.

Base_tertiary as top of hard event wedge… Mid Eocene or actually Paleocene? Base_tertiary cuts across backmound flanks and picking becomes unclear
Mound_top: 8x8

- **Amplitude:** mid-strong
- **Continuity:** discontinuous
- **Frequency:** mid-high frequency
- **Character:** Mounded and draped facies with generally a strong acoustic impedance contrast above the mound. Flanks tend to lose amplitude and do not always exhibit a split reflector / obvious termination point.
- **Package:** Internal mound seismic facies shows highly chaotic (but regular in relative) ‘mashed’ reflections which in particular cross-sections show a progradational character. The mounded package is distinctive when combined with the mounded draped geometries compared to the surrounding geology & linear reflector trends.
- Mounds relocate with respect to faulting “collapsing into hanging wall”
- The faultmound appears to sit above the base_tertiary, the backmound appears to be older and flanks can be traced under the base_tertiary
- Internal facies shows elements of constructional convex-up growth, however particular angles exhibit a more ‘prograding’ character
- Termination points landward above the footwall are not obvious due to the nature of the unconformity
- Faultmound: 8 km (length), 3.4 km (width), 190 m (max thickness), split into two main sections of growth/thickness.
- Backmound: 9 km (length), 5 km (width), 140 m (max thickness), split into two definitive ‘pinnacles’ and 2 linear trending ‘spines’ of greater thickness orientated east-west.
- Internal backmound facies differs with a far greater element of discontinuity and separated isolated peaks.

Backmound showing linear pinnacle trends and over all a wider profile

(TWT Structure Maps)
**Mound base: 8x8**

- **Amplitude:** variable
- **Continuity:** strong
- **Frequency:** variable
- **Character:** Varies with respect to faulting, unconformities along the base_tertiary and split reflectors
- Base of faultmound appears to sit above prominent high amplitude which is interpreted to be the base of the high amplitude wedged package between the faultmound and backmound.
- Backmound base in some dip-lines clearly terminates with a split reflector, and lies below the base_tertiary.
**Base tertiary wedge: 8x8**

- **Amplitude**: strong
- **Continuity**: strong – until faulted
- **Frequency**: very low
- **Character**: horizon distinctly bounds at the base of a high amplitude wedged package (bounded at the top by the base tertiary). Character proves sub-parallel and inverted with particular fault planes.
- **Package**: A wedge shaped downlapping high amplitude package which has been heavily faulted and offset towards the wedge end.
- **High continuity and ties between intersections**
- **Base of wedge fully limits both mound packages and is not cut by faultmound OR backmound.**
- **Flattening of sections and interpreted growth of packages into faults gives strong correlation for picking the surface between faults.**
- **Internal package reflections clearly show onlapping and pinching out of wedge before faulting occurs.**
- **Degree of erosion is unclear in relation to base tertiary surface**
- **Package shows lower amplitude facies landward beyond backmound – data ends, but suggests change in facies.**
Sediment wave: 4x4

- **Amplitude:** Mid
- **Continuity:** strong between faulted sections
- **Frequency:** low
- **Character:** Symmetrical ‘wavy’ 2 reflections thick
- **Package:** Thin 1-2 reflectors thick outstanding reflector geometry bounded by faults on either side which may or may not be the reason for the linear trend.
- Positioned in close proximity to mounds and within faulted wedged package
- May give indication of along-slope current features prevalent during times of mound growth
- Appears constructive opposed to erosional
- **Elongated linear trend, northwest-southeast**
- 25 km (length), 2 km (width), 50 m (thickness)
- Cut-out by high point on fault hanging wall

Linear “along-slope” trend in map view, bounded by faults on either side. Same faults interact with faultmound. Where in Tertiary?_wedge the wave package sits is unclear due to nature of base tertiary unconformity.
Mound_top: southeastern mounds: 16x16

- **Amplitude:** mid
- **Continuity:** low
- **Frequency:** variable
- **Character:** Same as faultmound and backmound
- **Package:** Separate feature with a package yet to be assigned. Does not appear to co-evolve with the tertiary? Sediment wedge like the backmound, nor is subjected to the same degree of faulting as the faultmound.
- **Differing geometries with ‘blocky’ sections and ‘triangular-pinnacle’ sections.**
- **Overlying a greater frequency of faults with apparently smaller offsets**
- **Thickness change with respect to faulting unclear**

Similar paleobathymetric setting?  NE-SW orientated linear trends  Equal size and thicknesses
**Future Work:**

- Picking of 1-2 more key underlying horizons
- 4x4 gridding of mounds for Geoprobe surface
- Collative mound and sediment wave map (Hussain)
- Fault interpretation, assignment and offset valuation
- Velocity model integration (wedge characterisation)
- Generation of Isochron maps
- Generation of Isopach maps
- Volume attributes of mounds ???
Advanced 3D Ceduna Mound Observations:
Following this report mound interpretation was refined, imported into Petrel and reworked from a later internship and stage in the Ph.D. Surfaces were rectified and attributes generated. Each mound was documented in significant detail from a seismic perspective of which a database of approximately 500 + seismic screenshots (Inlines, Xlines and Time-slices) were constructed. Obviously, this cannot be shown here, but is available on DVD. These screenshots were used to fuel discussion regarding chapter X. The following maps however give important perspective on mounds that could not be included in the paper for confidentiality reasons.
Figure 1: Extracted variance attribute (0 ms) along north, central and south swaths for surface H1a.
Figure 2: Extracted variance attribute (0 ms) along north, central and south swaths for surface H1a with mound TWT structure maps superimposed.
Mound #1: Trim/Fault Mound - Dimensions

<table>
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Two-way time thickness map (top to base H1a):

Representative seismic section:
Mound #2: ‘éra’ Victory’ Mound - Dimensions

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<td>2. Large ‘Spine’</td>
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Two-way time thickness map (top to base H1a):

Representative seismic section:
Mound #3: Twin Volcanoes - Dimensions

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Two-way time thickness map (top to base H1a):

Representative seismic section:
Mound #4: Large Linear - Dimensions

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Two-way time thickness map (top to base H1a):

Representative seismic section:
Mound #5: Small Linear - Dimensions

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Two-way time thickness map (top to base H1a):

Representative seismic section:
Mound #6: MTC Mound - Dimensions

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<td></td>
<td>10.2</td>
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<td>17.62</td>
</tr>
</tbody>
</table>

Two-way time thickness map (top to base H1a):

Representative seismic section:
Mound #7: Twin Mounds - Dimensions

<table>
<thead>
<tr>
<th>Mound</th>
<th>Dimensions</th>
<th>Flank Angles (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Small Linear Duo</td>
<td>Length: 4 km</td>
<td>Width: 1 km</td>
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</tbody>
</table>

Two-way time thickness map (top to base H1a):

Representative seismic section:
Mound #8: Mini Mound - Dimensions

<table>
<thead>
<tr>
<th>Mound</th>
<th>Dimensions</th>
<th>Flank Angles (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. Mini-Mound</td>
<td>2 km 1 km 25-75 m</td>
<td>4.2 6.87 8.28 8.79</td>
</tr>
</tbody>
</table>

Two-way time thickness map (top to base H1a):

Representative seismic section: