Sequence stratigraphy of the Lower to Upper Cretaceous sedimentary deposits in the Exmouth Plateau and Exmouth Sub-basin, North West Shelf of Australia

Suyoung Choi
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Sequence stratigraphy of the Lower to Upper Cretaceous sedimentary deposits in the Exmouth Plateau and Exmouth Sub-basin, North West Shelf of Australia

By

Suyoung Choi

B.S., Seoul National University, 2003
M.S., Seoul National University, 2005

A thesis submitted to the
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This thesis entitled:
Sequence stratigraphy of the Lower to Upper Cretaceous sedimentary deposits
in the Exmouth Plateau and Exmouth Sub-basin, North West Shelf of Australia
written by Suyoung Choi
has been approved for the Department of Geological Sciences

_______________________________________________
(Dr. Paul Weimer)

_______________________________________________
(Dr. Renaud Bouroullec)

Date _______________

The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of Scholarly work in the above mentioned discipline.
Choi, Suyoung (M.S., Geology)

Sequence stratigraphy of the Lower to Upper Cretaceous sedimentary deposits in the Exmouth Plateau and Exmouth Sub-basin, North West Shelf of Australia

Thesis directed by Professor Paul Weimer.

ABSTRACT

The Exmouth Sub-basin and Exmouth Plateau are a portion of the Northern Carnarvon Basin in the North West Shelf of Australia. This basin contains several major oil and gas fields in the Upper Triassic, Upper Jurassic, and lowermost Cretaceous reservoirs. A detailed sequence stratigraphic study of the Lower to Upper Cretaceous strata was done to evaluate their petroleum potential. Interpretation was done using an integrated regional exploration database including 2-D seismic data, wireline logs from six wells.

Nine stratigraphic sequences were defined from the Valanginian through Santonian. Sequences 1-3 (Zeepaard Formation) are part of a large progradational wedge of siliciclastic of slope to coastal plain strata, which show distinct topset-foreset-bottomset depositional geometry. Sequences 4 (Birdrong Formation) and 5 (Muderong Shale) backstep and overlie the underlying sequences 1-3. The overlying sequences 6-8 (Gearle Siltstone) thin across the Exmouth Plateau and thicken across the Exmouth Sub-basin, and are characterized by several distinct internal downlap surfaces. In sequence 8, a wedge-shaped interval thickens to the east. Sequence 9 (Toolonga
Calcilutite) marks the onset of marine carbonate sedimentation overlying the Gearle Siltstone.

The Lower Cretaceous strata are characterized by two phases of northward progradation of delta (Barrow Group and Zeepaard Formation), caused by the uplift and extensive erosion in the southern Exmouth Sub-basin. A regionally extensive marine transgression developed after the Valanginian continental breakup in the study area, resulting in deposition of the thick Muderong Shale, a regional seal, as far northwest as the edge of the Exmouth Plateau during the Hauterivian and Aptian. A continuous relative sea level rise during the Albian through Turonian resulted in a deepening of depositional environments with the deposition of the Gearle Siltstone. During this interval, there was a significant change in sediments’ provenance, which was influenced by various tectonism and eustasy. After the Turonian, stable tectonism with decreased terrigenous influx into the study area resulted in the initiation of widespread deposition of carbonate sedimentation.

Based on this study, several potential plays for future exploration were identified. Potential plays are primarily associated with the stratigraphic traps (e.g. pinchout trap, reefal trap), which are developed in multiple sequences from sequence 2 through 9.
ACKNOWLEDGMENTS

First, I would like to express my deepest and sincere gratitude to my graduate school advisor Dr. Paul Weimer for giving me the opportunity to study at the University of Colorado, Boulder and for guiding and supporting me to work on the Carnarvon Basin project. The completion of my thesis would not have been possible without his guidance and countless hours of work. I would also like to thank Dr. Renaud Bouroullec, and Dr. Geoff Dorn from my committee for their prudent efforts and time spent in reviewing and editing my thesis.

In particular, this thesis would not have been possible without the financial and various supports from Korea National Oil Corporation (KNOC). I warmly thank the Human Resources Team at KNOC for their generous support and management during my stay in the US. I also wish to extend my warmest thanks to the faculties of the Department of Geological Sciences at University of Colorado at Boulder; Dr. David Budd and Dr. Matthew Pranter, who have always guided my study and influenced me to the world of in-depth study of petrology and reservoir characterization. Furthermore, I wish to thank all the office staff in the Department of Geological Sciences at University of Colorado at Boulder.

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I. INTRODUCTION

The North West Shelf of Australia is a geographic term applied to the offshore and marginal sedimentary basin flanking the northwest coast of Australia (Purcell and Purcell, 1988) (Figure 1). Five major sedimentary basins are present; from north to south, the Bonaparte, Browse, Roebuck, Canning (offshore and onshore), and Carnarvon (Northern and Southern). These basins evolved initially as a series of rift-margin basins during the Permian-Carboniferous and continued until the separation of Australia from Greater India during the Valanginian (Early Cretaceous), which was the last major rift tectonism in the area. During the Santonian (Late Cretaceous), the region subsequently developed as a passive continental margin. The study area for this thesis includes one portion of the Northern Carnarvon Basin (Figures 1, 2), which includes a portion of the Exmouth Sub-basin and Exmouth Plateau. Present-day water depths range from 500 to 2,000 m, and include the modern continental shelf, slope and basin settings.

Since the 1950s, companies have drilled exploration wells in the Exmouth Sub-basin and Exmouth Plateau. The Exmouth Sub-basin only has significant petroleum discoveries along its structurally elevated eastern flank, with regional dip to the northwest (Longley et al., 2002) (Figure 2). The main discoveries were oil that produced from the faulted anticline and faulted block traps. In the late 1970s and early 1980s, the major focus of exploration in the region shifted to the northwest into the deepwater within the Exmouth Plateau. Although oil was expected to be present during the initial phase of drilling, two significant giant accumulations were discovered: Jupiter 1 (1979)
Figure 1. Map showing the major sedimentary basins of the North West Shelf of Australia with bathymetry. Index map (lower right) shows location of the Westralian Superbasin (Modified from Trendall et al., 1990; Hocking et al., 1994; Purcell et al., 1994).
Figure 2. Regional map showing the major fields (color coded by geologic ages) and structural elements of the Exmouth Plateau and Exmouth Sub-basin. The magenta outline shows the boundary of the 2D seismic survey lines utilized in this study. The distribution of wells and location of the cross-sections (red line) are shown. Index map (lower right) shows location of the Northern Carnarvon Basin (modified from Tindale et al., 1998; Geoscience Australia, 2010).
targeted Triassic reservoirs in a horst structure, and Scarborough 1 (1979) targeted a Lower Cretaceous Barrow Group basin-floor fan that drapes an inverted basement structure (Figures 2, 3). A second phase of drilling started in the mid 1990s, which focused on the gas-bearing Triassic reservoirs in faulted blocks along the northwest margin of the Exmouth Plateau. The result was the largest gas discovery in Australia, the Jansz gas field (Figures 2, 3). The gas was accumulated in Upper Jurassic deltaic channel-fill sandstone reservoir rather than in fluvial Triassic reservoirs. This new Oxfordian reservoir has an estimated 20 Tcf reserves. By the end of 2009, 87 exploration wells had been drilled resulting in 40 discoveries in the Exmouth Sub-basin and Exmouth Plateau. The estimated reserves of the entire Carnarvon Basin contained around 72.2 Tcf of gas, 565.7 mmbbls of condensate and 345.4 mmbbls of oil (Geoscience Australia, 2010).

The lowermost Cretaceous strata have been studied in detail, primarily due to the discoveries in Scarborough and other fields. This study focuses on evaluating the petroleum potential of the Lower to Upper Cretaceous strata, primarily from the base Valanginian to the Santonian (Figure 4). These units are part of major changes in the style and extent of deposition in the continental margin, whose petroleum prospectivity is good throughout the study area. During the Cretaceous, up to 1,200 m thick of siliciclastic deposition of fluvio-deltaic and shallow marine sand to shale, are overlain by up to 1,000 m of fine-grained siliceous deposits and siltstone (Hocking, 1987).
Figure 3. Base map showing the location of major oil and gas fields, and 2D seismic lines with well locations within the study area. Outline of study area is shown by magenta box (2008 Carnarvon 2D seismic data sets from Geoscience Australia).
Figure 4. Regional stratigraphy of the Northern Carnarvon Basin. Major petroleum-bearing formations are recognized. Modified from Longley et al. (2002); Gradstein et al. (2004); and Ogg et al. (2008).
The objectives of this study are to:

(1) develop a detailed sequence stratigraphic framework for the Cretaceous strata by defining the major sequence boundaries of the Valanginian through Santonian strata across the central Exmouth Plateau and western Exmouth Sub-basin, based on 2-D seismic and well dataset;

(2) identify the distribution of a Lower Cretaceous progradational delta and the overlying shale dominated strata to develop a depositional hierarchy for this interval;

(3) analyze the characteristics of seismic facies for the interpreted sequences on the regional seismic profiles, and map the lateral distribution of 2-D seismic facies within a chrono-stratigraphic framework;

(4) integrate seismic facies and sequence stratigraphic interpretation to interpret the paleo-depositional environments; and

(5) propose potential plays for future exploration.

II. DATA SET

The data set used in this study consists of regional exploration data set (Table 1). A total of 9,735 km of regional 2-D multifold seismic data and six conventional well logs were used (Figures 2, 3, 5). The seismic data were acquired in seven different surveys: X78A (1978), X79A, X79B (1979), S101 (1991), S110 (1992), CT93 (1993), HE94 (1994), and S136 (1994) (Table 2). The best quality data and most important surveys were the 1994 and 1992. Major acquisition directions of WNW-ESE and NNE-SSW correspond to dip and strike lines, respectively (Figure 3). The overall quality of seismic
Table 1. Data set used in this study

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Figure 5. Map showing the major structural elements of the study area with 2D seismic profiles and well locations. Five exploration wells and oil and gas field near the study area are shown. Key strike oriented (NE-SW direction) and dip-oriented (NW-SE direction) seismic profiles (violet lines) for major sequence interpretation and facies analysis are shown.
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<td>257</td>
<td>1979</td>
<td>Yes</td>
</tr>
<tr>
<td>X79B</td>
<td>Esso Australia</td>
<td>825</td>
<td>1979</td>
<td>Yes</td>
</tr>
<tr>
<td>S101</td>
<td>AGSO</td>
<td>60</td>
<td>1991</td>
<td>Yes</td>
</tr>
<tr>
<td>S110</td>
<td>Geoscience Australia</td>
<td>518</td>
<td>1992</td>
<td>Yes</td>
</tr>
<tr>
<td>CT93</td>
<td>Geco Prakla</td>
<td>290</td>
<td>1993</td>
<td>Yes</td>
</tr>
<tr>
<td>HE94</td>
<td>BHP</td>
<td>6346</td>
<td>1994</td>
<td>Yes</td>
</tr>
<tr>
<td>S136</td>
<td>AGSO</td>
<td>732</td>
<td>1994</td>
<td>Yes</td>
</tr>
</tbody>
</table>
data is good. In some cases, the different processing in different surveys caused the
data not to properly tie. Therefore, the interpretation of the HE94 lines was emphasized.
The other seismic data sets were used to help define the regional structural trends.

One shortcoming to the data set is the lack of the northeast to southwest strike
lines near the northwestern corner of the study area (Figures 3, 5). This lack of data
means there is less accuracy to the structural interpretation of the northwestern areas,
especially for the seismic correlation to the Investigator 1 and Scarborough 1, 2 wells
(Figures 2, 3). For better understanding of the regional seismic interpretation, the
longest seismic profiles were interpreted.

More than forty deepwater wells have been drilled on the Exmouth Plateau and
Exmouth Sub-basin (Figure 2). Six exploration wells have been drilled in the study area:
Investigator 1 (1979), Zeewulf 1 (1979), Resolution 1 (1979), Zeepaard 1 ST1 (1980),
Leyden 1B ST1 (1996) and Eskdale 1 (2003). All the available wells having
conventional log data within or nearby the study area are listed in the Table 3.

For this study, most well log data, well completion reports and literature related
with the study area were acquired from the Virtual Data Room (VDR) from the website
suites or composite logs such as resistivity, neutron-density, spontaneous potential (SP),
and sonic were not available for most wells. However, gamma-ray logs were used for
understanding the overall lithologic changes and well-to-well correlation across the
study area. Due to the lack of velocity survey of the well logs to help generate the
synthetic seismograms, the Scarborough 2 well (Figures 2, 3), which is located
northwest of the study area, was additionally used for time-depth conversion and for more precise well-to-seismic tie.

Seismic Micro-Technology (SMT) Kingdom software 2-D/3-D seismic interpretation package have been used for 2-D seismic interpretation, well-to-seismic ties and well-to-well correlation.
Table 3. Well lists in the Exmouth Plateau and Exmouth Sub-basin

<table>
<thead>
<tr>
<th>Well list</th>
<th>Hydrocarbons</th>
<th>Year</th>
<th>Field</th>
<th>Reservoir Age</th>
<th>Trap</th>
<th>TD (m)</th>
<th>TD (ft)</th>
<th>Log type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigator 1</td>
<td>gas</td>
<td>1979</td>
<td>Exmouth Plateau</td>
<td>Early Cretaceous (Barrow Group)</td>
<td>4-way closure</td>
<td>3746</td>
<td>12290</td>
<td>GR</td>
</tr>
<tr>
<td>Resolution 1</td>
<td>gas</td>
<td>1979</td>
<td>Exmouth Sub-basin</td>
<td>Triassic (Mungaroo Fm)</td>
<td>Fault trap</td>
<td>3797</td>
<td>12457</td>
<td>GR</td>
</tr>
<tr>
<td>Zeewulf 1</td>
<td>oil and gas</td>
<td>1979</td>
<td>Exmouth Plateau</td>
<td>Triassic (Mungaroo Fm)</td>
<td>Fault trap</td>
<td>3500</td>
<td>11483</td>
<td>GR</td>
</tr>
<tr>
<td>Leyden 1B</td>
<td>gas</td>
<td>1996</td>
<td>Exmouth Plateau</td>
<td>Triassic (Mungaroo Fm)</td>
<td>Fault trap</td>
<td>4300</td>
<td>14107</td>
<td>GR, Sonic Density</td>
</tr>
<tr>
<td>Eskdale 1</td>
<td>oil and gas</td>
<td>2003</td>
<td>Exmouth Sub-basin</td>
<td>Late Jurassic (Dupuy Fm)</td>
<td>Fault trap</td>
<td>3127</td>
<td>10259</td>
<td>GR, Sonic, Neutron, Density</td>
</tr>
<tr>
<td>Zeepaard 1 ST1</td>
<td>gas</td>
<td>1980</td>
<td>Exmouth Sub-basin</td>
<td>Triassic (Mungaroo Fm) / Early Cretaceous (Barrow Group)</td>
<td>Fault trap / pinchout</td>
<td>4215</td>
<td>13828</td>
<td>GR</td>
</tr>
<tr>
<td>Scarborough 1</td>
<td>gas</td>
<td>1979</td>
<td>Exmouth Plateau</td>
<td>Early Cretaceous (Barrow Group)</td>
<td>4-way closure</td>
<td>2350</td>
<td>7710</td>
<td>GR</td>
</tr>
<tr>
<td>Scarborough 2</td>
<td>gas</td>
<td>1996</td>
<td>Exmouth Plateau</td>
<td>Early Cretaceous (Barrow Group)</td>
<td>4-way closure</td>
<td>2068</td>
<td>6785</td>
<td>GR, Sonic, Neutron, Density</td>
</tr>
</tbody>
</table>
III. REGIONAL GEOLOGICAL SETTING

Regional Geological Setting of Study Area

The study area is located in a part of the Northern Carnarvon Basin, which is located at the southern part of the North West Shelf of Australia (Hocking et al., 1987) (Figures 1, 2, 5). The Northern Carnarvon Basin is one of the major extensional basins comprising the North West Shelf of Australia. The basin is part of the Westralian Superbasin (Figure 1), which underlies the northwestern continental margin of Australia from North West Cape in the south to the Arafura Sea in the north (Yeates et al., 1986; Bradshaw et al, 1988). The sedimentary fill is up to 15,000 m (49,000 ft) thick, and includes Paleozoic to Cenozoic strata dominated by deltaic to marine siliciclastics and shelfal carbonates (Geoscience Australia, 2010).

The study area is 17,180 km² in area and includes the portions of two distinctly separated areas of the Northern Carnarvon Basin: Exmouth Sub-basin and Exmouth Plateau (Figures 1-5). The major structural elements of the study area such as the Exmouth Plateau Arch, Kangaroo Syncline, Resolution Arch and Novara Arch are illustrated in Figures 5-13.

The Exmouth Sub-basin, located in the southernmost part of the Northern Carnarvon Basin, is composed of the northeast-southwest trending Jurassic syn-rift depocenter (Figures 1-3, 5, 6). Water depths within the sub-basin range from approximately 100 to more than 2,000 m (Figure 1). This sub-basin is bounded by the Alpha Arch to the east and the Exmouth Plateau to the northwest (Figures 2, 5, 6b). The Alpha Arch forms the boundary between the Exmouth Sub-basin and the Barrow Sub-
Figure 6a. Uninterpreted dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 6b. Dip-oriented seismic profile showing high-angle normal faults resulting from the Triassic rift tectonism. Inversion related monoclines that formed during the Miocene support the significant tectonic inversion during the Tertiary. Potential structural and stratigraphic plays (fault bounded three-way closure, stratigraphic pinch-out) are shown. Location of the profile is shown in Figures 3 and 5 (U/C = unconformity) (Modified from Tindale et al., 1998; Geoscience Australia, 2010).
Figure 7a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 7b. Regional dip-oriented 2D combined seismic profile showing the major interpreted megasequence boundaries (Valanginian, Aptian, Turonian, Base Tertiary, Oligocene, and Miocene) with reflection termination (colored arrows: red = onlap, green = downlap) and structural components in the study area. The Scarborough 1 well targeted the four-way closure composed of submarine fans underlying the Valanginian unconformity; the reservoir has high amplitude reflections (Direct Hydrocarbon Indicator - DHI, yellow shaded). Potential stratigraphic traps are shown (orange shaded). See Figures 3 and 5 for the location of this profile.
Figure 8a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 8b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap, green arrows = downlap) for the Lower Cretaceous to Neogene strata are shown. Time-based gamma ray log of the Investigator 1 well is displayed. The Barrow Group consists mainly of prograding deltas underlying the Valanginian unconformity in syn-rift tectonic phase. The increase in slope gradient above the Turonian unconformity resulted in a widespread, well developed sediment slumping. Younger sediments are primarily prograding carbonates, marls, and chalks. Potential structural and stratigraphic plays (orange shaded) are shown. See Figures 3 and 5 for the location of this profile. Also, see Figure 34 for details of the Investigator 1 well (OLS = onlap surface, DLS = downlap surface, U/C = unconformity).
Figure 9a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 9b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap, top lap, and truncation, green arrows = downlap) for the Lower Cretaceous to Neogene strata are shown. This profile shows the large-scale clinoforms of the Barrow Group that prograded to the northwest across the Exmouth Plateau and Exmouth Sub-basin. Uplift during late syn-rift phase (Base Cretaceous to Valanginian unconformity) provided a southern sediment source for a thick sequence of the Barrow Group. The Zeepaard Formation from sequence 1 to 3 shows prograding clinoforms. The sequences overlying the top Albian interval show a series of small faults. Well developed carbonate deposits overlie the Turonian unconformity. Slumping and channeling on the slope setting are present on the northern margin of the Exmouth Sub-basin. Potential stratigraphic plays (orange shaded) are shown. See Figures 3, 5, and 29 for the location of this profile (OLS = onlap surface, DLS = Two-way Travel Time (sec)).
Figure 9c. Dip-oriented 2D seismic profile shown in Figures 9a and 9b showing the stratigraphy with interpreted main sequence boundaries: (a) uninterpreted, (b) interpreted. The cross section is flattened on the Valanginian unconformity to illustrate the well defined progradational delta and backstepping deltaic phases during the Early Cretaceous. See the location of the profile in Figures 3, 5, and 29.
Figure 10a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 10b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap and toplap, green arrows = downlap) for the Lower Cretaceous to Neogene strata are shown. The Barrow Group consists mainly of two separate prograding deltas in a syn-rift and early passive margin tectonic phase, separated by the Valanginian unconformity. The lower delta shows high-gradient clinoforms (yellow solid lines in the Barrow Group). In contrast, the upper delta has low-gradient prograding clinoforms. Increase in slope gradient above the Turonian unconformity resulted in widespread, well developed sediment slumping, and progradation of carbonates deposits (condensed marls with chalks). Carbonate buildups developed as a mounded geometry above the Turonian unconformity are shown (blue shaded). Potential plays with stratigraphic pinch-out are shown (orange, green shaded). Incised channels with large erosional features are commonly recognized in the Upper Cretaceous to Paleogene sequences. See Figures 3, 5, and 29 for the location of this profile (OLS = onlap surface, DLS = downlap surface, U/C = unconformity).
Figure 10c. Enlarged section from seismic profile (Figure 10b) showing details in the Cretaceous strata. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap and toplap, green arrows = downlap) are shown. Potential deepwater (orange shaded) and carbonate buildup (blue shaded) plays are shown. See Figures 3, 5, and 29 for the location of the profile (U/C = unconformity, DLS = downlap surface).
Figure 10d. Enlarged section from seismic profile (Figure 10b) flattened on sequence boundary 1 (Valanginian unconformity). Well developed progradation is present in the Zeepaard Formation (sequences 1 to 3), and the underlying Barrow Group. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap and toplap, green arrows = downlap) are shown. Potential deepwater play with stratigraphic pinch-out is shown (orange shaded). See Figures 3, 5, and 29 for the location of the profile (U/C = unconformity, DLS = downlap surface).
Figure 11a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 11b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap, erosional truncation, green arrows = downlap) for the Lower Cretaceous to Neogene strata are shown. Time-based gamma ray log of the Investigator 1 well is displayed. The Barrow Group consists mainly of well developed prograding clinoforms underlying the Valanginian unconformity in late syn-rift tectonic phase. Uplift and erosion of the Barrow Group are shown near the Investigator 1 well. Potential deepwater play with stratigraphic pinch-out is shown (orange shaded). See Figures 3, 5, and 29 for the location of the profile. Also, see figure 34 for details of the Investigator 1 well (OLS = onlap surface, U/C = unconformity).
Figure 11c. Enlarged section from seismic profile (Figure 11b) flattened on sequence boundary 4 (Hauterivian unconformity). All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap and toplap, green arrows = downlap) for the Cretaceous strata are shown. Time-based gamma ray log of the Investigator 1 well is displayed. See Figures 3, 5, and 29 for the location of the profile. Also, see figure 34 for details of the Investigator 1 well (U/C = unconformity).
Figure 11d. Enlarged section from seismic profile (Figure 11b) flattened on sequence boundary 6 (Aptian unconformity). All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap and toplap, green arrows = downlap) for the Cretaceous strata are shown. Sequences 1 to 3 (Zeepaard Formation) show well developed prograding clinoforms. Potential deepwater play with stratigraphic pinch-out is shown (orange shaded). See Figures 3, 5, and 29 for the location of the profile (U/C = unconformity).
Figure 11e. Enlarged section from seismic profile (Figure 10b) flattened on sequence boundary 7 (Base Albian). All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap and toplap, green arrows = downlap) for the Cretaceous strata are shown. Sequences 1 to 3 (Zeepaard Formation) show well developed prograding clinoforms. Potential deepwater (orange shaded) and carbonate buildup (blue shaded) plays are shown. See Figures 3, 5, and 29 for the location of the profile (U/C = unconformity, DLS = downlap surface).
Figure 11f. Enlarged section from seismic profile (Figure 10b) flattened on sequence boundary 8 (Top Albian). All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap, green arrows = downlap) for the Lower Cretaceous strata are shown. Several downlap surfaces developed within the thick Gearle Formation. Potential deepwater (orange shaded) and carbonate buildup (blue shaded) plays are shown. See Figures 3, 5, and 29 for the location of the profile (U/C = unconformity).
Figure 11g. Enlarged section from seismic profile (Figure 10b) flattened on sequence boundary 9 (Turonian unconformity). All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap, green arrows = downlap) for the Lower Cretaceous strata are shown. Potential deepwater (orange shaded) and carbonate buildup (blue shaded) plays are shown. See Figures 3, 5, and 29 for the location of the profile (U/C = unconformity).
Figure 11h. Enlarged section from seismic profile (Figure 10b) flattened on sequence boundary 10 (Santonian). All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap, green arrows = downlap) for the Lower Cretaceous strata are shown. See Figures 3, 5, and 29 for the location of the profile (U/C = unconformity, DLS = downlap surface).
Figure 12a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 12b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = toplap, green arrows = downlap) are shown. The Barrow Group is related to a syn-rift tectonic phase. An increase in slope gradient above the Turonian unconformity in a southeast direction of the profile resulted in a widespread, well developed sediment slumping. Younger sediments are primarily prograding carbonates, marls, and chalks. A series of faults with small offset were developed after the Turonian and Santonian. See Figures 3, 5, and 29 for the location of this profile (OLS = onlap surface, U/C = unconformity).
Figure 13a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 13b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap and top lap, green arrows = downlap) for the Lower Cretaceous to Neogene strata are shown. This profile shows the large-scale prograding clinoforms developed in the Barrow Group. After the Aptian and Albian, a large amount of sediments, the Gearle Formation equivalent, were deposited from the southeast. The sequences overlying the top Albian interval show a series of faults with small offset, and carbonate deposits, the Toolonga Formation equivalent, that developed above the Turonian unconformity. A possible remobilized sand injectite geometry that developed due to the increase in overpressure associated with high rates of sedimentation during the Albian is shown (orange arrow). See Figures 3, 5, and 29 for the location of this profile (OLS = onlap surface, DLS = downlap surface, U/C = unconformity).
basin, and the Kangaroo Syncline forms the boundary between the Exmouth Sub-basin and the Exmouth Plateau (Figures 2, 5, 6b, 8b). The major regional tectonic elements are dominated by a series of northeast-southwest trending structural depressions consisting of grabens or half grabens with high-angle extensional normal faults (Figures 5-21) that were developed as a result of rift tectonism during the Early Jurassic (Pleinsbachian) to the Late Jurassic (Oxfordian) (Tindale et al., 1998; Smith et al., 2003; Sciborski et al., 2005) (Figure 4). The regional seismic profiles illustrate well-developed structural elements and show clearly the with major sequence boundaries from Lower Cretaceous to Neogene strata within the study area (Figures 6-18).

To the west, the Exmouth Plateau is a deepwater plateau in water depths of 800 to 3,000 m (Geoscience Australia, 2010) (Figures 6b, 22). This plateau covers a large area in the western and northern portion of the Northern Carnarvon Basin (Figures 1-3, 5-9, 19). The Kangaroo Syncline forms the boundary between the Exmouth Plateau and Exmouth Sub-basin (Figures 1, 2, 5-10, 12, 13). The plateau consists primarily of 10-15 km thick Triassic through Lower Cretaceous strata that are undeformed or present in large tilted or rotated fault blocks (Figures 6-8, 19). These strata were deposited during the major extension that preceded the two-step breakup of Australia from Argo Land during the Middle Jurassic, and then from Greater India during the Early Cretaceous (Stagg et al., 2004) (Figures 6-8, 11, 19). In general, up to 5,500 m of thick Paleozoic-Mesozoic strata were deposited prior to the final continental breakup during the Valanginian. The Triassic rocks are thick, fluvio-deltaic to marine strata, which are overlain by thin Upper Jurassic marine strata (Figures 6b, 19, 20). Deeply rooted high-angle normal faults, which strike northeast-southwest, are dominant in this plateau
Figure 14a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 14b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = onlap) for the Lower Cretaceous to Neogene strata are shown. This profile illustrates the progradation between the Valanginian and Hauterivian unconformity and subsequently the onlapping Muderong Formation onto the Hauterivian unconformity. The sequences overlying the top Albian interval show a series of nearly vertical small faults. Note that the Birdrong Formation is absent. Potential deepwater play with stratigraphic pinch-out is shown (orange shaded). See Figures 3, 5, and 29 for the location of this profile (OLS = onlapsurface, DLS = downlap surface, U/C = unconformity).
Figure 15a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 15b. All of the interpreted major sequence boundaries for the Lower to Upper Cretaceous strata are shown. The seismic profile shows an increase in faulting in the Barrow group to the southwestern edge of the Exmouth Plateau, associated with the continental breakup. Above the Valanginian unconformity, the early passive margin tectonic phase commenced. The sequences overlying the top Albian interval have a series of faults with small offset. See Figures 3, 5, and 29 for the location of this profile (DLS = downlap surface, U/C = unconformity).
Figure 16a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 16b. All of the interpreted major sequence boundaries for the Lower to Upper Cretaceous strata are shown. This profile shows the characteristic of prograding clinoforms of the Barrow Group, especially the lower delta portion that underlies the Valanginian unconformity. The sequences overlying the top Albian interval show a series of faults with small offset and well developed carbonate buildup above the Turonian unconformity. Potential deep-water play with stratigraphic pinch-out is shown (orange shaded). See Figures 3, 5, and 29 for the location of this profile (DLS = downlap surface, U/C = unconformity).
Figure 17a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 17b. All of the interpreted major sequence boundaries with reflection terminations (Red arrows = toplap, onlap and truncation, green arrows = downlap) for the Lower to Upper Cretaceous strata are shown. Sequences 1, 2, and 3 represent the progradation of upper delta, the Zeepaard Formation. Note that the Birdrong Formation is absent. Note the change in direction of progradation and sediment source from the top Albian sequence boundary. The sequences overlying the top Albian interval show a series of faults with small offset. See Figures 3, 5, and 29 for the location of this profile (DLS = downlap surface, U/C = Unconformity).
Figure 18. Regional strike-oriented seismic profile showing the interpreted megasequence boundaries and reflection terminations (Red arrows = onlap and erosional truncation) for the Lower Cretaceous to Base Tertiary strata. The major unconformities from the Valanginian unconformity which eroded the underlying uplifted Barrow Group to other unconformities such as the Hauterivian, Aptian, and Turonian unconformities associated with well developed erosional truncation and onlap termination are shown on this seismic profile. See Figure 3 for the location of this profile (U/C = unconformity).
Figure 19. Schematic structural evolution of the Exmouth Sub-basin and the Exmouth Plateau along the dip oriented cross section. Location of cross section is shown along line A-A' in Figure 2. Adapted from Tindale et al., (1998).
Figure 20. Schematic structural evolution of the Exmouth Sub-basin along the strike-oriented cross section. Location of cross section is shown along line B-B’ in Figure 2. Adapted from Tindale et al., (1998).
Figure 21. Regional strike-oriented seismic profile showing the interpreted major sequence boundaries from Lower to Upper Cretaceous strata and the relationship of uplift and erosion between the Valanginian and Turonian intervals. Two episodes of uplift related to the erosion over the Ningaloo Arch and Novara Arch are shown. Note a series of high-angle small faults offsetting seismic horizons between the Aptian unconformity and Turonian unconformity, which coincides with the Gearle Formation. Location of the profile is shown in Figures 2 and 3.
Figure 22. Schematic cross section showing the general chrono- and lithostratigraphy, major tectonic phases, and seismic horizons of the Northern Carnarvon Basin. Main elements of the petroleum systems are shown (Modified from Tindale et al., 1998).
(Figures 5, 8, 19). Major breaks in sedimentation were caused due to the uplift of the Exmouth Plateau during the Early to Middle Jurassic and Early Cretaceous. After the Early Cretaceous continental breakup, the plateau was largely starved of sediments.

**Tectonic Evolution**

The tectonic evolution of the study area, shown schematically in Figures 19 and 20, consists of four key phases (Geoscience Australia, 2010) (Figures 6, 19, 20, 22):

1) Pre-rift active margin phase (Triassic to Early Jurassic),
2) Syn-rift phase (Jurassic to Early Cretaceous),
3) Early passive margin phase (Early to Late Cretaceous), and
4) Late passive margin phase (Late Cretaceous to Miocene).

**Syn-rift Phase:** The syn-rift phase is divided by three successive phases of tectonic evolution: (1) early syn-rift (Toarcian to earliest Callovian), (2) main syn-rift (earliest Callovian to Berriasian), and (3) late syn-rift (Berriasian to Valanginian) phase (Figures 6b, 22).

The segmentation of the Westralian Superbasin (Figure 1) into platforms and troughs occurred during the Jurassic. As a result of the Early Jurassic rift tectonism, the Exmouth Sub-basin formed as a northeast-southwest trending structural depression comprising horst and graben (or half graben) topography with major rift-related faults (Figures 6, 19, 20, 22). The area including the Exmouth Sub-basin and other adjacent sub-basins consists of a series of Jurassic depocenters that developed during the early syn-rift phase of breakup of the northwestern Australian continental margin (Figures 6b, 22).
Although the trough areas filled with thick marine strata, only thin strata were deposited on the structural high areas in the central and western Exmouth Plateau (Exon and Willcox, 1978; Barber, 1982, 1988; Boyd et al., 1992) (Figures 6b, 22). As a consequence, the Middle to Upper Jurassic syn-rift strata are thinner on the Exmouth Plateau than other areas in the Northern Carnarvon basin (He et al., 2002) (Figure 19). Within the broad and fault-dominated Triassic platform of the Exmouth Plateau, some Jurassic syn-rift strata are either absent or thin across the plateau (Tindale et al., 1998) (Figures 6b, 19, 22). The Exmouth Plateau area has the same structural elements as the Exmouth Sub-basin: northeast-southwest or north-south trending high-angle normal or strike-slip faults with horst and graben topography (Figures 5-8, 19).

During the main syn-rift phase (Late Jurassic), the Kangaroo Syncline developed in the southern Exmouth Plateau and northern Exmouth Sub-basin, which was caused by the uplift of the Triassic tilted fault blocks overlying the Rankin Platform (Figure 1, 2, 5-10, 12, 13). Late syn-rift phase commenced with early Berriasian uplift and erosion. The last major rift-related tectonism occurred during the Valanginian, preceding the final continental separation of Greater India from Australia (Figures 19, 20, 22).

**Early Passive Margin Phase:** The separation of Great India from Australia during the Valanginian is associated with the uplift of the Ningaloo Arch, and subsequent erosion of Triassic-Jurassic strata and the Barrow Group across the Exmouth Sub-basin (Figures 20, 21). This tectonism resulted in the development of the regional structural dip to the north.
After tectonic uplift and continuous active faulting associated with the breakup of Greater India and Australia during the Valanginian, a large portion of the Carnarvon Basin was subjected to peneplanation (Geoscience Australia, 2010). This event was followed by the regional early passive margin sedimentation in the offshore part of the Carnarvon Basin from the middle Valanginian to middle Santonian (Figures 6b, 19, 20, 22). The Valanginian unconformity is interpreted as the end of active tectonism of the bounding normal faults across the study area.

During the Cretaceous, at least two phases of uplift and erosion occurred, and then further inversion and tilting occurred in the Tertiary (Tindale et al., 1998) (Figures 6b, 21). Due to the high sedimentation rate being much higher than the subsidence rate, there was increased progradation of sediments (Barrow Group) as the basin was filled (Figures 6-23).

**Late Passive Margin Phase:** The late passive margin phase is marked by the Santonian unconformity (or Turonian unconformity) (Figures 6b, 22). After the Santonian unconformity (or Turonian unconformity), siliciclastic sedimentation ended due to the decrease of terrigenous sediments supply from the south-southeast. Shelfal carbonate sediments with minor siliciclastic sediments developed on the passive continental margin throughout the Late Cretaceous and Cenozoic. The entire region continued to subside after the end of the rift tectonism (Figures 19D, 20D). In addition, because the subsidence rate was greater than the rate of sedimentary supply, the sediments deposited during this period are relatively thin, in particular across the Exmouth Plateau (Geoscience Australia, 2010). Towards the end of the Cretaceous,
however, the Kangaroo Syncline on the Exmouth Plateau became the major depocenter of the Carnarvon Basin (Geosience Australia, 2010) (Figures 1, 2, 5-10, 12, 13).

During the Late Cretaceous (Campanian), compression generated localized structural deformation and strike-slip faults throughout the North West Shelf (Tindale et al., 1998). An inversion tectonic phase, short and localized episodes of compression in the Exmouth Plateau and Exmouth Sub-basin were occurred by the uplift of the hinterland. This inversion formed the Exmouth Plateau Arch, Novara Arch, and Resolution Arch (Figures 6, 8-11, 18, 19). In addition, this tectonic inversion marked the onset of transpressional structural growth of pre-existing rift-related structures within the Barrow and Dampier Sub-basins (Longley et al., 2002). The reactivation by compressional and transpressional movements are indicated by the change of fault displacement along the bounding faults of the study area (Figure 6b). During the Miocene, a compressional event, related to the collision of the Australia-India and Eurasia plates, affected the entire northwest Australian margin, including the Northern Carnarvon Basin (Longley et al, 2002), resulting in structural inversion. Deep-seated normal faults were reactivated as reverse faults resulting in gently dipping monoclines formed in the Neogene strata (Figure 6). On the shelf, prograding wedges of carbonates built outward into the deeper water. Seismic profiles included in this study show that the carbonate wedges (Figures 6, 8) prograded on the order of 100 km (Westphal et al, 1997) and infilled the accommodation from the Oligocene to the Miocene.
Stratigraphic Evolution

The Mesozoic stratigraphic evolution of the Northern Carnarvon Basin is reviewed in some detail here to establish the regional setting for this study, as well as introduce the other elements of the petroleum systems of the Northern Carnarvon Basin.

During the Early Triassic, the Locker Shale was deposited in a regional marine transgression in shallow shelf environments (Figures 4, 22). The Locker Shale is overlain by a thick succession of the fluvio-deltaic Mungaroo Formation (Figures 4, 6b, 19, 20, 22), which was deposited in a broad, low relief, rapidly subsiding coastal plain including an extensive swamp system (Tindale et al., 1998). This fluvio-deltaic system prograded extensively northwestward, and covered most of the Northern Carnarvon Basin. The source of these strata was provided by major uplift and erosion in the onshore Northern Carnarvon Basin.

During the Late Triassic and Early Jurassic, the transgressive Brigadier Formation and Murat Siltstone were deposited in a marine shelf environment (Figures 4, 6b, 19, 20, 22). The overlying marine claystones of the Athol Formation and deltaic sandstones of the Legendre Formation were deposited locally during the Middle Jurassic (Figures 4, 6b, 19, 20, 22). During the Late Jurassic, the deep-water Dingo Claystone was deposited in the graben, particularly in the Exmouth Sub-basin in response to continental breakup (Figures 4, 6b, 20, 22).

During the early Berriasian, uplift of the southern Exmouth Sub-basin provided the primary source of sediments for the Barrow Group, which was a north-northeast trending major progradational delta across the Exmouth Sub-basin and the southern
and central Exmouth Plateau (Figures 6-23). Thus, the origin of the Barrow Group is considered to be caused by the tectonic uplift prior to the final phase of continental breakup and the onset of seafloor spreading during the Valanginian (Boote and Kirk, 1989). The strata of the Barrow Group are up to 2,500 m thick and they covered the Alpha Arch by the middle Berriasian (Smith et al, 2003) and extended to the Barrow Sub-basin (Figures 2, 23). This delta shows well-developed progradational clinoforms composed of two main phases of deltaic progradation, informally divided into the lower delta and upper delta (Figures 7-11, 19, 20, 23). The lower delta phase developed over the Exmouth Sub-basin as the sediments were derived from the south. The delta prograded rapidly to the north over a thick turbidites and prodelta shales to a maximum northward limit roughly west from Barrow Island across the Exmouth Plateau (Figures 2, 3, 23) (Geoscience Australia, 2010). On the Exmouth Plateau, the Barrow Group consists of variable facies of deposition such as turbidites, basin-floor fans and fluvio-deltaic strata of the lower delta. North of the delta front, a major deepwater fan was deposited that forms the reservoir at the Scarborough gas field (Cossey et al., 2008) (Figures 2, 3, 5-7).

During the Valanginian, the upper delta of the Barrow Group developed as a series of backstepping deltas in the Exmouth Sub-basin (Figures 7-13, 19B, 20B). This second phase of delta deposition extended its northern depositional limit around the Gorgon horst structure. The limit of the upper delta strata (Zeepaard Formation) is shown in Figure 23. The Zeepaard Formation was deposited across the Exmouth Sub-basin as well-developed progradational top-set units of the Barrow Group during the early Valanginian (Figures 6b, 9c, 19, 20, 21). Subsequently, the Birdrong Sandstone...
Figure 23. Paleogeographic map showing positions of maximum deltaic progradation during the Early Cretaceous, and directions of progradation (red arrows). The maximum areal extent of the Barrow Group delta and the overlying Zeepaard Formation are shown. Location of fields and key wells are shown (modified from Boyd et al., 1992; Smith et al., 2003; Geoscience Australia, 2008).
represents the localized deposits of the coastal plain or deltas and shelf environments overlying the Zeepaard Formation (Figures 8-13, 15, 16, 19B, 20B).

These upper delta strata of the Barrow Group are overlain by the transgressive marine Muderong Shale and Gearle Siltstone (Figures 6b, 9c, 14, 16, 19C, 20C). This regional transgression was caused by the subsidence associated with the continental breakup in the area. The base of the Muderong Shale is the Mardie Greensand Member, which is an extensive marine transgressive unit.

The Upper Cretaceous to Cenozoic strata were dominated by extensive deposition of marine carbonates (Toolonga Calcilutite) in an open marine shelfal environment. The source of siliciclastic sediments had been eroded by the Santonian, and local oceanographic conditions were favorable to the development of carbonate sediments.

IV. SEQUENCE STRATIGRAPHIC ANALYSIS

METHODOLOGY AND INTERPRETATION PROCEDURE

Seismic Interpretation

The basic sequence stratigraphic interpretation methodology was used for this study, as defined by Vail (1977) and Mitchum et al. (1993). The interpretation workflow chart is summarized in Figure 24. First, the major regional sequence boundaries were defined, specifically the Valanginian, Hauterivian, Aptian, Turonian, and Base Tertiary sequence boundaries (Figures 6-18, 21). Major megasequence boundaries were tied to the wells by the generation of the synthetic seismograms (Figures 25-28).
Figure 24. Interpretation workflow chart

SET STUDY
OBJECTIVES

DATA COLLECTION
(seismic, well logs, previous studies)

COMPREHENSION OF
REGIONAL GEOLOGIC SETTINGS

SEISMIC SEQUENCE STRATIGRAPHY INTERPRETATION
- Seismic interpretation of key regional surfaces (sequence boundaries)
  - Identify the type of reflection termination
    (onlap, downlap, toplap, erosional truncation)
  - Well-to-seismic tie by synthetic seismogram
  - Generate structural contour map and isochron map
- Well log data interpretation and regional well correlation
- Seismic facies analysis and facies mapping
- Interpret structural evolution with paleo-geographic reconstruction

DISCUSSION

CONCLUSION & RECOMMENDATION
Figure 25a. Time-depth conversion curve for the Scarborough 2 well. See Figures 2 and 3 for the location of this well.
Figure 25b. Time-depth conversion curve for the Leyden 1B ST well. See Figures 2, 3, and 5 for the location of this well.
Figure 26. Generated synthetic seismogram panels for the Scarborough 2 well based on using SMT SynPAK. Display shows the gamma ray log as a reference, calculated acoustic impedance (AI) curve, reflection coefficient (RC) and the comparison between seismic trace and the synthetic trace.
Figure 27: Seismic profile showing well-to-seismic tie using the synthetic seismogram of the Scarborough 2 well. Scarborough 1 and 2 wells penetrated four-way closure of turbidite fan reservoir (yellow shaded) in the Barrow Group. The profile clearly shows the high amplitude anomaly (flat spot - direct hydrocarbon indicator (DHI)) of fluid contact in the reservoir. See Figures 2 and 3 for the location of the wells and this seismic profile (GWC = gas-water contact).
Figure 28. Schematic interpretation of the cross section along the combined profile A-A' throughout the Exmouth Plateau and Exmouth Sub-basin. Note that the section is flattened on the Valanginian unconformity. See Figure 2 for the location of the combined line.
Due to relatively few exploration wells drilled near seismic profiles in this study area, well-to-seismic ties are limited to only two of wells in the Exmouth Plateau and Exmouth Sub-basin; Scarborough 2, and Leyden 1B ST1 wells (Figures 2, 3, 5, Table 3). To ensure the quality control of the initial sequence interpretation, the resultant horizon picking was compared with the previous studies of the area (Bradshaw et al., 1998; Tindale et al., 1998). Then, additional sequence boundaries were identified, based on the reflection terminations (erosional truncation, onlap, toplap and downlap).

The interpretation recognized fifteen sequence boundaries and three major downlap surfaces or flooding surfaces. Once the seismically mappable units representing either individual or composite depositional sequences were defined, then structural contour maps and isochron maps for each individual sequence were generated.

**Regional Well Correlation**

Based on the gamma-ray logs, correlatable marker surfaces are recognized by an abrupt change of the log responses due to the major lithology changes. The basic principle to perform regional multi-well correlation is to identify the laterally correlatable marker surfaces, formation tops of each well log, by displaying and interpreting geologic data in depth. The formation top information and litho-stratigraphic analysis data for each well was acquired from well completion reports in the web site of Geoscience Australia (Virtual Data Room [Web page]; http://vdr.ga.gov.at and Tables 3, 4).

Key marker horizons such as the Valanginian unconformity, Aptian unconformity, and Turonian unconformity were found in every well without exception (Figures 6-21).
Therefore, the marker horizons were correlated among the existing wells via formation top information (Table 4), and then facies distribution information was added onto the well log cross section (Figures 30, 32). In particular, the results of well correlations helped to identify the locally developed significant depositional sequences such as the Birdrong and Mardie Greensand Formations, which could not be easily identified in the 2-D seismic profiles. Last, the comparison between well-to-well correlation and stratigraphic analysis based on 2-D combined seismic lines was followed to provide a good understanding of the geometry and depositional setting of the sequences (Figures 30-33).
Table 4. Well log formation tops

<table>
<thead>
<tr>
<th>Formation Top</th>
<th>Wells</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Investigator 1 (MDRKB m)</td>
<td>Zeewulf 1 (MDRKB m)</td>
<td>Resolution 1 (MDRKB m)</td>
<td>Eskdale 1 (MDRKB m)</td>
<td>Leyden 1B ST1 (MDRKB m)</td>
<td>Zeepaard 1 ST1 (MDRKB m)</td>
</tr>
<tr>
<td>Base Tertiary</td>
<td>1,010</td>
<td>1,779</td>
<td>1,655</td>
<td>1,325</td>
<td>1,371</td>
<td>1,320</td>
</tr>
<tr>
<td>Top Toolonga</td>
<td>1,328</td>
<td>2,200</td>
<td>1,703</td>
<td>1,415.5</td>
<td>1,855 (?)</td>
<td>1,697</td>
</tr>
<tr>
<td>Base Toolonga</td>
<td>1,359</td>
<td>2,361</td>
<td>1,895</td>
<td>1,439</td>
<td>2,562</td>
<td>2,625</td>
</tr>
<tr>
<td>Top Gearle</td>
<td>1,402</td>
<td>2,361</td>
<td>1,895</td>
<td>1,439</td>
<td>2,562</td>
<td>2,625</td>
</tr>
<tr>
<td>Base Gearle</td>
<td>1,492</td>
<td>2,443</td>
<td>2,030</td>
<td>1,493.5</td>
<td>2,688</td>
<td>2,815</td>
</tr>
<tr>
<td>Top Mardie</td>
<td>1,513</td>
<td>2,630</td>
<td>2,239</td>
<td>1,511.5</td>
<td>2,887 (?)</td>
<td>3,041</td>
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<tr>
<td>Greensand</td>
<td>2,392</td>
<td>3,056</td>
<td>2,961</td>
<td>2,747</td>
<td>3,801</td>
<td>3,865</td>
</tr>
</tbody>
</table>

*MDRKB : measured depth from rotary kelly bushing

Turonian unconformity

Aptian unconformity

Hauterivian unconformity

Valanginian unconformity
Figure 29. Base map showing 2D seismic profiles and well locations for seismic facies analysis. Major oil and gas fields near the study area and five exploration wells are shown. Key strike oriented (NE-SW direction) and dip-oriented (NW-SE direction) seismic profiles (green lines) for major sequence interpretation and facies analysis are shown.
Figure 30. Well log cross section in the Exmouth Plateau and Exmouth Sub-basin along A-A' (Investigator 1 to Eskdale 1 well) showing the Lower to Upper Cretaceous strata. See Figures 2, 3, 5, and 29 for well locations.
Figure 31a. Regional dip-oriented combined seismic profile: (a) uninterpreted, (b) interpreted.
Figure 31b. Cross section of the regional dip-oriented combined seismic profile the comparison with well log correlation in Figure 30. All of the interpreted sequence boundaries with reflection terminations (arrows = onlap) were used to help constrain well correlation. Time-based gamma ray logs of the Investigator 1, Zeewulf 1 and Resolution 1 well are displayed. See Figure 2 for the location of the combined line A-A’. Also, see Figures 34-36 for details of the wells (U/C = unconformity).
Figure 32. Well log cross section in the Exmouth Plateau and Exmouth Sub-basin along B-B' (Zeewulf 1 to Zeepaard 1 ST1 well) showing the Lower to Upper Cretaceous strata. See Figures 2, 3, 5, and 29 for well locations.
Figure 33a. Regional dip-oriented combined seismic profile: (a) uninterpreted, (b) interpreted.
Figure 33b. Cross section of the regional strike-oriented combined seismic profile for the comparison with well log correlation in Figure 32. All of the interpreted sequence boundaries with reflection terminations (arrows = onlap, downlap) were used to help constrain well correlation. Time-based gamma ray logs of the Resolution 1, Zeewulf 1, Leyden 1B ST and Zeepaard 1 ST1 well are displayed. See Figure 2 for the location of the combined line B-B'. Also, see Figures 35-38 for details of the wells (DLS = downlap surface, U/C = unconformity).
Time-Depth Conversion and Synthetic Seismogram

Conversion from time-to-depth was required for constructing the synthetic seismograms, so that the depth-based well logs could be tied to the travel time-based seismic data (Figure 27). In general, time-depth conversion uses the check shot or VSP (Vertical Seismic Profile) data to generate a travel time to depth relationship. Synthetic seismograms were used to tie precisely the depth-based well logs to seismic to identify the major key stratigraphic markers such as formation tops (Table 4) and unconformities.

To create synthetic seismograms for the wells in the study area, sonic logs, density logs and time-depth conversion charts from Scarborough 2 and Leyden 1B ST1 well were used in the SMT 2-D/3-D seismic interpretation package. The VSP data, sonic log (DT), and density log (RhoB) were used for calculating the interval velocity, the acoustic impedance (AI) and reflection coefficient (RC). The acoustic impedance or AI response from the wells is calculated by:

\[
AI = \text{density } (\rho) \times \text{velocity } (v)
\]

From this equation, sonic and density data are averaged over chosen time intervals and reflection coefficients (RC) are then computed using:

\[
RC = \frac{\rho_2 \cdot v_2 - \rho_1 \cdot v_1}{\rho_2 \cdot v_2 - \rho_1 \cdot v_1}
\]

\(\rho_1\) = density of the layer above the reflection interface

\(\rho_2\) = density of the layer below the reflection interface

\(v_1\) = compressional wave velocity of the layer above the reflection interface

\(v_2\) = compressional wave velocity of the layer below the reflection interface
The resulting reflection coefficient curve was convolved with the seismic wavelet to create the synthetic seismogram using SynPAK module of SMT (Figures 26, 27). Well logs and well-to-seismic ties are shown in Figures 34-39.

**2-D Seismic Facies Analysis**

Once the major seismic sequence boundaries were identified, the seismic facies within each sequence were analyzed and plotted regionally on maps. The basic techniques for 2-D seismic facies analysis, as outlined by Ramsayer (1979), were followed in this study. The standard seismic facies code used for each facies map is shown in Table 5.

Seismic facies analysis was performed using approximately 915 km of the key regional 2-D seismic profiles (Figure 29). Based on the 2-D seismic interpretation conducted on Kingdom SMT, nine facies maps were created. These represent a spectrum of different depositional systems reflecting dynamic interactions among sediment influx, basin subsidence and eustasy.
Figure 34a. Investigator 1 well showing gamma ray log interval from 900 to 1750 m with stratigraphic column and depositional environment of the Cretaceous sequences. Interpreted grain size trends are shown by red arrows. See Figures 2, 3, 5, 40-42, 48-58, 64-72, and 80-84 for the well location and facies maps.
Figure 34b. Well-to-seismic tie in Investigator 1 well is shown. Interpreted sequence boundaries 1-10 and formations are illustrated on the seismic profile. See Figures 3, 5, and 29 for the location of seismic profile and well.
Figure 35a. Zeewulf 1 well showing the gamma ray log interval from 1750 to 2700 m with stratigraphic column and depositional environment of the Cretaceous sequences. Interpreted grain size trends are shown by red arrows. See Figures 2, 3, 5, 40-42, 48-58, 64-72, and 80-84 for the well location and facies maps (FS = flooding surface).
Figure 35b. Well-to-seismic tie in Zeewulf 1 well is shown. Interpreted sequence boundaries 1-10 and formations are illustrated on the seismic profile. See Figures 3, 5, and 29 for the location of seismic profile and well.
Figure 36a. Resolution 1 well showing the gamma ray log interval from 1600 to 2290 m with stratigraphic column and depositional environment of the Cretaceous sequences. Interpreted grain size trends are shown by red arrows. See Figures 2, 3, 5, 40-42, 48-58, 64-72, and 80-84 for the well location and facies maps (FS = flooding surface).
Figure 36b. Well-to-seismic tie in Resolution 1 well is shown. Interpreted sequence boundaries 1-9 and formations are illustrated on the seismic profile. See Figures 3, 5, and 29 for the location of seismic profile and well.
Figure 37a. Leyden 1B ST1 well showing the gamma ray log interval from 1600 to 2990 m with stratigraphic column and depositional environment of the Cretaceous sequences. Interpreted grain size trends are shown by red arrows. See Figures 2, 3, 5, 40-42, 48-58, 64-72 and 80-84 for the well location and facies maps (FS = flooding surface, MFS = maximum flooding surface).
Figure 37b. Well-to-seismic tie in Leyden 1B ST1 well is shown. Interpreted sequence boundaries 1-8 and formations are illustrated on the seismic profile. See Figures 3, 5, and 29 for the location of seismic profile and well (DSL = downlap surface).
Figure 38a. Zeepaard 1 ST1 well showing the gamma ray log interval from 2250 to 3800 m with stratigraphic column and depositional environment of the Cretaceous sequences. Interpreted grain size trends are shown by red arrows. See Figures 2, 3, 5, 40-42, 48-58, 64-72, and 80-84 for the well location and facies maps (FS= flooding surface).
Figure 38b. Well-to-seismic tie in Zeepaard 1 ST1 well is shown. Interpreted sequence boundaries 1-8 and formations are illustrated on the seismic profile. Shaded orange areas indicate presence of sandstone bodies. See Figures 3, 5, and 29 for the location of seismic profile and well.
Figure 39a. Eskdale 1 well showing the gamma ray log interval from 1230 to 1520 m with stratigraphic column and depositional environment of the Cretaceous sequences. Interpreted grain size trends are shown by red arrows. See Figures 2, 3, 5, 40-42, 48-58, 64-72, and 80-84 for the well location and facies maps.
Figure 39b. Well-to-seismic tie in Eskdale 1 well is shown. Interpreted sequence boundaries 1-10 and formations are illustrated on the seismic profile. See Figures 3, 5, and 29 for the location of seismic profile and well.
Table 5. Seismic facies codes and examples of seismic stratigraphic reflection terminations within idealized seismic sequence (after Mitchum et al, 1977)
SEQUENCE STRATIGRAPHY

Key Litho-Stratigraphic Intervals

One of the challenges in establishing the sequence stratigraphic framework is in the comparison of traditional litho-stratigraphic units and terminology with those sequences defined here. The key litho-stratigraphic intervals and terms used for the Northern Carnarvon Basin are reviewed here so that traditional litho-stratigraphic terms (Formation, Group) and informal terms (lithologies) can be related to the chrono-stratigraphic framework defined in this study. These terms and their relative ages are shown in Figures 30 and 32.

**Barrow Group:** This group includes formations between the Upper Jurassic Dingo Claystone and the Lower Cretaceous Muderong Shale. It consists of a deltaic complex, which prograded north from the southernmost area of the Barrow Sub-basin (Figures 4, 6-23, 30-33).

**Zeepaard Formation:** This formation is the upper part of the Barrow Group. It was deposited extensively across the Exmouth Sub-basin, Exmouth Plateau, Barrow Sub-basin, and Rankin Platform as progradational clinoforms (upper delta units) during the early Valanginian. It is informally called “upper delta unit” of the Barrow Group delta, and is largely sandstone (Figures 4, 9c, 19, 20). For this thesis, the Zeepaard Formation has been used for naming according to the well completion reports available in the study area to avoid confusion. This formation is equivalent to sequences 1 to 3 of this thesis (Figures 30, 32).
**Birdrong Formation:** The Birdrong Formation is a sandstone dominated, commonly glauconitic, and silty interval overlying the Zeepaard Formation, and conformably overlain by the Muderong Shale (Figures 4, 8-11, 19, 20). This formation is equivalent to sequence 4 of this thesis (Figures 30, 32).

**Mardie Greensand Member:** This formation is transitional between the Birdrong Sandstone and Muderong Shale in the Exmouth Sub-basin, and consists of dark-green, glauconitic and sandy siltstone interbedded with shale (Figures 4, 19, 20). This is the lower portion of sequence 5 of this thesis (Figures 30, 32).

**Muderong Shale:** This is a shale dominated interval rests conformably and unconformably on the Barrow Group and in some cases older rocks. The Muderong Shale was deposited in a low energy, offshore marine environment during a transgression (Figures 4, 19, 20). This is equivalent to sequence 5 of this thesis (Figures 30, 32).

**Gearle Siltstone:** This is a silty and clayey interval from Albian to Turonian in age, which overlies the Muderong Shale and is unconformably overlain by the Toolonga Calcilutite (Figures 4, 19, 20). This is equivalent to sequences 6 to 8 of this thesis (Figures 30, 32).

**Toolonga Calcilutite:** These are calcareous pelagic deposits, which unconformably overlie the Gearle Siltstone. Deposition of the Upper Cretaceous Toolonga Calcilutite marked the beginning of widespread carbonate sedimentation and the end of significant terrigenous influx into the study area (Figures 4, 19, 20). This is equivalent to sequence 9 of this thesis (Figures 30, 32).
Regional Summary of Cretaceous History

The Cretaceous sequences on the Exmouth Plateau and the Exmouth Sub-basin overlie (a) the sequences of the Jurassic shelf sediments, which are equivalent to the Dingo Claystone, or (b) the Triassic paralic to fluvio-deltaic non-marine sequences (Haq et al, 1992). Nine depositional sequences in the Lower and Upper Cretaceous (Valanginian to Santonian) have been identified and correlated on reflection seismic profiles and mapped throughout the Exmouth Plateau and Exmouth Sub-basin study area (Figures 10-18). The depositional sequences are named as sequence 1 to 9 in decreasing age.

All nine Cretaceous sequences represent a spectrum of the depositional systems that illustrate interactions between the sediment supply, basin subsidence, and global eustasy. The ages of the sequence boundaries are: SB1 (lower Valanginian), SB2 (middle Valanginian), SB3 (upper Valanginian), SB4 (lower Hauterivian), SB5 (Top Birdrong Formation – middle Hauterivian), SB6 (lower Aptian), SB7 (Base Albian), SB8 (Top Albian), SB9 (lower Turonian), and SB10 (upper Santonian). Most of the interpreted sequences contain shelf facies or delta-slope-basin facies.

Each sequence from the upper Barrow Group to Toolonga Formation is described systemically, which includes seismic interpretation on the key 2-D seismic profiles, time-structure contour maps, isochron maps, and facies analysis (including facies tables summary and seismic facies maps).
Sequence 1: lower to middle Valanginian (140-138 Ma)

Time Thickness and Structure

The isochron (time thickness) values of the sequence 1 range from 0 to 140 msec (two-way travel time), with the thickest interval in the Exmouth Plateau (Figure 35). The sequence displays northwestward thinning toward the Exmouth Plateau, where it thins and pinches out (Figures 9-13, 17, 19, 20). The sequence also thins appreciably to the southeast. This overall thickness distribution is due to the features of prograding delta and related sediments (Figure 40).

The time-structure map of the lower Valanginian unconformity (SB1) illustrates the three arches distributed across the study area, all of which are cut by high-angle normal faults (Figure 41): (1) the northeast-southwest trending Exmouth Plateau Arch, located in the northwestern corner of the study area (Figures 8, 11); (2) northeast-southwest trending Resolution Arch (Figures 5, 6, 8-10, 12, 13, 19, 20, 31, 33); and (3) northwest-southeast trending Novara Arch (Figures 5, 8, 10), both of which are located in the southeastern corner of the study area. The Kangaroo Syncline trends southwest-northeast and is located in the middle of the study area; it marks the boundary between the Exmouth Plateau and the Exmouth Sub-basin (Figures 1, 2, 5-10, 12, 13, 19, 20, 41).

Upper and Lower Boundaries

Sequence 1 is defined at its base by sequence boundary 1 (SB1) and the top by sequence boundary 2 (SB2) (Figures 8-17). The basal horizon of sequence 1, which coincides with the lower Valanginian unconformity, is a laterally continuous, high-
Figure 40. Isochron map (in TWTT msecs) of sequence 1 (lower Valanginian - middle Valanginian). The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
Figure 41. Time-structure map of the Valanginian unconformity (SB1) in the study area. Contour interval is 50 msec. Major northeast-southwest striking normal faults are shown. Note the marked structural highs of the Resolution Arch (NE-SW) and Novara Arch (NW-SE), and the major northeast to southeast elongate Kangaroo Syncline in the study area. To the northwest, Exmouth Plateau Arch is shown. Location of five exploration wells are shown. See Figures 29, 40, and 42 for the distribution of seismic profiles used for generating this map.
amplitude reflection compared with the over- and underlying intervals of laterally discontinuous, low-amplitude reflections (Figures 8-18). In addition, the lower boundary is a prominent unconformity across the Exmouth Plateau Arch where the Investigator 1 well is located (Figures 8, 11); the erosion becomes gradually conformable toward the Kangaroo Syncline and Exmouth Sub-basin (Figures 5, 11, 20). The top of sequence 1 is defined by sequence boundary 2 (SB2) that is approximately middle Valanginian. This sequence boundary (SB2) is identified by locally developed toplapping reflection terminations with relatively discontinuous, moderate-amplitude reflection in one area (Figures 18, 19, 21, 22). Throughout most of the study area, the reflections are concordant (parallel) in under- and overlying reflections within the progradational package in the upper delta of the Barrow Group. Seismically, the underlying lower delta unit of the Barrow Group consists of numerous higher-order sequence boundaries and downlap surfaces (Ross and Vail, 1994) (Figures 8-11).

**Seismic Facies**

Two dominant seismic facies were identified and mapped throughout the study area (Figures 42-47). The seismic facies are summarized in Table 6, and are illustrated on the seismic facies map (Figure 42).

Internally, sequence 1 is characterized by high-amplitude reflections that are generally parallel or subparallel with fair to good continuity for more than 100 kilometers. Seismic facies 1 shows toplap terminations along the upper sequence boundary and downlap terminations onto the lower sequence boundary. The internal reflections are mostly sigmoid or complex sigmoid-oblique geometry with moderate- to high-amplitude reflections.
Figure 42. 2D seismic and geologic facies map of sequence 1 (lower to middle Valanginian). The red arrows indicate the direction of deltaic progradation. The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. See Table 6 for a summary of the coded seismic facies. Location of figures of key regional profiles (blue lines), and five exploration wells are shown.
Figure 43. Strike-oriented seismic profile illustrating the seismic facies of sequence 1 (lower Valanginian unconformity to middle Valanginian), sequence 2 (middle to upper Valanginian) and sequence 3 (upper Valanginian to lower Hauterivian unconformity): (a) uninterpreted, (b) interpreted. Sequences 1 to 3 have similar seismic facies associated with progradation. See Tables 3, 6, 7, 8 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile (U/C = unconformity).
Figure 44. Dip-oriented seismic profile illustrating the seismic facies of sequence 1 (lower Valanginian unconformity to middle Valanginian), sequence 2 (middle to upper Valanginian) and sequence 3 (upper Valanginian to lower Hauterivian unconformity): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 1 (Magenta), sequence 2 (orange), and sequence 3 (yellow). Colored arrows indicate reflection terminations (red = onlap and toplap; green = downlap). A potential play is shown (orange shaded). See Tables 3, 6, 7, 8 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 45. Strike-oriented seismic profile illustrating the seismic facies of sequence 1 (lower Valanginian unconformity to middle Valanginian), sequence 2 (middle to upper Valanginian) and sequence 3 (upper Valanginian to lower Hauterivian unconformity): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 1 (Magenta), sequence 2 (orange), and sequence 3 (yellow). Time-based gamma ray log of the Zeewulf 1 well is displayed. See Tables 3, 6, 7, 8 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile (DLS = downlap surface, U/C = unconformity).
Figure 46. Strike-oriented seismic profile illustrating the seismic facies of sequence 1 (lower Valanginian unconformity to middle Valanginian), sequence 2 (middle to upper Valanginian) and sequence 3 (upper Valanginian to lower Hauterivian unconformity): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 1 (Magenta), sequence 2 (orange), and sequence 3 (yellow). Colored arrows indicate reflection terminations (green = downlap). A carbonate buildip above the Turonian unconformity is shown. A potential play (deepwater onlap play) is shown (orange shaded). See Tables 3, 6, 7, 8 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile (DLS = downlap surface, U/C = unconformity).
Figure 47. Dip-oriented seismic profile illustrating the seismic facies of sequence 1 (lower Valanginian unconformity to middle Valanginian), sequence 2 (middle to upper Valanginian) and sequence 3 (upper Valanginian to lower Hauterivian unconformity): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 1 (magenta), sequence 2 (orange), and sequence 3 (yellow). Colored arrows indicate reflection terminations (red = toplap; green = downlap). The Birdrong Formation is not present in this part of the profile. A potential play (deepwater onlap play) is shown (orange shaded). See Tables 3, 6, 7, 8 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile (DLS = downlap surface, U/C = unconformity).
and poor continuity (Figures 43-47). In contrast, seismic facies 2 shows concordant reflections at both the upper and lower sequence boundaries, with subparallel and partially hummocky internal reflections, moderate-amplitude, and fair continuity (Figures 43-47).

Table 6. Seismic facies and geologic interpretation of sequence 1

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>toplap</td>
<td>downlap</td>
<td>complex sigmoid-oblique</td>
<td>moderate to high</td>
<td>poor</td>
<td>delta front</td>
</tr>
<tr>
<td>2</td>
<td>concordant</td>
<td>concordant</td>
<td>subparallel (partially hummocky)</td>
<td>moderate</td>
<td>fair</td>
<td>delta plain</td>
</tr>
</tbody>
</table>

**Wireline log**

Sequence 1 is thickest in the Zeewulf 1, Resolution 1, Leyden 1B ST1 and Zeepaard 1 ST1 wells (Figures 35-38), where the deltaic-related lithofacies are best developed. In Zeepaard 1 ST1 and Leyden 1B ST1 wells (Figures 37, 38), well-defined upward coarsening patterns associated with deltaic progradation are present. In contrast, in the Resolution 1 well (Figure 36), a sharp base, upward fining pattern is present (2239-2200 m), representing the initial transgression after the Valanginian unconformity. The deepest water associated with the transgression is the shale unit between 2170 and 2200m. The progradation of the delta is present between 2170 and 2080 m.

In contrast, sequence 1 is considerably thinner in Investigator 1 and represents distal bottomset of the progradation (Figures 8-13, 17, 34). Sequence 1 is also thinner in
Eskdale 1 due to the convergence and thinning of the sequences overlying the Resolution Arch (Figures 5, 6, 8-10, 12, 13, 19, 20, 31, 33, 39).

**Interpretation**

Tectonically, the lower Valanginian unconformity is interpreted as the sequence boundary between the late syn-rift and passive margin phase of tectonism in the Northern Carnarvon Basin (Figures 4, 6b). Numerous high-angle normal faults and strike-slip faults cut the underlying Jurassic strata and form a series of grabens, half-grabens, and horsts (Figures 6, 7, 8, 10, 19, 20). However, the faults do not cut significantly into the overlying Lower Cretaceous strata (Figures 8-10).

Sequence 1 represents initial deposition on the pre-existing shelf of the "lower delta" of the Barrow Group. After the development of the lower Valanginian unconformity, there was a regional transgression and backstepping of shallow marine environments across the pre-existing shelf, as indicated by the Resolution 1, Leyden 1B ST1, and Zeepaard 1 ST1 wells (Figures 36-38).

Based on the integration of isochron map, well log interpretation, and 2-D facies map, sequence 1 is composed of a delta-to-prodelta succession (Figures 34-38, 40-42). The interpreted depositional environments from the facies analysis suggest that sequence 1 is a composite of several depositional systems related to prograding deltas. In particular, seismic facies 1 and 2 are interpreted to represent the delta front and delta plain depositional setting, respectively. The depositional environments change from delta plain, through delta front, to pro-delta from southeast to a more northwest direction following deltaic migration from the continental shelf located in southeast direction. This
is shown in detail in the facies map (Figure 42). The source of sediments for this sequence as well as the overlying deltaic packages are interpreted to be south of the Exmouth and Barrow Sub-basins, which is related to uplift during the Valanginian (Figure 6).

Sequence 2: middle to upper Valanginian (138-136 Ma)

Time Thickness and Structure

The isochron values of the sequence 2 range between 0 to more than 100 msec (two-way travel time) in the study area (Figure 48). Similar to the underlying sequence 1, this sequence also displays thinning northwestward toward the Exmouth Plateau, which indicates the depositional limit of the progradational delta, and thins to the east/southeast (Figures 8-13, 16-20, 43).

The time-structure map of the sequence boundary 2 (SB2) illustrates the same structural features that are present in the time-structure map of sequence boundary 1 (Figure 49): (1) northeast-southwest trending Resolution Arch (Figures 5, 6, 8-10, 12, 13, 19, 20, 31, 33), (2) northwest-southeast trending Novara Arch, both of which are located in the southeastern corner of the study area (Figures 5, 8, 10), and (3) southwest-northeast elongate Kangaroo Syncline that is located in the middle of the study area (Figures 1, 2, 5-10, 12, 13, 19, 20, 41).

Upper and Lower Boundaries

Sequence 2 is defined at its base by sequence boundary 2 (SB2) and the top by sequence boundary 3 (SB3) (Figures 8-17, 43-47). The basal horizon of sequence 2,
Figure 48. Isochron map (in TWTT msecs) of the sequence 2 (middle Valanginian - upper Valanginian). The average thickness of sequence 2 ranges between 20 to 50 msec with maximum thickness of 80 to 100 msec along the delta front setting. The northwest-southeast thickness trend is caused in part by regional facies changes. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
Figure 49. Time-structure map of SB2 (middle Valanginian) in the upper delta of the Barrow Group. Contour interval is 50 msec. Major northeast-southwest trending normal faults and southeastern structural elements are shown; Novara Arch, Resolution Arch and Kangaroo Syncline. Location of five exploration wells are shown. See Figures 29, 48, and 50 for the distribution of seismic profiles used for generating this map.
which approximately coincides with the middle Valanginian, is a laterally continuous to discontinuous, moderate- to high-amplitude reflection characterized by locally developed toplapping reflection terminations below in underlying sequence 1. In addition, the basal horizon of sequence 2 is characterized by subtle downlapping reflection terminations (Figures 9-11). The top of sequence 2 is also defined by locally developed toplapping reflections with continuous and partially discontinuous reflection with moderate- to high-amplitude. Thus, the upper and lower sequence boundaries of sequence 2 are characterized by partially developed, toplapping reflection terminations, and the correlative and conformable surface related to the deltaic progradation. The toplapping reflections are restricted to the area of progradational clinoforms. Thus, the sequence boundaries across the remainder of the area appear to have concordant reflections with laterally continuous as well as moderate- to high-amplitude observed on seismic profiles (Figures 12-17).

**Seismic Facies**

Two dominant seismic facies (facies 1 and 2), which are similar to the main seismic facies of sequence 1, were identified and mapped throughout the study area based on the seismic facies analysis (Figures 43-47, 50). The seismic facies are summarized in Table 7 and illustrated on the seismic facies map (Figure 50).

In seismic facies 1, the upper and lower sequence boundaries show toplap and downlap reflection terminations, respectively. The internal reflections are a sigmoid or complex sigmoid-oblique progradational geometry (Figures 43-47). The reflections are characterized by moderate-amplitude and poor continuity. In seismic facies 2, the upper
Figure 50. 2D seismic and geologic facies map of sequence 2 (middle Valanginian - upper Valanginian) in the Zeepaard Formation. The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. See Table 7 for a summary of coded seismic facies and geologic information. Location of figures of key regional profiles (blue lines), and five exploration wells are shown.
and lower sequence boundaries are characterized by more concordant reflections (Figures 43-47). The internal reflections are generally subparallel with moderate- to partially high-amplitude and fair to good continuity.

Table 7. Seismic facies and geologic interpretation of sequence 2

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>toplap</td>
<td>downlap</td>
<td>complex sigmoid-oblique</td>
<td>moderate</td>
<td>poor</td>
<td>delta front</td>
</tr>
<tr>
<td>2</td>
<td>concordant</td>
<td>concordant</td>
<td>subparallel</td>
<td>moderate to high</td>
<td>fair to good</td>
<td>delta plain</td>
</tr>
</tbody>
</table>

Wireline log

Four wells have relatively thick penetrations of sequence 2. In the Resolution 1 well (Figure 36), the gamma-ray log has an upward coarsening and thickening; this pattern (2170-2140 m) is overlain by a distinct upward fining and thinning (2140-2120 m). In the Leyden 1B ST1 well (Figure 37), the gamma-ray (GR) pattern is one of upward coarsening and thickening (2790-2725 m), indicative of progradation of the delta. In Zeepaard 1 ST1 well (Figure 38), sequence 2 shows a series of cycles of upward coarsening and fining pattern with interbedded siltstones and sandstones. In the Zeewulf 1 well (Figure 35), sequence 2 has a blocky pattern like a distributary mouth bar (channel-fill sandstone). In contrast, sequence 2 is either not present or extremely thin in Investigator 1 well (Figures 8, 11, 34). Also, sequence 2 is thinner in Eskdale 1 well (Figure 39) due to the thinning of the sequences overlying the Resolution Arch (Figures 5, 6, 8-10, 12, 13, 19, 20, 31, 33).
Interpretation

Sequence 2 represents continued progradation across the pre-existing shelf to the “lower delta” of the Barrow Group. This sequence prograded 5-6 km farther basinward (northwest) than did sequence 1. The gradual changes of seismic facies within sequence along a northwest/southeast direction are due to the progradation of delta and represent the regional changes in the lithofacies. Seismic facies 1 and 2 are interpreted to represent the delta front and delta plain depositional setting, respectively. The change of depositional environment from delta plain, through delta front, to prodelta is following southeast to northwest direction (Figure 50). Overall, the vertical association of the facies of sequence 1 and 2 suggest the deposition at the base-of-slope or further basinward.

Locally, the clinoforms are laterally discontinuous and display deformed geometries, suggesting slumping of a prograding muddy slope (Figure 49). The overall geometry and position of the clinoform seismic facies present in the sequences 1 and 2 suggest that they were deposited as a part of one or more progradational deltas during the transgression within the study area.

The gamma-ray log patterns all indicate deposition within shallow to marginal marine setting that prograded basinward. Similar to sequence 1, the source of sediments for sequence 2 is interpreted to be the southeast associated with erosion of uplifts created from the Early Cretaceous tectonism (Figure 21).
Sequence 3: upper Valanginian to lower Hauterivian (136-134 Ma)

Time Thickness and Structure

Sequence 3 is present throughout most of the study area, and its isochron values range from 0 to up to 150 msec (two-way travel time) (Figure 51). Sequence 3 is thickest along its clinoforms and thin northward toward the Exmouth Plateau due to the depositional limit of progradation (Figures 8-11). The areal extent of the top of the progradational delta is clearly shown in the isochron map of the sequence (Figure 51).

The time-structure map of the upper Valanginian sequence boundary (SB3) illustrates the same structural elements as that of SB1 and SB2 including the extensively developed two arches and depressed depocenter (Figure 52): (1) northeast-southwest trending Resolution Arch, (2) northwest-southeast trending Novara Arch, both of which are located in the southeastern corner of the study area, and (3) southwest-northeast elongate Kangaroo Syncline that is located in the middle of the study area.

Upper and Lower Boundaries

Sequence 3 is defined at its base by sequence boundary 3 (SB3) and the top by sequence boundary 4 (SB4) (Figures 8-17, 43-47). The basal horizon of sequence 3, which approximately coincides with upper Valanginian, is a laterally continuous to discontinuous, moderate- to high-amplitude reflection characterized by locally developed toplapping reflection terminations over the area of the delta front (Figures 9-11). As the toplapping geometry is locally developed and deformed by the successive progradation, it is difficult to pick the horizon on the regional seismic profiles across the
Figure 51. Isochron map (in TWTT msecs) of sequence 3 (upper Valanginian - lower Hauterivian). In general, the formation is thickening to the north and northwest, which is caused in part by regional facies changes. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
Figure 52. Time-structure map of SB3 (upper Valanginian) in the Upper delta of the Barrow Group. Contour interval is 50 msec. Major northeast-southwest trending normal faults and southeastern structural elements are shown; Novara Arch, Resolution Arch and Kangaroo Syncline. Location of five exploration wells are shown. See Figures 29, 51, and 53 for the distribution of seismic profiles used for generating this map.
study area due to the lack of reflection continuity. In addition, the basal horizon of sequence 3 is characterized by subtle overlying downlapping reflection terminations (Figures 9-11). In contrast, the top of sequence 3, which approximately coincides with the lower Hauterivian Unconformity, is easily identified by marked onlapping reflection terminations. The top of sequence 3 appears as laterally continuous to partially discontinuous and moderate- to high-amplitude reflection.

**Seismic Facies**

2-D seismic and geologic facies maps of the sequence 3 (Figure 53), based on the facies analysis of the key seismic profiles (Figures 43-47), illustrate two seismic facies: facies 1 and 2, which are the same seismic facies distribution of previously described main seismic facies in sequence 1 and 2. The seismic facies are summarized in Table 8 and illustrated on the seismic facies map (Figure 53). Internally, the sequence 3 has relatively transparent and thin interval of moderate-amplitude with poor to fair continuity over the Exmouth Sub-basin.

In seismic facies 1, the upper and lower sequence boundaries show toplapping and downlapping reflection terminations, respectively. The internal reflections are sigmoid or complex sigmoid-oblique geometry, which are a characteristic of foreset facies in a prograding delta (Figures 43-47). The reflections are characterized by moderate to high-amplitude with poor continuity. In seismic facies 2, the upper and lower sequence boundaries are characterized by more concordant reflections. The internal reflections are generally subparallel with moderate-amplitude and fair continuity.
Figure 53. 2D seismic and geologic facies map of sequence 3 (upper Valanginian - lower Hauterivian). This map shows the progradational limit of delta front of upper delta of the Barrow Group, which correlated with the slope and delta front of the Zeepaard Formation. The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. See Table 8 for a summary of coded seismic facies and geologic information. Location of figures of key regional profiles (blue lines), and exploration wells are shown.
Table 8. Seismic facies and geologic interpretation of sequence 3

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>toplap</td>
<td>downlap</td>
<td>complex sigmoid-oblique</td>
<td>moderate to high</td>
<td>poor</td>
<td>delta front</td>
</tr>
<tr>
<td>2</td>
<td>concordant</td>
<td>concordant</td>
<td>subparallel</td>
<td>moderate</td>
<td>fair</td>
<td>delta plain</td>
</tr>
</tbody>
</table>

**Wireline log**

The wireline logs in sequence 3 consist primarily of shallow to marine strata. In Zeepaard 1 ST1 well (Figure 38), sequence 3 has a sharp base associated with a shale (2875 m) and then has several cycles of upward coarsening and thickening pattern (2875-2866 m, 2855-2840m, 2830-2815 m) associated with deltaic progradation. In Resolution 1 well (Figure 36), the gamma-ray (GR) has an overall backstepping pattern (2110-2080 m), which is overlain by thickening pattern (2090-2060 m) and then a blocky pattern of channel-fill (2060-2030 m). The gamma-ray log in Leyden 1B ST1 well (Figure 37) has a blocky pattern associated with a channel-mouth bar sandstones (2725-2688 m). Like the underlying sequence 2, sequence 3 is not present in Investigator 1 well (Figure 34). Due to the thinning of the sequences overlying the Resolution Arch, sequence 3 is thinner in Eskdale 1 (Figures 5, 6, 8-10, 12, 13, 19, 20, 31, 33, 39).
**Interpretation**

The integration of well logs and studies of well completion reports show that sequence 3 is the final deposition of the upper delta portion of the Barrow Group (top of the Zeepaard Formation).

In general, all of sequence 3 is considered to represent topset and foreset facies of delta front that were deposited on a marine shelf associated with prograding deltaic environments, and delta plain that is characterized by parallel or subparallel reflections. As a result of the facies analysis, the interpreted depositional environments suggest that sequence 3 has the same depositional settings as sequences 1 and 2. Facies 1 and 2 are interpreted to represent the delta front and delta plain depositional setting, respectively. In particular, the internal reflections of facies 2 are generally subparallel with moderate-amplitude and fair continuity, which gives an impression that the overall strata of sequence 3 were deposited horizontally in a delta plain setting.

In particular, the reflections in facies 1 show much higher angle dip to the north and northwest than the same foreset position composed of more gently dipping convex-upward progradational clinoforms in sequence 2 (Figures 9-11). This higher slope gradient is interpreted as the result of more rapid progradation during the deposition of sequence 3 that caused relatively high deformation of progradational clinoforms and accordingly lose the lateral reflection continuity. In addition, there are obvious changes of seismic facies within sequence 3 along northwest to southeast direction due to the rapid basinward deltaic progradation (Figure 53). In comparison with the underlying
sequence 2, the delta front in sequence 3 prograded slightly further basinward associated with transgressive cycle (Figures 50, 53).

**Sequence 4: lower to upper Hauterivian (134-132 Ma)**

**Time Thickness and Structure**

Sequence 4 is present mostly within the Exmouth Sub-basin area. The isochron values ranges from 0 to 60 msec (two-way travel time). This sequence has relatively constant and thin thickness compared to the overly- and underlying sequences. The isochron map (Figure 55) shows the areal extent of this sequence, which displays the thinning of strata in a northwestward direction from the Exmouth Sub-basin to the Exmouth Plateau. This pattern is exactly the same as the directional pattern of the progradation of the underlying Zeepaard Formation (Figure 54).

The time-structure maps of the Hauterivian unconformity (SB4) and top of the Birdrong Formation (SB5) illustrate the major structural elements including Kangaroo Syncline, Resolution Arch and Novara Arch in the central and southeastern corner of the study area (Figures 56, 57). Sequence 4 may not be distinct throughout the study area on seismic data because of the limited seismic resolution and in particular due to its relative thinness. The isochron map of the Zeepaard Formation including sequences 1, 2, 3 and the Birdrong Formation of sequence 4 was created to show the depositional patterns of Lower Cretaceous deltaic sediments with the structural elements (Figure 54).
Figure 54. Isochron map (in TWTT msecs) of the Zeepaard Formation (sequence 1 to 3) between the Valanginian and the Hauterivian unconformity. The Zeepaard Formation was deposited across wide areas of the Barrow and Exmouth Sub-basins, Rankin Platform and Exmouth Plateau as progradational top-set units of the Barraow Delta in the early Valanginian. Thin Birdrong Formation overlies the Zeepaard Formation. In general, the formation is thickening to the north and northwest, which is caused by regional facies changes. Red-dot outline indicates a potential play. See Figures 29, 42, 50, and 53 for the distribution of the 2D seismic profiles used to generate the map. Five exploration wells are shown.
Figure 55. Isochron map (in TWTT msecs) of the sequence 4 (lower Hauterivian unconformity - Top Birdrong Formation), which is equivalent to the Birdrong Formation. Overall thickness and extent of the Birdrong Formation is thin and limited respectively. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
Figure 56. Time-structure map of Hauterivian unconformity (SB4), which correlates with base Muderong Shale Formation. Contour interval is 50 msec. The display apparently shows the broad arches referred to as the Resolution Arch (NE-SW) and Norvara Arch (NW-SE) which overprinted each other and the major depressed depocenter of the Kangaroo Syncline in the study area. Location of five exploration wells are shown. See Figures 29, 55, and 58 for the distribution of seismic profiles used for generating this map.
Figure 57. Time-structure map of the Top of Birdrong Formation (backstepping delta) with limited areal extent. Contour interval is 50 msec. The display apparently shows the broad arches referred to as the Resolution Arch (NE-SW) and Norvara Arch (NW-SE) which overprinted each other and the major depressed depocenter of the Kangaroo Syncline in the study area. Location of five exploration wells are shown. See Figures 29, 55, and 58 for the distribution of seismic profiles used for generating this map. Location of five exploration wells are shown.
Upper and lower boundaries

Sequence 4 is locally recognized on the seismic profiles (Figures 8-17, 59-63) throughout the Exmouth Sub-basin and a part of the Exmouth Plateau where it is tied to the Zeewulf 1, Resolution 1, Leyden 1B ST1, and Eskdale 1 wells (Figures 35, 36, 37, 39). Sequence 4 is defined at its base by sequence boundary 4 (SB4) and the top by sequence boundary 5 (SB5). The base horizon of sequence 4, which coincides with the lower Hauterivian unconformity, is a laterally continuous, high-amplitude reflection. On seismic profiles, the sequence boundary 4 is well identified by remarkable onlapping reflection terminations (Figures 9-11). The top of sequence 4, which approximately coincides with the top of the Birdrong Formation in the upper Hauterivian, is defined by laterally continuous, moderate- to high-amplitude reflection (Figures 8-13, 15, 16).

Seismic Facies

As one of the backstepping deltas, sequence 4 appears to be a smaller scale depositional sequence throughout the study area. Nevertheless, two seismic facies are present that have been explained in the previously analyzed sequences 1 to 3 and on the key seismic profiles (Figures 58-63). The seismic facies are summarized in Table 9 and illustrated on the seismic facies map (Figure 58).

In seismic facies 1, the upper and lower sequence boundaries are characterized by concordant reflections (Figures 59-63). The internal reflections are generally parallel to partially hummocky with low-amplitude and relatively poor to fair continuity. Seismic facies 2 also consists of similar facies to that of seismic facies 1: concordant reflection
Figure 58. 2D seismic and geologic facies map of sequence 4 (lower Haterivian unconformity - Top Birdrong Formation). Due to the major transgression in the Exmouth Plateau and Exmouth Sub-basin, this package shows a backstepping delta (Birdrong Formation equivalent?). The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. Red-dot outline indicates the areal extent of potential play. See Table 9 for a summary of coded seismic facies and geologic information. Location of figures of key regional profiles (blue lines), and five exploration wells are shown.
Figure 59. Strike-oriented seismic profile illustrating the seismic facies of sequence 4 (lower Hauterivian unconformity to Top Birdrong Formation), sequence 5 (lower Hauterivian to lower Aptian unconformity), and sequence 6 (lower Aptian unconformity to Base Albian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 4 (light green), sequence 5 (green), and sequence 6 (light blue). See Tables 3, 9, 10, 11 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 60. Dip-oriented seismic profile illustrating the seismic facies of sequence 4 (lower Hauterivian unconformity to Top Birdrong Formation), sequence 5 (lower Hauterivian to lower Aptian unconformity), and sequence 6 (lower Aptian unconformity to Base Albian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 4 (light green), sequence 5 (green), and sequence 6 (light blue). See Tables 3, 9, 10, 11 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 61. Strike-oriented seismic profile illustrating the seismic facies of sequence 4 (lower Hauterivian unconformity to Top Birdrong Formation), sequence 5 (lower Hauterivian to lower Aptian unconformity), and sequence 6 (lower Aptian unconformity to Base Albian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 4 (light green), sequence 5 (green), and sequence 6 (light blue). Time-based gamma ray log of the Zeewulf 1 well is displayed. See Tables 3, 9, 10, 11 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 62. Strike-oriented seismic profile illustrating the seismic facies of sequence 4 (lower Hauerivian unconformity to Top Birdrong Formation), sequence 5 (lower Hauerivian to lower Aptian unconformity), and sequence 6 (lower Aptian unconformity to base Albian) interval: (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 4 (light green), sequence 5 (green), and sequence 6 (light blue). A potential play (deepwater onlap play) is shown (orange shaded). See Tables 3, 9, 10, 11 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 63. Dip-oriented seismic profile illustrating the seismic facies of sequence 5 (lower Hauterivian unconformity to lower Aptian unconformity), and sequence 6 (lower Aptian unconformity to base Albian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 5 (green), and sequence 6 (light blue). The Birdrong Formation is not present in this part of the profile. A potential play (deepwater onlap play) is shown (orange shaded). See Tables 3, 9, 10, 11 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
characteristics at the upper and lower sequence boundaries with parallel to subparallel internal reflections, moderate-amplitude and fair to good continuity.

Table 9. Seismic facies and geologic interpretation of sequence 4

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>concordant</td>
<td>concordant</td>
<td>parallel and partially hummocky</td>
<td>low</td>
<td>poor</td>
<td>delta plain</td>
</tr>
<tr>
<td>1</td>
<td>concordant</td>
<td>concordant</td>
<td>parallel to subparallel</td>
<td>moderate</td>
<td>fair to good</td>
<td>delta plain</td>
</tr>
</tbody>
</table>

**Wireline log**

Sequence 4 is thin in all wells (less than 30m) and is present roughly to the Exmouth Sub-basin and southeastern part of the Exmouth Plateau. The wireline logs all indicate interbedded sandstones, siltstones and shales, in both upward coarsening and thinning patterns.

In Zeewulf 1 well (Figure 35), sequence 4 is thinner and has a sharp base. Overall, the gamma-ray shows an upward coarsening pattern (2412-2443 m). In Resolution 1 well (Figure 36), two upward coarsening cycles, punctuated by marine shales, are present (2020-2000, 1990-1975 m). In Leyden 1B ST1 well (Figure 37), sequence 4 is also thin and has an upward coarsening pattern with sandstone unit (2688-2660 m). In Eskdale 1 well (Figure 39), sequence 4 has four distinct thinning and fining upward cycles (1493.5-1470 m). Sequence 4 is not present in both Investigator 1 and Zeepaard 1 ST1 wells (Figures 34, 38).
Interpretation

Uplift on the Ningaloo Arch at the end of the Berriasian resulted in the erosion of the Barrow Group across the region, with the eroded sediments forming a deltaic wedge of the Zeepaard Formation and the Birdrong Formation across the eastern Exmouth Plateau and northern Exmouth and Barrow Sub-basins with a small time gap at the Base Valanginian unconformity due to erosion at the top of the Barrow Group (Geoscience Australia, 2010).

As a result of sequence and well log interpretation, sequence 4 is equivalent to the Birdrong Formation that is present in the Northern Carnarvon Basin. Sequence 4 indicates an episode of backstepping deltaic deposition during a major marine transgression and subsequent sediment starvation due to a relative rise in sea level. However, sequence 4 may not be clearly identified on the seismic profiles and from well-to-seismic ties throughout the study area due to its relative thinness (mostly 20-30 m thick) as well as limited seismic resolution. Fortunately, it is recognized on the log data and well log cross sections (Figures 30, 32, 35, 36, 37, 39).

As a backstepping delta, sequence 4 shows mainly deltaic depositional facies of delta plain environment. Based on the facies analysis, facies 1 and 2 are interpreted a delta features with no typical progradational deltaic geometry during the major transgression in the Exmouth Plateau and Exmouth Sub-basin. The pattern of gradual facies change is shown on the facies map (Figure 58). However, the boundary between facies 1 and 2 is not clear due to the similarity of those two seismic facies and the subjectivity of the facies analysis.
The main sediment supply for the Birdrong Formation came partly from reworking of residual material and partly from reworking of contemporaneously supplied terrigenous detritus (Hocking et al., 1988). Unlike the underlying progradational deltas, it is difficult to recognize any prograding clinoforms within the sequence.

Sequence 5: lower Hauterivian to lower Aptian (134-122 Ma)

Time Thickness and Structure

The isochron values for sequence 5 vary from 100 to 500 msec (two-way travel time) (Figure 64). The average time thickness is about 100 msec for most of the study area (central and southeast). However, to the northeast of the study area, the maximum thickness reaches up to 500 msec or more in two-way travel (Figure 64).

The time-structure map of the lower Aptian unconformity (SB6) (Figure 65) illustrates the same structural features as illustrated in the time-structure maps of the underlying Valanginian and Hauterivian unconformities (Figures 41, 56). The two-way travel time values range from 1,205 to 3,053 msec. The map shows the shallowest structural features of the northeast-southeast trending Resolution Arch and northwest-southeast trending Novara Arch with the deepest depocenter within the Kangaroo Syncline. The Kangaroo Syncline trends southwest-northwest and is clearly shown in the middle of study area (Figure 65).

Upper and Lower Boundaries

Sequence 5 is defined at its base by sequence boundary 4 (SB4) and the top by sequence boundary 6 (SB6), and is recognized on all of the regional seismic profiles
Figure 64. Isochron map (in TWTT msecs) of sequence 5 (lower Hauterivian unconformity - lower Aptian unconformity) which is equivalent to the Muderong Shale Formation. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
Figure 65. Time-structure map of the Aptian unconformity (SB6). Contour interval is 50 msec. It shows the broad arches referred to as the Resolution Arch (NE-SW) and Norvara Arch (NW-SE) which overprinted each other and the major depressed depocenter of Kangaroo Syncline which marks the boundary between the Exmouth Plateau and the Exmouth Sub-basin. To the northwest, the Exmouth Plateau Arch is shown. See Figures 29, 64, and 66 for the distribution of seismic profiles used for generating this map. Location of five exploration wells are shown.
(Figures 7-27, 59-63) throughout the study area where it is tied to all wells (Figures 2, 3, 27, 34-39). The locally developed sequence boundary 5, i.e. the top of Birdrong Formation, which is present in between the sequence boundary 4 and 6, is ignored to describe sequence 5 due to its limited areal extent of deposition and thin thickness.

The basal horizon of sequence 5, which coincides with the lower Hauterivian unconformity, is a laterally continuous, high-amplitude reflection. The top of sequence 5 is defined by sequence boundary 6 (SB6), which coincides with the lower Aptian unconformity. Due to the laterally continuous and high-amplitude reflection, the Aptian unconformity is easily identified on the seismic profiles (Figures 7-27).

**Seismic Facies**

Four seismic facies were distinguished (Figures 59-63, 66), and are summarized in Table 10 and illustrated on the seismic facies map (Figure 66).

Seismic facies 1 has concordant and onlapping reflections at the upper sequence boundary and lower sequence boundary, respectively. The internal reflections are mainly hummocky or chaotic with moderate-amplitude and poor continuity for the wedge-type geometry associated with prodelta setting. The updip onlap limit (Figures 10, 11) of sequence 5 is well defined on the 2-D facies map (Figure 66). Facies 1 corresponds to the thickest part of the sequence. In seismic facies 2, the upper and lower sequence boundaries are characterized by distinctly concordant reflections. The internal reflections are mostly parallel or slightly subparallel with high-amplitude and fair to good continuity. However, near the northeastern corner of study area, facies 2 shows a markedly decrease in amplitude and continuity likely due to the abrupt changes of
Figure 66. 2D seismic and geologic facies map of sequence 5 (lower Hauterivian unconformity - lower Aptian unconformity). This package is equivalent to the Muderong Shale Formation. The Muderong Formation is onlapping onto the underlying Zeepaard Formation. Onlap limit is shown on the map. The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. Red-dot outline indicates the areal extent of potential play. See Table 10 for a summary of coded seismic facies and geologic information. Location of figures of key regional profiles (blue lines), and five exploration wells are shown.
thickness or depositional setting. Seismic facies 3 has similar seismic reflection to facies 2. The upper and lower sequence boundaries are characterized by concordant reflections, whereas the internal reflections have changed laterally into subparallel with low to moderate and poor to fair continuity. Finally, seismic facies 4 shows concordant reflections at the upper and lower sequence boundary. The internal reflections are characterized by parallel to slightly subparallel with moderate-amplitude and fair to good continuity.

Table 10. Seismic facies and geologic interpretation of sequence 5

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>concordant</td>
<td>onlap</td>
<td>hummocky/chaotic</td>
<td>moderate</td>
<td>poor</td>
<td>base-of-slope</td>
</tr>
<tr>
<td>2</td>
<td>concordant</td>
<td>concordant</td>
<td>parallel to subparallel</td>
<td>high</td>
<td>good</td>
<td>prodelta</td>
</tr>
<tr>
<td>3</td>
<td>concordant</td>
<td>concordant</td>
<td>subparallel</td>
<td>low to moderate</td>
<td>poor to good</td>
<td>delta front</td>
</tr>
<tr>
<td>4</td>
<td>concordant</td>
<td>concordant</td>
<td>parallel</td>
<td>moderate</td>
<td>fair to good</td>
<td>delta plain</td>
</tr>
</tbody>
</table>

**Wireline log**

In Investigator 1 well (Figure 34), sequence 5 is about 90 m thick and consists primarily of interbedded shales and thin sandstone units. Approximately 5m thick sandstone unit (1435-1430 m) is present in the middle of the sequence. In Zeewulf 1 well (Figure 35), sequence 5 consists of two units. The lower unit is the Mardie Greensand, which has a shale unit at its base (2410 m), and consists of an upward thickening sandstone package (2410-2384 m). The overlying unit is a shale unit.
(Muderong Shale) (2384-2361 m). In Resolution 1 well (Figure 36), sequence 5 has three distinct units. The lower unit is a thin shale (1995-1980 m), overlain by a thick sandstone (1980-1950 m). The upper unit has an upward thinning sandstone (1950-1930 m). In Leyden 1B ST1 well (Figure 37), sequence 5 shows a similar pattern to Resolution 1 well. Three distinct cycles of coarsening upward pattern (2640-2562 m) are overlain by upward fining sandstone unit (2660-2640 m). Sequence 5 is 190 m thick in Zeepaard 1 ST1 well (Figure 38). At the base, a slightly upward thinning package (2815-2800 m) that appears as backstepping parasequences. The overlying interval (2625-2785 m) shows an overall upward thickening from shale at the base to sandstone at the top associated with regional progradation. In Eskdale 1 well (Figure 39), sequence 5 has two distinct units that show primarily an upward coarsening sandstone trend (1470-1447 m). The top consists of a sharp contact (flooding surface) overlain by a shale (Muderong Formation).

**Interpretation**

The interpreted depositional environments from the facies analysis indicate that sequence 5 can be divided into four settings from shelf margin through base-of-slope to basinal deposits. Facies 1 is interpreted to an onlapping base-of-slope deepwater system. Facies 2, 3 and 4 are interpreted to represent the prodelta, delta front, and delta plain deposits, respectively (Table 9). In general, shelf sequence units are identified by high-amplitude and good continuity reflection events.

The wireline logs show three distinct units in the deposition of sequence 5. A thin transgressive marine shale is present at the base overlying a flooding surface; benthic
biofacies indicate a neritic environment. The middle unit is a progradational unit, comprising one to several parasequences. This unit corresponds to the Mardie Greensand (Figures 30, 32, 35-37).

The Muderong Shale, at the top of the sequence, overlies a flooding surface and is a marine transgressive shale with neritic fauna. The top of the sequence is the Aptian unconformity, a prominent sequence boundary. The thick, basinal onlapping unit (facies 1), represents significant bypass across the shelf area. The Investigator 1 well indicates sandstones are present in the deepwater, with potential for petroleum accumulation where a trap has developed (Figures 9-11, 34). The overall fine-grained nature of sequence 5 makes the Muderong Shale an ideal regional seal.

**Sequence 6: lower Aptian to lower Albian (122-112 Ma)**

**Time Thickness and Structure**

The isochron values of sequence 6 ranges from 0 to up to 450 msec (two-way travel time) throughout the study area (Figure 67). The thickest area (> 300 msec) is located near the northeastern corner of the study area and generally thickens across the Exmouth Plateau. Most of the area has 100 to 200 msec isochron values.

The time-structure map of the base Albian (SB7) apparently illustrates three arches distributed over the study area: (1) northeast-southwest trending Resolution Arch; (2) northwest-southeast trending Novara Arch, both of which are located in the southeastern corner of the study area; and (3) northeast trending Exmouth Plateau Arch over the Investigator 1. The southwest-northeast elongate Kangaroo Syncline, which is
Figure 67. Isochron map (in TWTT msecs) of sequence 6 (lower Aptian unconformity - Base Albian). The average thickness ranges from 50 to 200 msec. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
located in the middle of the study area, is much wider areally than the underlying sequences (Figure 68).

**Upper and Lower Boundaries**

Sequence 6 is defined at its base by sequence boundary 6 (SB6) and the top by sequence boundary 7 (SB7) (Figures 8-17, 59-63). The basal horizon of sequence 6, which marks the lower Aptian unconformity, is identified in most areas as a laterally continuous, high-amplitude reflection. The lower boundary is a prominent unconformity across the Exmouth Plateau and the erosion becomes conformable on the Exmouth Sub-basin (Figures 18, 59-63). The top of sequence 6 is defined by sequence boundary 7 (SB7) that approximately coincides with base Albian age. This sequence boundary (SB7) is identified by onlapping reflections landward, and characterized mainly by paralleling with under- and overlying reflection, and a laterally continuous, high-amplitude reflection (Figures 9, 11). The isochron map of sequence 6 displays the rough boundary between the wedge geometry and sheet geometry (Figure 67).

**Seismic Facies**

The overall geometry of sequence 6 shows a parallel and sheet-like geometry over the Exmouth Sub-basin and a wedge-type geometry over the Exmouth Plateau (Figures 9-14). Three distinct seismic facies were identified on the key seismic profiles (Figure 29) and mapped throughout the study area (Figures 59-63, 69). These are summarized in Table 11 and are illustrated on the seismic facies map (Figure 69).

Seismic facies 1 shows mainly concordant reflections at the upper and lower sequence boundaries, respectively. The internal reflections are mostly subparallel with
Figure 68. Time-structure map of the Base Albian (SB7). Contour interval is 50 msec. The display shows the broad arches referred to as the Resolution Arch (NE-SW) and the Norvara Arch (NW-SE) which overprinted each other and the major depressed depocenter of the Kangaroo Syncline which marks the boundary between the Exmouth Plateau and Exmouth Sub-basin. To the northwest, the Exmouth Plateau Arch is shown. See Figures 67, 69 for the distribution of seismic profiles used for generating this map. Location of five exploration wells are shown.
Figure 69. 2D seismic and geologic facies map of sequence 6 (lower Aptian unconformity - Base Albian) interval. The external geometry of this sequence is wedge type and it is onlapping onto underlying Muderong Formation. The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. Red-dot outline indicates the areal extent of potential play. See Table 11 for a summary of coded seismic facies and geologic information. Location of figures of key regional profiles (blue lines), and five exploration wells are shown.
moderate- to high-amplitude, and poor to fair continuity. Seismic facies 2 consists of the similar reflection configuration as seismic facies 1. The upper and lower sequence boundaries are characterized by concordant reflections. The internal reflections are mostly parallel with high-amplitude and good continuity. Seismic facies 3 is characterized by concordant reflections at the upper and lower sequence boundaries and subparallel internal reflections with low- to moderate-amplitude and poor to fair continuity.

Table 11. Seismic facies and geologic interpretation of sequence 6

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>concordant</td>
<td>concordant</td>
<td>subparallel</td>
<td>moderate to high</td>
<td>poor to fair</td>
<td>basinal deposits</td>
</tr>
<tr>
<td>2</td>
<td>concordant</td>
<td>concordant</td>
<td>parallel</td>
<td>high</td>
<td>good</td>
<td>shelf</td>
</tr>
<tr>
<td>3</td>
<td>concordant</td>
<td>concordant</td>
<td>subparallel</td>
<td>low to moderate</td>
<td>poor to fair</td>
<td>inner shelf</td>
</tr>
</tbody>
</table>

**Wireline log**

Sequence 6 is equivalent to the lower portion of the Gearle Formation (Figures 30, 32). In Investigator 1 well (Figure 34), sequence 6 is approximately 43 m thick, based on regional correlations. Overall, the sequence has an upward thickening/coarsening log pattern. Benthic biofacies suggests bathyal. In Zeewulf 1 well (Figure 35), sequence 6 is thin sandstone unit with a blocky GR log pattern (2330-2361 m). In Resolution 1 well (Figure 36), sequence 6 has also a sandstone unit with a blocky GR pattern (1900-1920 m), with an upward fining/thinning at the top (1900-1895 m).
Leyden 1B ST1 well (Figure 37), sequence 6 is relatively thick (67 m) and characterized by overall upward fining and thinning pattern (2562-2495 m). In Zeepaard 1 ST1 well (Figure 38), two distinct patterns of interbeds of siltstone, shale, and sandstone are present (2625-2580 m, 2580-2565 m). A slightly overall upward fining and thinning with shale dominant unit is developed from 2565 to 2475 m. In Eskdale 1 well (Figure 39), sequences 6-8 are relatively thin and therefore, separating the three sequences are difficult. Overall, there is an upward fining and thinning in the three sequences (1439-1415 m).

**Interpretation**

Sequence 6 includes the initial deposition of the Gearle Siltstone Formation, composed mainly of silt- and clay-rich strata with considerable amount of radiolarian siltstone. The benthic biofacies for this unit is described as neritic (Figures 34-38). The sandstones present in Investigator 1, Resolution 1, Zeewulf 1, and Leyden 1B ST1 wells are likely fluvial or reworked shallow marine sandstones.

The interpreted depositional environments from the facies analysis suggest that facies 1 represents the basinal deposition slightly onlapping against the underlying Muderong Shale Formation. Facies 2 is interpreted to represent the shelf setting. Last, facies 3 is associated with inner shelf and the structural high setting across the southeastern corner of the study area.
**Sequence 7: lower to upper Albian (112-100 Ma)**

**Time Thickness and Structure**

The isochron values of sequence 7 vary from 0 to up to 230 msec (two-way travel time) throughout the study area (Figure 70). Sequence 7 thins over the Exmouth Plateau and thickens over the Exmouth Sub-basin. Two areas are anomalously thick to the southern Kangaroo Syncline, and to the northeastern part of the study area.

The time-structure maps of the base Albian (SB7) (Figure 68) and top Albian (Figure 71) illustrate the regionally developed structural features in the study area: (1) northeast-southwest trending Resolution Arch, (2) northwest-southeast trending Novara Arch, both of which are located in the southeastern margin of the study area, and (3) northeast trending Exmouth Plateau Arch over the Investigator 1 well are clearly seen in the time-structure maps. Areally, the extent of the Kangaroo Syncline that is located across the center of the study area is much widened compared to that of the underlying sequences.

**Upper and Lower Boundaries**

Sequence 7 is defined at its base by sequence boundary 7 (SB7) and the top by sequence boundary 8 (SB8) throughout the Exmouth Plateau and Exmouth Sub-basin (Figures 8-17, 73-77).

The basal horizon of sequence 7, which coincides with the base of Albian, is defined as a sequence boundary by the onlapping reflections onto a laterally continuous, high-amplitude reflection (Figures 9, 11). In addition, subtle downlapping
Figure 70. Isochron map (in TWTT msecs) of sequence 7 (Base Albian - Top Albian). The thickness trend is much more irregular across the study area. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
Figure 71. Time-structure map of the Top Albian (SB8). Contour interval is 50 msec. It shows the broad arches referred to as the Resolution Arch (NE-SW) and Novara Arch (NW-SE) which overprinted each other and the major depressed depocenter of the Kangaroo Syncline which marks the boundary between the Exmouth Plateau and the Exmouth Sub-basin. To the northwest, Exmouth Plateau Arch is shown. See Figures 70, 72 for the distribution of seismic profiles used for generating this map. Location of five exploration wells are shown.
Figure 72. 2D seismic and geologic facies map of sequence 7 (Base Albian - Top Albian). This package is a middle part of Gearle siltstone Formation deposited in a shallow marine environment. Note that the partially hummocky and discontinuous reflections of facies 1 are deformed by the abundant faults and channels. A potential play is observed (red-dot outline). The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. See Table 12 for a summary of coded seismic facies and geologic information. Location of figures of key regional profiles (blue lines), and five exploration wells are shown.
Figure 73. Strike-oriented seismic profile illustrating the seismic facies of sequence 7 (Base Albian to Top Albian), sequence 8 (Top Albian to lower Turonian unconformity), and sequence 9 (lower Turonian unconformity to Santonian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 7 (blue), sequence 8 (red), and sequence 9 (violet). See Tables 3, 12, 13, 14 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 74. Dip-oriented seismic profile illustrating the seismic facies of sequence 7 (Base Albian to Top Albian), sequence 8 (Top Albian to Turonian unconformity), and sequence 9 (Turonian unconformity to Santonian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 7 (blue), sequence 8 (red), and sequence 9 (violet). Potential plays are shown (orange shaded). See Tables 3, 12, 13, 14 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 75. Strike-oriented seismic profile illustrating the seismic facies of sequence 7 (Base Albian to Top Albian), sequence 8 (Top Albian to lower Turonian unconformity), and sequence 9 (lower Turonian unconformity to Santonian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 7 (blue), sequence 8 (red), and sequence 9 (violet). Time-based gamma ray log of the Zeewulf 1 well is displayed. See Tables 3, 12, 13, 14 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 76. Strike-oriented seismic profile illustrating the seismic facies of sequence 7 (Base Albian to Top Albian), sequence 8 (Top Albian to lower Turonian unconformity), and sequence 9 (lower Turonian unconformity to Santonian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 7 (blue), sequence 8 (red), and sequence 9 (violet). A potential play (deepwater onlap play) is shown (orange shaded). See Tables 3, 12, 13, 14 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
Figure 77. Dip-oriented seismic profile illustrating the seismic facies of sequence 7 (Base Albian to Top Albian), sequence 8 (Top Albian to Turonian unconformity), and sequence 9 (Turonian unconformity to Santonian): (a) uninterpreted, (b) interpreted. The sequence boundaries are noted by prominent colored vertical arrows: sequence 7 (blue), sequence 8 (red), and sequence 9 (violet). The Birdrong Formation is not present in this part of the profile. A potential play (deepwater onlap play) is shown (orange shaded). See Tables 3, 12, 13, 14 for facies codes and Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, 84 for the location of the profile.
reflections are present across the Kangaroo Syncline. Seismic correlation among the base-of-slope, slope and shelf was difficult due to the convergence of the sequence boundaries across the slope area. The top of sequence 7, which approximately coincides with the top of Albian, is also defined by mainly continuous, high-amplitude reflection observed on seismic profiles (Figures 73-77).

**Seismic Facies**

Three seismic facies were identified on the key seismic profiles (Figure 13) and mapped throughout the study area (Figures 72-77). These are summarized in Table 12 and illustrated on the seismic facies map (Figure 72).

Seismic facies 1 shows concordant reflections at the upper sequence boundary and subtle onlap reflections onto the lower sequence boundary (Figures 9, 11). The internal reflections are mostly parallel to subparallel with variable amplitude (low to high) and poor to fair continuity. Some hummocky and discontinuous reflections are present across the Exmouth Plateau (Figures 10, 11). The updip boundary of onlap limit of the sequence is shown in the facies map (Figure 72). Seismic facies 2 consists of concordant reflections at the upper and lower sequence boundaries with parallel to subparallel internal reflections with moderate- to high- amplitude and fair to good continuity. Seismic facies 3 is also characterized by concordant reflection at the upper sequence boundary and concordant or partially downlapping reflections along the lower sequence boundary. The internal reflections are mainly subparallel with low-amplitude and poor to fair continuity.
Table 12. Seismic facies and geologic interpretation of sequence 7

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>concordant</td>
<td>onlap</td>
<td>parallel to subparallel (partially hummocky)</td>
<td>moderate to high</td>
<td>poor to fair</td>
<td>basinal deposits</td>
</tr>
<tr>
<td>2</td>
<td>concordant</td>
<td>concordant</td>
<td>parallel to subparallel</td>
<td>moderate to high</td>
<td>fair to good</td>
<td>base-of-slope</td>
</tr>
<tr>
<td>3</td>
<td>concordant</td>
<td>downlap or concordant</td>
<td>subparallel</td>
<td>low</td>
<td>poor to fair</td>
<td>slope deposits</td>
</tr>
</tbody>
</table>

**Wireline log**

Sequence 7 (middle portion of the Gearle Formation) is fairly thin in the six wells. For most wells, the overall gamma-ray log show relatively high and constant values with minor fluctuation for sequence 7 due to the shale or siltstone dominant lithology. An upward thinning/fining pattern is present in the Investigator 1 well (Figure 34). From 1359 to 1348 m, the gamma-ray shows an upward thinning pattern, which represents possible backstepping delta. In Zeewulf 1 well (Figure 35), sequence 7 is thin and characterized at the base by an upward fining (2330-2323 m), and then upward coarsening (2323-2315 m) pattern. In Resolution 1 well (Figure 36), sequence 7 is relatively thick (80 m). It has a sharp base and is characterized by four distinct interbedded cycles of upward coarsening (1895-1880 m, 1865-1860 m, 1845-1840 m, 1835-1830 m), and upward fining (1880-1865 m, 1860-1845 m, 1840-1835 m, 1830-1818 m). In Leyden 1B ST1 well (Figure 37), sequence 7 is relatively thin (37 m), and has an upward fining pattern with interbedded sandstones and shales (2495-2460 m). One small prograding sandstone unit is present at the top of sequence from 2470 to
2460 m. In contrast, sequence 7 is relatively thick (145 m) in Zeepaard 1 ST1 well (Figure 38). Most of sequence is primarily shale (2475-2385 m), and is overlain by an upward coarsening pattern (2385-2350 m). Interbedded sandstones and shales are developed with upward coarsening (2350-2335 m) and upward fining (2335-2330 m) pattern at the top. For Eskdale 1 well (Figure 39), sequences 6-8 are thin and are difficult to separate into three sequences. However, the overall pattern is an upward fining and thinning for the entire Gearle Formation.

**Interpretation**

Overall, sequence 7 over the Exmouth Plateau area shows a wedge-shaped geometry (Figure 11). This small wedge geometry over the Exmouth Plateau is resulted from the uplifted southern margin and largely deformed by a series of small faults that cut the successive sequences from the Albian to the Lower Cenozoic sequences (Figures 11, 13, 14).

The interpreted depositional environments of this unit based on the facies analysis indicate a deepwater setting deposited on the basin, base-of-slope and slope. Facies 1 represents the basinal deposits. The partially hummocky and discontinuous reflection characteristics of facies 1 are related to the deformation caused by abundant small faults during the Late Cretaceous inversion. Facies 2 is interpreted to represent the base-of-slope setting. Last, all of the characteristics of facies 3 are associated with the slope and the structural high setting across the southeastern corner of the study area.
Sequence 8: upper Albian to lower Turonian (100-94 Ma)

Time Thickness and Structure

The isochron values of sequence 8 vary from 0 to up to 800 msec thick (two-way travel time) throughout the study area (Figure 79). Sequence 8 is relatively thin across the Exmouth Plateau (< 200 msec) and thickens appreciably to the east in the Exmouth Sub-basin (300-800 msec). The thickest strata extend from the Kangaroo Syncline near the northeastern corner of the study area (Figure 79).

The time-structure maps of the top Albian (Figure 71) and Turonian unconformity (Figure 80) apparently show the major structural features in the study area: (1) northeast trending Exmouth Plateau Arch located in the northwestern corner of the study area, (2) northeast-southwest trending Resolution Arch, (3) northwest-southeast trending Novara Arch, both of which are located in the southeastern margin of the study area. The Kangaroo Syncline, which is the deepest part of the structure, trends southwest-northeast and is located in the middle of the study area.

Upper and Lower Boundaries

Sequence 8 is defined at its base by sequence boundary 8 (SB8) and the top by sequence boundary 9 (SB9) throughout the study area (Figures 8-17, 73-78). The basal horizon of sequence 8, which coincides with the top Albian, is a laterally continuous, high-amplitude reflection characterized by major onlapping reflections that are present in most study area (Figure 17). The top of sequence 8, which coincides with the Turonian unconformity, is identified as the sequence boundary having laterally...
Figure 78a. Regional dip-oriented seismic profile: (a) uninterpreted, (b) interpreted.
Figure 78b. The interpreted sequence boundaries with reflection terminations (Red arrows = onlap and erosional truncation, green arrows = downlap) for the Lower Cretaceous to Neogene strata are shown. Note several downlap surfaces developed between the Top Albian and Turonian unconformity and large amount of erosion above the Santonian. The Gearle Formation was deposited in a shelf-slope setting with a thick sequence of siltstone and shales. Reflection terminations indicate large scale erosional features (lateral accretion, incised channel fill - red arrows and yellow colored area) above the Santonian. An increase of slope angle due to a second major phase of uplift during the early Turonian in the southern part of the Exmouth Sub-basin forming the Novara Arch resulted in widespread well developed sediment slumping. Younger sediments are primarily prograding carbonates, marls, and chalks. See Figures 3 and 5 for the location of seismic profile (DLS = downlap surface, U/C = unconformity).
Figure 79. Isochron map (in TWTT msecs) of sequence 8 (Top Albian - lower Turonian unconformity). The thickness varies from 100 to 800 msec. Note a thickening of the sequence over the eastern portion of the study area, which is caused by the change of sediment source area. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
Figure 80. Time structure map of the Turonian unconformity (SB9). The Resolution and Novara Arches are extended further northeastern direction. The Kangaroo Syncline which marks the boundary between the Exmouth Plateau and the Exmouth Sub-basin shows deepening to the southeast. To the northwest, the Exmouth Plateau Arch is shown. See Figures 79, 81 for the distribution of seismic profiles used for generating this map. Location of five exploration wells are shown.
continuous, high-amplitude reflection. In addition, this horizon shows an erosional truncation especially along the regional strike-oriented seismic profiles (Figures 9, 18).

**Seismic Facies**

Four seismic facies are recognized in sequence 8 (Figure 81) and summarized in Table 13. The upper and lower sequence boundaries of sequence 8 show mainly concordant seismic reflections. However, the seismic reflection also show partially developed onlapping and downlapping reflection terminations over the Exmouth Sub-basin area (Figures 17, 74, 75, 77). Internally, sequence 8 is characterized by alternating amplitude from moderate to high with variable continuity from poor to good.

Seismic facies 1 shows concordant reflections at the upper sequence boundary and onlapping reflection termination against the lower sequence boundary. The internal reflections are characterized by parallel to subparallel reflections with moderate- to high-amplitude (partially low) and poor to fair continuity. Seismic facies 2 consists of concordant reflections at the upper and lower sequence boundary with parallel internal reflections, high-amplitude and good continuity. Seismic facies 3 is also characterized by concordant reflections at the upper sequence boundary and concordant or partially downlapping reflections on lower sequence boundary. The internal reflections show subparallel and partially developed hummocky reflections with low- to moderate-amplitude and poor to fair continuity. Seismic facies 4 has almost similar characteristics to facies 3. It shows a mostly concordant reflection relationship at the upper sequence boundary and concordant with partial downlapping reflection terminations onto the lower...
Figure 81. 2D seismic and geologic facies map of sequence 8 (Top Albian - Turonian unconformity) interval. This package is a part of the Gearle siltstone Formation deposited in a shelf, slope, and basinal setting. There was a shift of main sedimentation direction from the feeder of sedimentary deposits from continental shelf, which was initially northwest to southeast (NW-SE) trending and changed to east to west (E-W) direction. This might be caused by the beginning of the uplift tectonism of the Novara Arch. Poor continuity of facies 1 is due to highly developed high-angle normal faults over the area. The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. See Table 13 for a summary of coded seismic facies and geologic information. Location of figures of key regional profiles (blue lines), and five exploration wells are shown.
sequence boundaries. The internal reflections are parallel to subparallel with high-amplitude and fair to good continuity.

Table 13. Seismic facies and geologic interpretation of sequence 8

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>concordant</td>
<td>concordant/partially onlap</td>
<td>parallel/subparallel</td>
<td>moderate to high</td>
<td>poor to fair</td>
<td>basinal deposits</td>
</tr>
<tr>
<td>2</td>
<td>concordant</td>
<td>concordant</td>
<td>parallel</td>
<td>high</td>
<td>good</td>
<td>base-of-slope</td>
</tr>
<tr>
<td>3</td>
<td>concordant</td>
<td>downlap or concordant</td>
<td>subparallel/hummocky</td>
<td>low to moderate</td>
<td>poor to fair</td>
<td>slope deposits</td>
</tr>
<tr>
<td>4</td>
<td>concordant</td>
<td>downlap or concordant</td>
<td>parallel/subparallel</td>
<td>moderate to high</td>
<td>fair to good</td>
<td>shelf margin deposits</td>
</tr>
</tbody>
</table>

**Wireline log**

Based on the regional correlations, sequence 8 correlates with the upper portion of the Gearle Siltstone Formation.

In Investigator 1 well (Figure 34), sequence 8 is thin and characterized by a flooding surface at its base, overlain by upward fining/thinning at the base (1335-1330 m) and then upward coarsening and thickening at the top (1330-1328 m). In Zeewulf 1 well (Figure 35), sequence 8 is thicker; there is a slight upward fining and thinning pattern at its base (2315-2305 m), and then an upward coarsening sand unit (2305-2275 m). There is a sharp lithological change at 2275 m associated with flooding surface. This is overlain by an upward fining and thinning pattern with shale (2275-2250 m) and then overlain by an upward coarsening and thinning pattern with interbedded
sandstone (2250-2200m). In Resolution 1 well (Figure 36), sequence 8 is 112 m thick and is characterized by upward fining with shale at the base (1815-1790 m), overlying thin sandstone (1790-1780 m), and upward coarsening pattern at the middle (1780-1755 m). A shale unit, with interbedded sandstones and siltstones, is developed at the top (1755-1703 m). In Leyden 1B ST1 well (Figure 37), sequence 8 is the thickest (606 m) within the well, and is primarily shale unit with many interbedded sandstones (2460-1855 m). The overall sequence consists of several cycles of upward fining and thinning at the base (2460-2385 m), and then upward coarsening and thickening (2385-2240m, 2130-2120 m, 1910-1880 m) and upward fining (2240-2130 m, 2120-2110 m, 1950-1910 m) cycles from the middle through the top. In Zeepaard 1 ST1 well (Figure 38), only the lower portion of sequence 8 was logged; it is composed primarily of shales with a series of small coarsening and fining upward cycles (> 2350 m). In Eskdale 1 well (Figure 39), sequence 8 is the top of the Gearle Formation, and consists of relatively thin, shale-dominant unit with upward fining and coarsening cycle (1418-1415.5 m).

**Interpretation**

The most prominent depositional feature in sequence 8 is the wedge-shaped body that thickens to the east (Figure 79). Several downlap surfaces are present within this sequence indicating that it includes several depositional sequences, and multiple transgression and regressions are present (Figure 78).

The distribution of sequence 8 indicates a dominant eastern sediment source region during the deposition of this interval. The isochron map (Figure 79) and 2-D facies map (Figure 81) of sequence 8 indicates that there are major changes in the
direction of sedimentation from sequence 7; the progradation direction changed specifically from southeast-northwest to east-west direction.

The interpreted depositional environments of this depositional unit from the facies analysis can also be described as four distinct facies deposited in a shallow marine or continental shelf environments; basin, base-of-slope, slope and shelf margin (Table 12, Figure 81). The area dominated by facies 1 represents the basinal deposition, and is affected by a series of small faults, which results in discontinuities of the reflections. In contrast, facies 2 represents the base-of-slope setting. The seismic characteristics of facies 3 are also mostly affected by the slope setting. Last, facies 4 which has better amplitude and continuity than facies 3 represents shelf margin deposits.

According to the well logs and benthic biofacies, the depositional environment of this depositional unit, the Gearle Siltstone Formation, is described as a low-energy, middle shelf to outer shelf marine. The Gearle Formation formed in a shelf-slope setting with a thick sequence of siltstone and shales.

**Sequence 9: lower Turonian to upper Santonian (94-84 Ma)**

**Time Thickness and Structure**

The isochron values of sequence 9 range between 0 to 800 msec (two-way travel time) throughout the study area (Figure 82). For most of the area, sequence 9 has less than 200 msec of strata. A distinct northeast trending isochron is present in the eastern portion of the area.
Figure 82. Isochron map (in TWTT msecs) of sequence 9 (lower Turonian unconformity - Santonian). The overall thickness is irregularly distributed with maximum thickness over the north-eastern corner of the study area, which is caused by the change of sediments provenance. The distribution of the 2D seismic profiles used to generate the map are shown with white lines. Five exploration wells are shown.
The time-structure maps of the lower Turonian unconformity (SB9) and upper Santonian unconformity (SB10) illustrate more extensively developed arches near the southeastern margin (Figures 80, 83). The northeast trending Exmouth Plateau Arch is located in the northwestern corner of the study area. Both the northeast-southwest trending Resolution Arch and northwest-southeast trending Novara Arch are located in the southeastern corner of the study area. The structural high area of the Resolution and Novara Arches is at 1.50 seconds two-way travel time. The Kangaroo Syncline trends southwest-northeast and is located in the middle of the study area.

**Upper and Lower Boundaries**

Sequence 9 is defined at its base by sequence boundary 9 (SB9) and the top by sequence boundary 10 (SB10) (Figures 8-17, 73-77). The basal horizon of sequence 9, which coincides with the lower Turonian unconformity, is a laterally continuous, high-amplitude reflection. Like the Valanginian and Aptian unconformity, the lower boundary is a prominent unconformity across the Exmouth Plateau Arch where the Investigator 1 well is located; the erosion becomes gradually conformable toward the Kangaroo Syncline and Exmouth Sub-basin (Figures 7, 11, 18, 21). In contrast, the top of sequence 9 is defined by sequence boundary 10 (SB10) that is approximately upper Santonian unconformity. This sequence boundary (SB10) is identified by a laterally continuous, high-amplitude reflection with locally developed erosional truncation (Figures 74, 75, 77). Both sequence boundary 9 and 10 merge gradually and become a single reflection across the southwestern portion of the study area.
Figure 83. Time-structure map of the Santonian surface (SB10). Contour interval is 50 msec. The map apparently shows widely extended arches which are called Resolution Arch (NE-SW) and Norvara Arch (NW-SE) respectively and the major depressed depocenter called the Kangaroo Syncline in the study area. To the northwest, the Exmouth Plateau Arch is shown. See Figures 82, 84 for the distribution of seismic profiles used for generating this map. Location of five exploration wells are shown.
Seismic Facies

Five dominant seismic facies were identified and mapped throughout the study area (Table 13, Figures 73-77, 84). The upper sequence boundary (SB10) of sequence 9 shows partially developed large erosional truncation (Te) features near the slope settings associated with the Novara Arch and the Resolution Arch, and is characterized by concordant reflections on the seismic profiles for the remainder of the study area (Figures 73-77). The lower sequence boundary (SB9) of sequence 9 also shows mainly concordant reflection characteristics with also partially developed erosional truncation. Internally, sequence 9 is characterized by parallel to subparallel reflections with moderate- to high-amplitude and variable continuities (poor to good) depending on the depositional environment (Figures 73-77).

Both facies 1 and 2 have concordant reflections at the upper and lower sequence boundaries with parallel to subparallel internal reflections with moderate- to high-amplitude and variable continuity from poor to good. In contrast, facies 3 has a mounded external geometry and chaotic internal reflections with moderate- to high-amplitude and poor continuity (Figures 74, 76, 84). Facies 4 is illustrated as a large erosional features characterized by the erosional truncation at the upper sequence boundary and concordant reflection on the lower sequence boundary. The internal reflections are subparallel with high-amplitude and poor continuity. Finally, facies 5 has concordant reflections at the upper and lower sequence boundary. The internal reflections are same as the facies 4, whereas it has fair to good continuity.
Figure 84. 2D seismic and geologic seismic facies map of sequence 9 (lower Turonian unconformity - Santonian). This package is a base part of the Toolonga Formation deposited in a slope and basinal environment. After the Turonian unconformity, abundant carbonate deposits were accumulated with at the base of the slope. The distribution of the 2D seismic profiles used to generate the map are shown with gray lines. Red-dot outline indicates the areal extent of potential play. See Table 14 for a summary of coded seismic facies and geologic information. Location of key figures of regional profiles (blue lines), and five exploration wells are shown.
Table 14. Seismic facies and geologic interpretation of sequence 9

<table>
<thead>
<tr>
<th>Seismic Facies</th>
<th>Upper Sequence Boundary</th>
<th>Lower Sequence Boundary</th>
<th>Internal Reflections</th>
<th>Amplitude</th>
<th>Continuity</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>concordant</td>
<td>concordant</td>
<td>parallel/subparallel</td>
<td>moderate</td>
<td>poor</td>
<td>basinal deposits</td>
</tr>
<tr>
<td>2</td>
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<td>concordant</td>
<td>parallel/subparallel</td>
<td>high</td>
<td>fair to good</td>
<td>basinal deposits</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
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<td>moderate to high</td>
<td>poor</td>
<td>carbonate buildup</td>
</tr>
<tr>
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<td>subparallel</td>
<td>high</td>
<td>poor</td>
<td>slope deposits</td>
</tr>
<tr>
<td>5</td>
<td>concordant</td>
<td>concordant</td>
<td>subparallel</td>
<td>moderate to high</td>
<td>fair to good</td>
<td>upper slope deposits</td>
</tr>
</tbody>
</table>

**Wireline log**

Based on the cuttings described in all of the well logs, all strata overlying the Turonian unconformity are carbonates. Based on the wireline log interpretation and regional correlations, sequence 9 was deposited as the base portion of the carbonate-dominated Toolonga Formation during the Santonian. In Investigator 1 and Zeewulf 1 wells (Figures 34, 35), sequence 9 is relatively thin (30-40 m thick), and has a sharp base overlying the Turonian unconformity. The overlying strata have a slightly upward coarsening pattern (argillaceous calcilutite). In Resolution 1 (Figures 36), sequence 9 is 8 m thick with constant gamma-ray values (1703-1690 m). In Eskdale 1 well (Figure 39), sequence 9 has a blocky gamma-ray with minor fluctuation, which represents argillaceous calcilutite unit. In contrast, in Leyden 1B ST1 well (Figure 37), sequence 9 has a sharp base at 1855m and is characterized by upward coarsening (1855-1850 m),
overall upward fining pattern with shale units (1850-1790 m), and then upward coarsening and thinning (1790-1740 m).

**Interpretation**

A significant change in the overall sedimentation along the northwest shelf happened above the Turonian unconformity. In the Northern Carnarvon Basin, the area changed from a siliciclastic dominated margin to a carbonate dominated margin.

After the Turonian unconformity, siliciclastic sedimentation ceased, likely as the result of tectonic stability and primarily from a decrease in terrigenous sediment supply from onshore sedimentary source feeders. Instead, the shelfal carbonate Toolonga Formation, which has sparsely developed carbonate build-ups with minor siliciclastic sediments, was deposited during the Late Cretaceous (Figures 10, 16, 74, 76). An increase in slope gradient over the Novara Arch and Resolution Arch after the Turonian unconformity resulted in widespread, well-developed sediment slumping with large erosional features (Figures 8-10). These large erosional features are more intensively developed during the depositional process of successive sequences overlying sequence 9.

The depositional environment of this depositional unit can be described as marine-neritic (0-200 m in water depth) or outer shelf and upper slope settings which are same depositional environment as the Gearle Siltstone Formation. The difference is that the Toolonga Formation has dominant pelagic carbonate accumulations due to a decreasing of terrigenous sediments supply from the sedimentary source.
The area dominated by facies 1 and 2 represents the basinal deposition. In particular, facies 1 over the northwestern margin of the study area is affected by a series of small faults, which results in discontinuities of the reflection. Facies 3 is interpreted to represent the main characteristics of a carbonate buildup facies which represent an outer shelf setting. Those facies 4 and 5 are interpreted to be deposited within the slope or upper slope settings (Table 13). The areal extent of facies 4 which contains large erosional features is almost coincident with the boundary of steepy slopes of the Resolution and Novara Arches (Figure 84).

**Post-Santonian Sequences**

In the strata younger than the Santonian in the Northern Carnarvon Basin, five distinct stratigraphic features are present that are worth discussing briefly. Large incised channels or large erosional features are present in the Upper Cretaceous and lower Tertiary strata. The channels trend north-south and southwest-northeast, which is oblique to the paleo-slope that dips to the northwest (Figures 7b, 9b, 10b, 13b, 17b). These erode up to 70 msec (80 m) of sediments, and are 2.8 km wide (Figure 78b). The irregular relief and large scale erosional features overlying the Santonian sequence boundary may be the results of massive failures of the slope; these sediment failures may have been induced by an abrupt relative lowering of base level, and the corresponding high rates of sedimentation creating overpressured slope sediments. The relative lowering was either the result of tectonic activity or sea level fall. Thus, slope instability may have induced large mass failure and slumping, which may be associated with slope-oblique submarine channels (Figures 9, 10, 17, 47, 63, 77).
Because of these large erosional morphologies as well as abundant small faults that cut across the Upper Cretaceous sequences, the picking of additional candidates of the sequence boundaries between Santonian and Base Tertiary was complicated (Figures 7-11). However, a major erosional surface characterized by a marked truncation of the underlying Upper Cretaceous strata was identified on the seismic profiles (Figures 7-11, 73-77).

More sequence boundaries characterized by well defined major onlapping reflection terminations were identified above the Base Tertiary surface, in particular on the dip-oriented regional seismic profiles throughout the study area (Figures 7-11). These sequence boundaries are approximately correlated with Eocene (SB13), Oligocene unconformity (SB14), and Late Miocene (SB15) respectively (Figure 9c).

In one area, there are potential remobilized or intruded sandstones through multiple layers of strata after the burial of the Gearle Formation (Figure 85). The possible dike-like sand injectites are observed on 2-D seismic profiles as cross-cutting reflections (Figures 13, 85). The Gearle Formation is the host rock, and consists of siltstone and calcareous shale. These features have not been penetrated by any exploration wells, so no direct evidence such as coring or logging has been done to support the seismic interpretation of sand injectites. The development of sand injectites would be associated with horizontally well-connected systems within low-permeability strata (Hurst et al., 2007).

The study area is characterized by the episodes of structural inversion during the Turonian. The main inversion within the Exmouth Sub-basin happened (Figures 6, 8-11,
Figure 85. Dip-oriented seismic profiles showing the potential sand injectite geometry developed in the Gearle Formation: (a), (b) uninterpreted, (a’), (b’) interpreted. See Figures 3, 5, 29, 42, 50, 53, 58, 66, 69, 72, 81, and 84 for the location of the profile.
18, 19). Stratigraphically, it is correlated with the Toolonga Formation and the Upper Gearle Formation. During the Miocene (Figure 6b), additional inversion was caused by the compression resulted from the continental collision of Indian and Australian plates. As the deep seated normal faults were reactivated as reverse faults in the passive margin phase, the inversion related monocline structures formed in the shallow area (Figure 6b).

V. PETROLEUM SYSTEMS

Regional Petroleum Systems

The study area is dominated by two main groups of petroleum systems: (a) the gas prone Locker-Mungaroo/Barrow petroleum system across the Exmouth Sub-basin and to the northern edge of the Exmouth Plateau, and (b) the oil prone Dingo-Mungaroo/Barrow petroleum system which is restricted to within the Exmouth Sub-basin (Figures 22, 86) (Bishop, 1999). The Locker-Mungaroo/Barrow petroleum system consists of gas accumulations generated mainly from the Triassic to Jurassic fluvial-deltaic source rocks, whereas the Dingo-Mungaroo/Barrow petroleum system consists of oil accumulations generated from the Jurassic marine source rocks (Figure 86). The major aspects of these petroleum systems including source rocks, reservoir rocks, seals, traps, and migration are addressed as follows.

Source Rocks

Three major petroleum source rocks have been recognized in the Northern Carnarvon Basin based on geochemical analyses of samples acquired from the reservoirs in multiple stratigraphic levels (He, 2002) (Figures 4, 22). Most of petroleum
Figure 1. Map showing the major sedimentary basins of the Northwest Shelf of Australia with bathymetry (Modified from Trendall et al., 1990; Hocking et al., 1994; Purcell et al., 1994).

Figure 86. Map showing the areal distribution of the two petroleum systems in the Northwest Shelf of Australia: the Dingo-Mungaroo/Barrow and Locker-Mungaroo/Barrow. Modified from Bishop (1999).
discoveries have been developed. In particular, two gas-prone source rocks were derived from the Triassic marine and fluvio-deltaic facies, and one oil prone source rock was derived from Upper Jurassic marine facies (Figures 4, 7, 22).

The organic-rich transgressive marine Locker Shale (Lower Triassic) was deposited throughout the entire study area. This unit is considered to be the primary source rock for gas with the overlying deltaic Middle to Upper Triassic Mungaroo Formation (e.g. Scarborough, Jansz fields) (Figures 2-4, 6b, 22). Second, the deeply-buried coals and carbonaceous claystones of the Middle to Upper Triassic Mungaroo Formation are interpreted to be the source rocks for the gas at Scarborough, and Jansz fields (Geoscience Australia, 2010) (Figures 6b, 19, 20, 22). Triassic source rocks are generally of moderate quality with local areas of high quality: an average total organic carbon content (TOC) of 1 to 3 wt % and hydrogen index (HI) of 200 to 300 (Scott, 1994). The dominant organic matter type in the Triassic and Jurassic source rocks is type III kerogen (He, 2002). The Locker and Mungaroo source rocks are interpreted to have begun generating during the Late Jurassic with the deposition of the thick, prograding Dingo Claystone (Figures 4, 6b, 20).

The Upper Jurassic Dingo Claystone is also interpreted to have been a primary source rock potential for oil in the Exmouth Sub-basin (Tindale et al., 1998) (Figures 4, 6b, 20). This claystone is a fine-grained marine unit deposited in partly restricted deep water environment. The source rocks in the Dingo Claystone began generating oil during the Early Cretaceous, from the burial of the Barrow Group Delta (Tindale et al., 1998; Smith et al., 2003). This claystone has a moderate quality with an average TOC
content of > 2 wt % and HI of >150. The kerogen type is generally a mixture of marine and terrigenous organic matter (type II and III kerogen) (Kopsen and McGann, 1985).

**Reservoir Rocks**

To date, the reservoir rocks in the study area are mainly represented by the fluvial-deltaic sandstones of the Middle to Upper Triassic Mungaroo Formation (e.g. Geryon, Eurytion, Chrysaor, Dionysus, Orthrus, Urania fields), locally developed Upper Jurassic channel-fill sandstones (e.g. Jansz field), and the Lower Cretaceous Barrow Group (e.g. Scarborough, Coniston, Stybarrow, Enfield, Vincent fields) (Figures 2, 5b, 6b, 18, 19, 21, 27). The Mungaroo Formation consists of interbedded fluvial, deltaic, and alluvial strata. These strata prograded to the northwest, across the subsiding sub-basin trend and graded into prodelta marine facies toward the northwestern edge of the Exmouth Plateau. Reservoirs are up to 30 meters thick of delta plain sandstones with 15-35 % porosity and 1000 md permeability. More than 35 mmbbls of oil, 44 Tcf of gas, and 836 mmbbls of condensate of estimated recoverable reserves are assigned to the Mungaroo Formation to date (Geoscience Australia, 2010).

The deltaic and related strata of the Lower Cretaceous Barrow Group also prograded north-northwestward across the Exmouth Sub-basin and Exmouth Plateau (Figure 23). The Barrow Group is, by far, the most important reservoir within the study area with good reservoir quality: 20-27 % porosity and 3000-4000 md permeability. The estimated recoverable reservoirs are 400 mmbbls of oil, 4 Tcf of gas, and 108 mmbbls of condensate (Geoscience Australia, 2010).
Seals

Two major seals are present. The Upper Triassic shales of the Brigadier Formation form the seals for the Mungaroo Formation (Figures 4, 22). The Muderong Shale, which is up to 900 m thick, plays an important role as the regional seal across the study area for the Barrow Group reservoirs as a result of a major transgression in the Valanginian (Figures 21, 22, 28). Additionally, potential intraformational seals formed by the interbedded claystone of the Mungaroo Formation and Barrow Group may act as an important barriers and baffles to hydrocarbon-bearing reservoirs.

Traps and Migration

To date, four major trap types produce petroleum from the Triassic, Jurassic, and Cretaceous reservoirs in the study area: (1) fault bounded three-way closure (Figures 6b, 38b), (2) four-way closure (Figures 6b, 7b, 27) as a result of stratigraphic depositional relief with differential compaction, (3) four-way closure associated with rollover against a fault (Figure 8b), and (4) stratigraphic pinchouts beneath the regional seal (Figures 6b, 8b). Mostly the traps developed after the Turonian. The reactivation of the faults due to the inversion during the Late Cretaceous and Tertiary allowed for significant vertical migration of petroleum from the expelling kitchen into the overlying strata (Figure 6b).

Potential Plays

Although many parts of the Northern Carnarvon Basin have been extensively explored, the exploration has mainly focused on the proven hydrocarbon-rich Barrow
and Dampier Sub-basins (Figures 1, 2). Therefore, the Exmouth Sub-basin and Exmouth Plateau where this study area is located have been significantly less explored.

Most of the drilling has been restricted to the rotated, high relief Triassic fault block plays under large anticlinal structures (Figures 6b, 8b) near the southern edge of the Exmouth Sub-basin (Figures 2, 3, 5, 29), and the Lower Cretaceous turbidite fan plays with four-way closure over the Exmouth Plateau (Figures 2, 3, 5, 7b, 27, 29). Seismic-amplitude anomalies, which are sometimes characterized by direct hydrocarbon indicators (DHIs), are specifically present within the Lower Cretaceous turbidite play (Figures 7b, 27). Most of petroleum accumulations discovered to date are associated with the Early Cretaceous Barrow Group structural plays beneath the base regional seal of the Muderong Shale. Other conceptual types of plays include stratigraphic plays in the upper delta unit of the Barrow Group, post-Muderong Shale and carbonate buildup or pinnacle reef. These plays have not been tested probably due to the risks of structures and traps of the petroleum system.

One of the objectives of this study is to evaluate the Valanginian through Turonian strata for potential plays for the successful future exploration. Interpretation of regional seismic and well data suggests that five potential plays could be present in the study area (Figure 87, Table 15).

First, the delta front area of the Zeepaard Formation (Figures 10b, 54, 87) has a potential as a possible stratigraphic trap. The progradational delta of sequences 1 to 3 consists mainly of reservoir quality sandstones with minor interbeds of siltstones. In particular, sequences 2 and 3 in the Zeepaard Formation have blocky sandstone
packages, based on the well logs in Zeewulf 1, Resolution 1 and Leyden 1B ST 1 wells (Figures 36-38). These sequences have the maximum thickness across the delta front area (Figures 51, 54), and may trap hydrocarbons where the overlying, thick Muderong Shale is onlapping against them as a wedge-type geometry (Figures 7-11). Thus, the fine-grained Muderong Shale has good potential as a regional seal (top seal) not only for the proven reservoir in the lower delta of the Barrow Group, but also the upper delta (Zeepaard Formation). In addition, the Muderong Shale and overlying Gearle Siltstone may provide a source rock potential for the post-Muderong Strata. Additional seals are the intraformational sealing siltstones and shales developed within the Zeepaard Formation. In general, the migration of hydrocarbons from the source rocks of the Triassic Mungaroo Formation and Jurassic Dingo Claystone is considered to follow reactivated faults during the Late Cretaceous to Tertiary inversion.

Second, the basinal unit present within sequence 5 over the Exmouth Plateau, is onlapping updip against the underlying delta front area of the Zeepaard Formation (Figures 7-11, 14, 44, 46, 47, 60, 62, 63, 74, 76, 77). This deepwater onlap play (or stratigraphic updip pinchout play) is present to the northwest on the Exmouth Plateau (Figures 66, 87). This trap type has favorable location for migration and charge from the syn-rift Triassic source rocks in the Exmouth Plateau via major normal faults (Figure 11b). Potential reservoir quality sandstone for this play are present in Investigator 1 well (Figure 34). Again, the overlying thick, fine-grained Muderong Shale has an effective top seal capacity.

Third, the Birdrong Formation and Mardie Greensand in sequences 4 and 5 may have a possible stratigraphic updip pinchout play (Figures 6, 8-10). These thin units
Figure 87. Map showing the distribution of potential play types identified in the study area: 1) deepwater onlap (SQ5, magenta), 2) stratigraphic trap in prograding wedge (SQ2-3, orange), 3) updip pinchout (SQ4,violet), 4) updip pinchout (SQ6-7, yellow), and 5) carbonate buildup (SQ9, blue) (SQ = sequence).
consist of a few cycles of sandstone and siltstone with restricted areal extent within the Exmouth Sub-basin (Figures 30, 32, 35-37, 39, 87). Like the other proven reservoirs in the study area, the overlying Muderong Shale provides a good regional top seal. The base seal can be intraformational marine shales developed at flooding surfaces between the Birdrong Formation and Mardie Greensand (Figures 35a, 36a, 37a). In the southern Exmouth Sub-basin, the Birdrong Formation and Mardie Greensand have a stratigraphic play potential, as they are also overlain by the Muderong Shale (Figure 6b).

Fourth, sequences 6 and 7, which are the lower to middle portion of the Gearle Formation, show also a presence of possible stratigraphic plays in the Exmouth Plateau. These sequences show updip pinchouts toward the Resolution Arch (Figures 8b, 9b, 10b). Blocky sandstone units, which developed at the base of sequence 6 and the top of sequence 7 (Figures 35-38), may provide a reservoir potential when trapped properly. In Zeepaard 1 ST1 well (Figure 38b), these sand units are developed in a closure associated with rollover against a major fault (Figure 38b). Specifically, the under- and overlying shale dominated Gearle Formation may provide an effective top and base seal as well as be a source rock. In addition, seismic amplitude anomalies are observed in these traps (Figures 10, 74). In general, when two beds merge in a pinchout trap, these tend to cause an increase in seismic amplitude. Therefore, further favorable AVO responses are needed to support this play.

Finally, the carbonate buildup or pinnacle reefal trap, which is locally developed as a mounded feature (60 m thick) in the Turonian or Santonian strata, may also have a significant reservoir potential to be tested (Figures 10b, 44, 46, 60, 62, 74, 76, 87). To
identify and image this potential play accurately, 3-D seismic and exploration drilling are necessary.

Table 15. Potential play types identified in the study area

<table>
<thead>
<tr>
<th>Play</th>
<th>Play type</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>deepwater onlap play</td>
<td>sequence 5</td>
</tr>
<tr>
<td>2</td>
<td>stratigraphic play</td>
<td>sequence 2-3</td>
</tr>
<tr>
<td>3</td>
<td>updip pinchout play</td>
<td>sequence 4</td>
</tr>
<tr>
<td>4</td>
<td>updip pinchout play</td>
<td>sequence 6-7</td>
</tr>
<tr>
<td>5</td>
<td>carbonate buildup play</td>
<td>sequence 9</td>
</tr>
</tbody>
</table>

VI. DISCUSSION

Based on this study, understanding the sequence stratigraphic framework for the Cretaceous strata has led to the identification of several significant potential plays and the corresponding consideration for developing new strategies for the future exploration. Considerable exploration potential still remains for the Lower to Upper Cretaceous sandstone reservoirs in the Exmouth Sub-basin and Exmouth Plateau. Mostly these potential plays are associated with the stratigraphic traps (e.g. pinchout trap, reefal trap). These are primarily developed in sequences 2 through 9. To reduce the main risks for the future exploration, the evaluation of play risk and additional work are worth discussing briefly.
In sequence 5, a reservoir quality sandstone unit is onlapping against the underlying progradational delta in a deepwater setting across the Exmouth Plateau. This onlapping potential reservoir unit is mainly sealed by the overlying impermeable, marine shale (Muderong Shale). Identification of flooding surfaces (FSs) also indicates the probability that intraformational sealing shales may be present and may trap hydrocarbons (gas-prone in the Exmouth Plateau). Thus, this deepwater onlap play may offer a good potential for stratigraphic entrapment. However, a key uncertainty for this play may be associated with the timing of migration. Regional migration pathways may vary through time. In particular, gases need to have migrated after the top seals were deposited during the Early Cretaceous to Cenozoic. Probably, these gases would have to travel a short- to long-distance, either via vertical migration pathway through reactivated faults from underlying Triassic source rocks (Mungaroo Formation, Locker Shale), or via lateral migration pathway from the Muderong Shale itself. The adjacent stratigraphic play developed in the delta front area of sequences 2-3 (Zeepaard Formation) is also evaluated to have a key uncertainty of migration pathway. However, the sandstone units in this play may have better reservoir quality with considerable thickness, and intraformational sealing shales than other potential plays identified in the area.

Potential stratigraphic traps are present within sequences 4 through 7 over the southeast of Exmouth Plateau. These traps are associated with lateral updip stratal pinchouts. Sandstone units are present within these stratigraphic plays, and sealed primarily by Muderong and Gearle Formation, and intraformational sealing shales at the numerous flooding surfaces, which are developed in sequences 4, 5, and 8.
Hydrocarbon charge is particularly the key uncertainty for the stratigraphic traps in sequences 6-8 (Gearle Formation), because of the long migration pathways needed for these plays. Migration would occur either from the underlying Triassic source rocks in the Exmouth Plateau (gas-prone), or from the Triassic, or Jurassic source rocks (oil-prone) in the Exmouth Sub-basin. However, unlike the other stratigraphic pinchout or onlap play developed in sequences 4 and 5, the source rocks and migration pathway for these plays have more possibility to be associated with the post-Muderong Shale strata. This is because the major normal faults, which are interpreted to play a critical role for the hydrocarbon migration from the Triassic or Jurassic source rocks in the area, do not significantly cut across the successive strata from sequences 6 through 8 on the seismic profiles. Instead, a series of nearly vertical normal faults, which may provide a vertical migration pathway from overlying Gearle Formation, are developed within the Upper Cretaceous strata. Lateral migration from the Gearle Formation may be another possibility.

For the carbonate buildup play identified in sequence 9, a key uncertainty is evaluated to be associated with leaky top and lateral seals due to the dominated carbonate lithology within this sequence. However, seals may be provided by a variety of mechanisms including porosity differences in the reservoir rock, overlying carbonates, and interbedded shale.

Overall, these types of stratigraphic plays tend to lack obvious structural closure and are not usually discovered using the standard exploration strategies designed for the structural traps. In particular, most potential stratigraphic plays are identified in a small part of single or double reflections with a slight change of external shape and
amplitude anomaly. Therefore, high resolution seismic acquisition with a wide range of frequencies and velocity surveys to create accurate synthetic seismograms are essential to resolve these small features and predict the reservoir distribution.

For the successful future exploration, the development of further detailed sequence stratigraphic framework from the integration of 3-D seismic, new well logs, and core data should be preceded. In addition, well-constrained use of seismic techniques such as AVO analysis is appropriate to map potential trap geometry and determine drilling locations.

VII. CONCLUSIONS

1) A sequence stratigraphic framework has been developed for the Cretaceous strata in the Exmouth Sub-basin and Exmouth Plateau, by integrating regional 2-D seismic data and the currently available well data. Nine sequences were defined on seismic profiles and correlated through most of the study area between Valanginian and Santonian. These sequences vary in thickness and areal extent.

2) Sequences 1-3 (Zeepaard Formation) are part of a large progradational wedge of siliciclastic of slope to coastal plain strata. This is the informal “upper delta” portion of the Barrow Group. Distinct topset-foreset-bottomset depositional geometries are present.

3) Sequence 4 (Birdrong Formation) and 5 (Muderong Shale) were deposited during a regional transgression. These formations backstep and overlie the underlying sequences 1-3. Thick and shale-dominant Muderong Formation
shows a blanket-like, partially wedge-type geometry over the Exmouth Plateau, which plays a major role as a top seal of the underlying Barrow Group reservoirs.

4) Sequences 6-8 (Gearle Formation) were deposited in a relatively continuous seal level rise during the Albian to Turonian. This resulted in a deepening of depositional environment with the deposition of siltstone and shale. This formation overall thins across the Exmouth Plateau and thickens across the Exmouth Sub-basin area where it has the maximum thickness. In particular, wedge-shaped body that thickens to the east is present in sequence 8.

5) The source area for the Cretaceous strata changed from the southeast to east. For sequences 1-7, the dominant direction of progradation was southeast to northwest. For sequences 8-9, the direction became east to west.

6) Several distinct downlap surfaces are present in the Gearle Formation across the Exmouth Sub-basin. This indicates the Gearle Formation includes several depositional sequences with multiple transgression and regression. Due to a structural instability caused by the uplift tectonism and lack of permeability within the siltstone and claystone-dominated strata, remobilized or intruded sediments of possible sand injectites through multiple layers of strata were developed within the Gearle Formation.

7) Increased accommodation from the flexible subsidence of the margin and high carbonate sedimentation rates were dominant during the Turonian and Santonian. An increase in slope angle after the Turonian unconformity resulted in widespread and well-developed sediment slumping and progradation of carbonate deposits up until the end of the Cretaceous. Carbonate buildups were
commonly developed as a typically mounded geometry after the Turonian unconformity or Santonian unconformity. Incised channels with large erosional features were created due to the results of massive failures of a marine slope, which may have been induced by an abrupt lowering of base level, either as the result of tectonic activity or eustatic fall of relative sea level.

8) During the Miocene, there was local inversion on selected basement structures. This reactivation of deep seated normal faults to become the reverse faults created monocline structures that create potential for traps in some area.

9) The main potential plays of the study area are associated with stratigraphic plays including the deepwater onlap play in sequence 5 and additional updip pinchout plays in sequences 4-8.

**VIII. RECOMMENDATIONS**

As a result of this study, the following recommendations are proposed to enhance future exploration efforts:

1) The regional sequence stratigraphic framework for the Cretaceous should be extended to the entire Exmouth Plateau and Exmouth Sub-basin.

2) 3-D seismic data need to be acquired to help identify and image additional structural, and combined structural/stratigraphic traps in the areas including the carbonate reefs with high-amplitude anomaly within the study area.

3) Geophysical attribute techniques, specifically AVO analysis tied with accurate rock physics studies, are key interpretation tools to contribute exploration success in the study area.
4) In addition, integration of all the recently drilled well log and core data from the wells within or near the study area is necessary for more detailed stratigraphic analysis.

5) Additional work for analyzing reservoir potential of post-Muderong shale is recommended, in particular focusing on the presence of stratigraphic plays.

6) More available electric logs including resistivity logs and neutron-density logs should be added for improving the accuracy of well correlation. In addition, the generation of accurate synthetic seismograms for all key wells in the study area is necessary for the accuracy of well-to-seismic tie within the study area.

References Cited


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