
Allison Jean Kimbrough
University of Colorado at Boulder, allison.kimbrough@colorado.edu

Follow this and additional works at: https://scholar.colorado.edu/geol_gradetds
Part of the Petroleum Engineering Commons, and the Sedimentology Commons

Recommended Citation
https://scholar.colorado.edu/geol_gradetds/140

This Thesis is brought to you for free and open access by Geological Sciences at CU Scholar. It has been accepted for inclusion in Geological Sciences Graduate Theses & Dissertations by an authorized administrator of CU Scholar. For more information, please contact cuscholaradmin@colorado.edu.
Seismic sequence stratigraphy of Cretaceous rocks and mechanisms controlling basin evolution, Falkland Plateau Basin, southern Atlantic Ocean

By

ALLISON JEAN KIMBROUGH

B. S. Geological Sciences, University of California Santa Barbara, 2014

A thesis submitted to the Faculty of the Graduate School of the University of Colorado in partial fulfillment of the requirements for the degree of Master of Science Department of Geological Sciences 2018
This thesis entitled:
Seismic sequence stratigraphy of Cretaceous rocks and mechanisms controlling basin evolution,
Falkland Plateau Basin, southern Atlantic Ocean
written by Allison Jean Kimbrough
has been approved for the Department of Geological Sciences

____________________________________________
Dr. Paul Weimer

____________________________________________
Dr. David Budd

____________________________________________
Dr. Carmen Fraticelli, Noble Energy

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.
The Falkland Plateau Basin, including the Fitzroy sub-basin, is a frontier petroleum exploration area, which records a unique tectonic and stratigraphic evolution. Interpretation of a 6000 km$^2$ 3D, time-migrated seismic data set focused on the Cretaceous section, which is the most prospective in the area. The sequence stratigraphic architecture is defined, in detail, with emphasis on the evolution of the marginal marine depocenters and their downdip deepwater deposits.

Five second-order Cretaceous megasequences were defined, each comprising multiple third-order sequences. Each megasequence varies in terms of its structure, time-thickness, systems tracts, seismic facies, and their linkage between coeval shelf and basin-floor strata. The Cretaceous strata consist of a series of shallow marine deltaic systems that prograded to the southeast and delivered sediment to deepwater. At both the sequence and megasequence scale, sediments preferentially accumulated in either the shelf, slope or basin-floor settings, rather than being evenly distributed across the depositional profile. Variations in the depositional patterns are interpreted to be caused by a changing balance between sediment supply, relative changes in sea level, and tectonic events.

Megasequences 1 and 2 are overall aggradational, indicating a balance in sediment supply and basin subsidence. The extensive base-of-slope channel-levee systems in Megasequence 3 are the most favorable reservoirs. An extended relative lowstand in sea level
associated with a second-order sequence boundary was the likely control on these thick deposits. Megasequence 4 consists of thick sigmoidal clinoforms that prograded 20-40 km basinward. Megasequence 5 is an entirely onlapping package whose sediment was sourced from a different direction than the underlying megasequences.

The presence of reservoir quality sand (Lower Cretaceous) and organic-rich source rocks (Lower Cretaceous and Upper Jurassic) has been documented by six exploration wells drilled on the Falkland Plateau, as well as DSDP sites 311 and 511. These wells confirm a working petroleum system in the region. The lack of structure in the basin means stratigraphic traps are the most prospective. The highest risk is the presence of source rock within the study area, as the nearest penetrations are over 100 km away.
# CONTENTS

I. Introduction ........................................................................................................... 1  
   A. Terminology .................................................................................................... 4  
   B. Exploration History ......................................................................................... 4  

II. Data Set ............................................................................................................. 9  

III. Regional Geography and Tectonics .................................................................... 11  

IV. Methods ........................................................................................................... 18  

V. Sequence Stratigraphy ........................................................................................ 19  
   A. Overview of Megasequences .......................................................................... 19  
   B. Interpretation Challenges ............................................................................... 23  
   C. Megasequence 1 .............................................................................................. 29  
   D. Megasequence 2 .............................................................................................. 48  
   E. Megasequence 3 .............................................................................................. 64  
   F. Megasequence 4 .............................................................................................. 90  
   G. Megasequence 5 ............................................................................................. 104  

VI. Discussion ....................................................................................................... 111  

VII. Conclusion ..................................................................................................... 125  

VIII. References .................................................................................................... 129
<table>
<thead>
<tr>
<th>FIGURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Base Map…………………………………………………………………………… 2</td>
</tr>
<tr>
<td>2. Sedimentary thickness in Falkland Plateau Basin map…………………….. 3</td>
</tr>
<tr>
<td>3. Exploration wells map…………………………………………………………… 6</td>
</tr>
<tr>
<td>4. Geologic map of the Falkland Islands…………………………………….… 7</td>
</tr>
<tr>
<td>5. Seismic conditioning/footprint removal……………………………………… 10</td>
</tr>
<tr>
<td>6. Formation of Falkland Plateau Basin schematic……………………………. 12</td>
</tr>
<tr>
<td>7. Paleogeographic map of Falkland Plateau…………………………………… 13</td>
</tr>
<tr>
<td>8. Falkland Plateau Basin in downdip position from Outeniqua Basin……….. 14</td>
</tr>
<tr>
<td>9. Igneous dikes on Falkland Islands map……………………………………….. 17</td>
</tr>
<tr>
<td>10. Seismic profile with all megasequences…………………………………….. 21</td>
</tr>
<tr>
<td>11. Biostratigraphic ages of megasequence boundaries………………………… 22</td>
</tr>
<tr>
<td>12. Polygonal faults…………………………………………………………………… 25</td>
</tr>
<tr>
<td>13. Topset faults………………………………………………………………………. 27</td>
</tr>
<tr>
<td>14. Gas and igneous intrusions……………………………………………………… 28</td>
</tr>
<tr>
<td>15. Megasequence 1 dip profile (center)………………………………………….. 30</td>
</tr>
<tr>
<td>16. Megasequence 1 dip profile (southwest) ……………………………………… 31</td>
</tr>
<tr>
<td>17. Megasequence 1 dip profile (northeast) ……………………………………….. 32</td>
</tr>
<tr>
<td>18. Base Megasequence 1 time structure map……………………………………. 33</td>
</tr>
<tr>
<td>19. Top Megasequence 1 time structure map………………………………………. 34</td>
</tr>
<tr>
<td>20. Megasequence 1 isochron map………………………………………………….. 36</td>
</tr>
<tr>
<td>21. Crossline through volcanic-influenced basin floor thicks…………………… 37</td>
</tr>
<tr>
<td>22. Megasequence 1 strike profile at shelf edge………………………………… 38</td>
</tr>
<tr>
<td>23. Megasequence 1 seismic facies map…………………………………………… 40</td>
</tr>
<tr>
<td>24. Megasequence 1 variation……………………………………………………….. 45</td>
</tr>
<tr>
<td>25. Megasequence 2 dip profile (southwest) ……………………………………… 49</td>
</tr>
<tr>
<td>26. Megasequence 2 dip profile (center) …………………………………………. 50</td>
</tr>
<tr>
<td>27. Megasequence 2 dip profile (northeast) ………………………………………. 51</td>
</tr>
<tr>
<td>28. Top Megasequence 2 (upper Valanginian) time structure map………………. 52</td>
</tr>
<tr>
<td>Number</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>29</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>31</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>33</td>
</tr>
<tr>
<td>34</td>
</tr>
<tr>
<td>35</td>
</tr>
<tr>
<td>36</td>
</tr>
<tr>
<td>37</td>
</tr>
<tr>
<td>38</td>
</tr>
<tr>
<td>39</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>42</td>
</tr>
<tr>
<td>43</td>
</tr>
<tr>
<td>44</td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>46</td>
</tr>
<tr>
<td>47</td>
</tr>
<tr>
<td>48</td>
</tr>
<tr>
<td>49</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>51</td>
</tr>
<tr>
<td>52</td>
</tr>
<tr>
<td>53</td>
</tr>
<tr>
<td>54</td>
</tr>
<tr>
<td>55</td>
</tr>
<tr>
<td>56</td>
</tr>
<tr>
<td>57</td>
</tr>
</tbody>
</table>
58. Base Megasequence 5 distal onlapping wedge ........................................110
59. Tectonic map of Atlantic-margin basins..............................................116
60. Final shelf edge positions map..............................................................119
61. Distribution of wells penetrating organic-rich source rocks..................122
62. DSDP site locations map......................................................................124
INTRODUCTION

This thesis describes the sequence stratigraphy of the Cretaceous linked shallow to deepwater strata in a 6000 km² area of the Fitzroy sub-basin, offshore Falkland Islands (Figure 1). The goal is to establish a predictable relationship between variations in shelf-margin depositional systems, and associated slope and basin-floor deposition, and to consider the implications for the distribution of petroleum system elements.

The Cretaceous succession in the Fitzroy sub-basin was deposited in an actively subsiding area with similarities to a divergent margin. The strata are interpreted as a series of deltaic or shelf margin fan systems prograding and thickening towards the southeast, where they merge with possible slump masses and/or basin-floor turbidite deposits (Richards et al. 2006). The petroleum play that is generally considered the most prospective in the Falkland Plateau Basin is Lower Cretaceous, deep-marine, slope channels and basin-floor fans, sitting within and above the Lower Cretaceous source rocks (Stone, 2016).

Five major stratigraphic packages, referred to herein as megasequences, are recognized and mapped across the study area. Each have differing stratigraphic architecture indicating that the depositional system in the basin varied throughout the Cretaceous. Recognizing the relationship between shallow and deepwater deposition in a changing environment based on the stratigraphic record is key to understanding the evolution of this basin, and source-to-sink processes in passive margin settings around the world.

Four sedimentary basins surround the Falkland Islands in the South Atlantic Ocean: Falkland Plateau Basin (east), South Falkland Basin (south), North Falkland Basin (north), and Malvinas Basin (west) (Figure 1). The Falkland Plateau Basin is composed of two sub-basins:
Figure 1: Bathymetric and topographic map showing the tectonic setting of southern South America and the Falkland Plateau. Locations of adjacent basins, Maurice Ewing Bank, the Berkley Arch (BA), and the Falkland Plateau. The green area shows the 3D seismic survey of the study area.
Figure 2: Sedimentary thickness in the basins surrounding the Falkland Islands. It was compiled by Kimbell and Richards et al. 1996.
the Fitzroy sub-basin and the Volunteer sub-basin, which are separated to the south and north, respectively, by the Berkeley Arch (Figure 1). The Fitzroy sub-basin is elongate and trends SW-NE, parallel to the shelf edge and the coastline of East Falkland Island. The sedimentary thicknesses of the four basins surrounding the Falkland Islands range from 1 to 15 km (Figure 2). The Falkland Plateau Basin contains the greatest thickness of sedimentary rocks, exceeding 10 km of Jurassic-Eocene fill along its western side (Figure 2). The study area for this thesis is located along this trend of thick sedimentary fill.

**Terminology**

The terminology for the geography of this area is potentially confusing because of the similarity of terms that have been used in the literature. For clarification, the following terms are used throughout this thesis. The *Falkland Plateau* is inclusive of the Falkland Islands, the surrounding sedimentary basins, and the Maurice Ewing Bank (Figure 1). The Falkland Plateau is bounded to the north by the Agulhas Fracture Zone, and to the south by North Scotia Ridge. The *Falkland Platform* is the microplate that the Falkland Islands occupy; the Falkland Platform does not include any of the surrounding basins. The *Falkland Plateau Basin* is the sedimentary basin that lies east of the Falkland Islands and west of the Maurice Ewing Bank (Figure 1). The *Fitzroy sub-basin* is the southern of two sub-basins (Fitzroy and Volunteer) within the Falkland Plateau Basin (Figure 1).

**Exploration History**

The earliest subsurface penetrations of the Falkland Plateau Basin was between 1977 and 1983, during DSDP Legs 36 and 71. These expeditions collected regional 2D seismic data
across the Falkland Plateau and cored wells on the western edge of the Maurice Ewing Bank (Barker et al, 1977, Ludwig et al, 1983). These wells are approximately 600 km east of the study area (Figure 1). The cores recovered Upper Jurassic and Lower Cretaceous organic-rich, marine source rocks, establishing the presence of a possible working petroleum system (Comer et al, 1977, Von der Dick et al, 1983).

An exploration drilling campaign, beginning in 1998, marked the first episode of petroleum exploration activity in the basins around the Falkland Islands. In 2002, exploration acreage in the Falkland Plateau Basin was licensed, and the first commercial seismic data were acquired in 2004. In 2012, the Loligo-A well, drilled in the Volunteer sub-basin (Figure 3), had gas shows, but was not classified as a discovery. Noble Energy drilled the Humpback exploration well in 2015 within the Fitzroy sub-basin (Figure 3) and found thick sands; however, hydrocarbons were not encountered, and the well was plugged and abandoned.

The potential presence of reservoir facies in the area is supported additionally by the Toroa-1 well, located ~100 km to the southwest of this study area in the South Falkland Basin (Figure 3). This well demonstrated the presence of thick, good reservoir quality, Lower Cretaceous, shelfal sandstones that were derived from Paleozoic quartzite formations on the Falkland Islands (Figure 4).

The Darwin gas condensate field was discovered by Borders and Southern in the South Falkland Basin in 2012 (Figure 3). The exploration play in this basin is in Lower Cretaceous shallow-marine reservoir sandstones with source rocks consisting of Late Jurassic to Early Cretaceous anoxic marine shales, trapped in well-defined tilted fault blocks (Farrer, et al 2015).
Figure 3: Well locations and license blocks in the North Falkland Basin, Falkland Plateau Basin, and the South Falkland Basin as of May 2016. The study area is outlined. (Modified from Falkland Islands Department of Mineral Resources, 2016).
Figure 4: Geologic map of the Falkland Islands. Note that much of the land mass, which is the source area for sediment supplied to the Falkland Plateau Basin consists of sandstone and quartzite, which is promising for reservoir quality.
The North Falkland Basin has been the primary focus of recent successful exploration efforts by Falklands Oil and Gas, Noble Energy, and Rockhopper Exploration. The 2010 discovery of the Sea Lion field in North Falkland Basin was the largest commercial discovery in the region (Figure 3). The play consists of syn-rift Neocomian lacustrine sandstones that drape and onlap rotated fault blocks. The source rocks are lacustrine shales (MacAulay, 2015).
DATA SET

The seismic reflection data set analyzed in this study is a post-stack time migrated 3-dimensional volume. The full-stack time data cover 6000 km² and extend to 12 seconds two-way-time, which is approximately 14,000 meters or 45,000 feet deep. The data were acquired in 2012, and generously provided by Noble Energy Corporation.

The seismic reflection data had been previously processed for Noble Energy by Petroleum Geo-Services. The data were further conditioned by this author using CGG InsightEarth software. First, acquisition footprint removal was performed to eliminate vertical striping in the data that is a result of the original data collection and processing. Second, a statistical filter was applied to remove less coherent noise and static from the volume. These processes were iterative and improved the signal-to-noise ratio, resulting in a volume with less noise that can be more confidently interpreted (Figure 5).

Limited well data were available for this study. The ages of some key surfaces, based on biostratigraphic interpretation from the Humpback well, were provided by Noble. Note that the ages of stratigraphic surfaces referenced in this thesis are approximate. Other data from this well are not publically available and were not accessible for this work. Wells 330 and 511 from the DSDP Legs 36 and 71, respectively, were drilled on the Maurice Ewing Bank, and provided some insight into regional geology and presence of potential source rock.
Figure 5: Time Slice at 1260 ms before and after footprint removal and statistical filtering. Vertical striping from data acquisition has been almost entirely removed in the conditioned volume. Note that these slices are rotated from north such dip lines and acquisition are horizontal.
To understand the tectonic setting of the study area, the evolution of the Falkland Plateau within the greater South Atlantic is reviewed here in some detail. The regional tectonics had distinct effects on the stratigraphic evolution of the basin in terms of basin formation and subsidence history, igneous intrusions, and source-to-sink relationships.

Before the break-up of Gondwana, the Falkland Plateau was in a rotated position east of southern Africa and form the ‘missing’ southeast corner of the Karoo Basin (Adie, 1952). During the Late Jurassic, the Falkland Plateau detached from southern Africa. As the Falkland Plateau was translated westward along the Agulhas Fracture Zone, the Falkland Platform separated from the Maurice Ewing Bank and rotated clockwise (Figure 6). The Falkland Plateau Basin has been previously interpreted as a failed rift between the Falkland Platform and the Maurice Ewing Bank (Figure 6).

Different models for the timing of the extension that created the Falkland Plateau Basin have been proposed. Lorenzo & Mutter (1988) estimated that extension occurred within the Falkland Plateau Basin during the Middle Jurassic to Early Cretaceous, whereas Marshall (1994) identified the main extensional phase to be during the Early Jurassic. Thomson (1998) places the extension during the Valanginian. Richards et al. (1996) noted that the large extensional faults on the Falkland Plateau appear to terminate upwards at about top Jurassic level, suggesting that rifting was over by that time.

The data set used in this study, however, does not show clear evidence of rifting. The lack of major observable extensional faults in this study area raises the question: by what mechanism did the Fitzroy sub-basin subside enough to accommodate 10-15 km of sedimentary
Figure 6: (A) Pre-drift reconstruction of the Falkland Plateau (FP) and the Maurice Ewing Bank (M) and the Malvinas Fracture Zone (AFZ). (B) Proposed model for the timing of the rotation of the Falklands microplate and formation of the Falkland Plateau Basin (FPB). (C) The final positions of all elements of the Falkland Plateau before the opening of the South Atlantic. (Thomson 1998)

Figure 7: Reconstruction of the Falkland Platform and the Maurice Ewing Bank in their Lower Jurassic position and orientation with respect to Africa. Note that the Falkland Platform is in a rotated position from its modern orientation. The future location of the Falkland Plateau Basin is shown (FPB). OB = Outeniqua Basin, NFB = North Falkland Basin, NE/NV = Natal Embayment/Valley, MR = Mozambique Ridge, NE/NV = Natal Embayment/Valley, K = Karoo.

(Thomson 1998)
Figure 8: Paleogeographic reconstruction of the Late Jurassic to Early Cretaceous of the southern South Atlantic region. Note that the Falkland Plateau Basin forms part of the downstream depocenter of the Outeniqua Basin. (Figure from Richardson, 2017)
fill? Subsidence of the sub-basin, particularly during the Cretaceous, may be attributable to thermal sag during the “drift” phase of Gondwana break-up. This is a topic that requires further research, and is outside the scope of this thesis.

The provenance for the Cretaceous strata in the Fitzroy sub-basin is controlled by the complex tectonic evolution of the Falkland Plateau. During the Late Jurassic and possibly earliest Cretaceous, the Falkland Plateau Basin formed the distal extension of the Pletmos and Bredasdorp basins, collectively named the Outeniqua basin (Figure 8) (Ludwig, 1983, Macdonald et al., 2003, Richardson, 2017). The Falkland Plateau is separated from this original source area (Outeniqua Basin) by ~6000 km in the modern day (Figure 8) (Richardson, 2017). As the Falkland Plateau moved westward past southern Africa during the Early Cretaceous, the source area for the sediment in the Falkland Plateau Basin (Fitzroy and Volunteer sub-basins) switches to the Falkland Platform (Figure 6).

In addition, the Falkland Platform has undergone a rotation of ~120 degrees from its Paleozoic position in Gondwana on the eastern margin of modern-day South Africa (Figure 6). Timing of this rotation is described as either Late Jurassic (Marshall 1994; Storey et al, 1999) or Early Cretaceous (Thomson 1998). If this rotation was on-going during the Cretaceous, then the strata in the Fitzroy sub-basin may have had a constantly changing source area from different parts of the Falkland Platform.

Sedimentary fill in the Fitzroy sub-basin spans Jurassic to Eocene time (Fraticelli, 2016). The sediments in the shelf-to-deepwater systems in the Fitzroy sub-basin were likely derived from the Falkland Platform to the west, where Ordovician-Permian Lafonia & West Falklands Group sediments were eroded and transported into the basin (Figure 4). Based on the lithologies
present in this sedimentary hinterland, strata eroded from this landmass may be rich in quartzitic sand (Richards et al, 2006). Geologic reconstructions show that Paleozoic rocks of the Falkland Platform and of South Africa are similar; therefore, the lithology of sedimentary fill in the Falkland Plateau Basin is expected to be similar to that of South African basins. (Figure 7).

The presence of Cretaceous dikes on the Falkland Islands is important to understanding the early sedimentary history of the Falkland Plateau Basin in terms of the evolution of some areas and the timing of intrusion in the Cretaceous section in the subsurface. Onshore dikes in East Falkland Island have been dated using Ar-Ar isotope analysis (Figure 9). Their ages range between 135 Ma (Valanginian-Hauterivian) to 121 Ma (Aptian). This magmatism is linked to regional Berriasian-Hauterivian uplift associated with initial opening of the South Atlantic Ocean. This thermally-driven uplift of the Falkland Platform region played a crucial role in elevating potential sediment source areas and providing the large volumes of sand that were shed intermittently into the surrounding basins from the Valanginian to the Aptian or Albian (Richards, 2013).

In the southern part of the study area, volcanic strata cut the Lower Cretaceous section in the subsurface (Figure 9). The Valanginian – Aptian dikes onshore were likely contemporaneous with the intrusion of dikes and sills, and the extrusion of lavas in the Falkland Plateau Basin.
Figure 9: Map of the Falkland Islands showing the distribution and main trends of dyke swarms. The relevant data are on East Falkland from Richards et al., 2013 (Mussett & Taylor, 1994, Stone et al., 2008, Richards et al., 2013).
METHODS

The seismic volume was mapped using IHS Kingdom Suite and CGG InsightEarth interpretation software packages. Significant stratigraphic surfaces were picked as horizons and correlated throughout the 6000 km$^2$ volume. These horizons were then interpreted in a sequence stratigraphic framework and identified as sequence boundaries (unconformities) or flooding surfaces, according to stratal terminations along those surfaces.

Time-structure and isochron (time-thickness) maps were generated from interpreted surfaces to evaluate structural trends and sub-regional variations in stratigraphic thickness of each interval. The stacking patterns and thicknesses of and within each megasequence has significant impact on the potential for and distribution of hydrocarbon-bearing strata.

Seismic facies maps were generated for each megasequence. Seismic facies are "mappable, three dimensional seismic units composed of groups of reflections whose parameters differ from those of adjacent facies units" (Mitchum, 1977). These maps show the spatial distribution of seismic reflections based on changes in configuration, continuity, and amplitude within the megasequence.

The stratigraphic intervals between interpreted surfaces were identified as highstand, lowstand, and transgressive systems tracts based on Vail (1987). Shelf-margin and shelf-edge deposits are correlated to their coeval slope and basin-floor deposits to better understand the patterns of sediment distribution within the depositional profile.
SEQUENCE STRATIGRAPHY

Overview of Megasequences

The sequence stratigraphy of Cretaceous rocks in the Fitzroy sub-basin consists of a series of progradational margins comprising topset, foreset, and bottomset geometries (Figure 10). These units dip southeast toward the basin in a linked shelf-to-deepwater setting. The Cretaceous strata are underlain by dominantly parallel reflections, indicative of a uniformly subsiding basin. The stratigraphy has some similarities to a typical passive margin fill with progradational shelf sequences separated by flooding surfaces and basinal, stacked deepwater deposits.

Five megasequences were defined in the Cretaceous (Figure 10). Each megasequence contains two or more depositional sequences. In general, within the thickest portion of each megasequence, multiple sequences can be identified. This location of the isothick changes for each megasequence as the depocenters within the basin shift through time. These higher-frequency, internal sequences typically cannot be easily correlated across the study area due to decreases in megasequence thickness, lack of seismic resolution, and/or extensive faulting.

Ages of key surfaces were provided by Noble Energy, Inc., and are derived from biostratigraphic data from the Humpback well (Figure 11). The well just penetrated the upper sequence boundary of Megasequence 2; therefore, ages below that surface are speculative. The most notable unconformity identified by the biostratigraphy is at the Valanginian-Aptian and lies near the base of Megasequence 3. There were no Hauterivian or Barremian strata encountered, which suggests a gap of ~8 million years. There are multiple stacked unconformities and merged
surfaces at the top of Megasequence 2. The Cenomanian-Santonian section also contains multiple unconformities including between the Albian-Cenomanian, the Cenomanian-Turonian and the Turonian-Santonian boundaries; no Coniacian strata remain (Figure 11).

The base of Megasequence 1 is estimated to be the base of the Cretaceous, and the top of Megasequence 1 is estimated to be top Berriasian. Based on the biostratigraphic data, the ages of the remaining sequence boundaries are as follows: top Megasequence 2 is upper Valanginian, the backstep in Megasequence 3 is top Aptian, the top of Megasequence 3 is mid-Albian, the top of Megasequence 4 is top Santonian, and the top of Megasequence 5 is mid-Maastrichtian (Figure 11).

Megasequence 1 (Berriasian?) and Megasequence 2 (Valanginian) are stacked sub-vertically (Figure 10). There is a significant back-step in the upper part of Megasequence 3 (uppermost Valanginian-Albian) at the end of the Aptian (Figure 10). Megasequence 4 (Albian-Santonian) progrades basinward from the underlying shelf edge, and Megasequence 5 (Santonian-Maastrichtian) is entirely composed of onlapping sediments (Figure 10). The overall stratal pattern is one of backstepping during the Early Cretaceous (Megasequences 1-3), as expected from the global eustatic onlap curve during this period, combined with basin subsidence. The Upper Cretaceous strata (Megasequences 4 and 5) appear to record a tectonic shift that significantly changed the style and direction of basin fill.

The five megasequences are reviewed in detail, including their structure, isochron, seismic facies, and systems tracts. The linkage between shallow and deep marine settings is discussed with the ultimate goal of documenting the variabilities both within and between megasequences.
Figure 10: Regional dip line through the Fitzroy sub-basin with five interpreted Cretaceous sequences and intrusive volcanics annotated.
Figure 11: Biostratigraphic ages of Megasequence boundaries from the Humpback Exploration well, provided by Noble Energy (Carmen Fraticelli, 2018, personal communication).
Interpretation Challenges

Both geologic features and seismic processing make seismic the data challenging to interpret in some areas. Three challenges are present: (1) extensive small-scale faulting, (2) gas chimneys and associated data deterioration, and (3) igneous intrusions obscuring strata.

Most megasequences have been deformed by faulting. In Megasequences 4 and 5, many normal faults with minor extension cut the strata (Figure 12). In horizon view, polygonal fault patterns are present. The faulting is likely caused by vertical expulsion of water in sediments, a common process in many continental margins. In Megasequences 1-3, steeply dipping normal faults offset reflections, particularly in the topset strata. In the topset reflections, the faults typically appear as sharp discontinuities offsetting subparallel reflections (Figure 13). At the paleo-shelf edge and slope clinoforms, the dip of the faults is often parallel to the orientation of prograding reflections, making precise interpretation of horizons difficult. As a consequence of both types of faulting, detailed attribute maps that illustrate the stratigraphy are only possible to generate in parts of the data set. Instead, qualitative seismic facies maps were generated that show the general trends of facies.

A second interpretation problem is present in shallow strata, mostly Upper Cretaceous and Cenozoic. There are local clusters of anomalously high-amplitude reflections that are interpreted as shallow gas accumulations (Figure 14). In some places, apparent gas chimneys that underlie these anomalies appear to source these accumulations. Therefore, differentiating between data deterioration below the anomalies and a gas feeder is difficult in some areas. In other areas, the seismic data below these shallow gas accumulations exhibits an abrupt decrease in reflectivity making correlation of horizons through these areas approximate. These areas
exhibit low amplitude, chaotic seismic facies, which in some cases, are a consequence of data “wipe outs” rather than the actual character of the internal stratigraphy.

The third interpretation challenge is caused by the presence of igneous intrusions in the subsurface (Figure 14). The dikes and sills cross-cut Lower Cretaceous strata, and are thought to be contemporaneous with dikes observed onshore. The intrusions are of particular consequence in the southern, downdip region of the study area, where Megasequences 1 and 2 are impossible to fully interpret. The interference of these intrusions both obscures strata completely and uplifts basinal strata. This relationship is particularly evident in Megasequence 2. The impact of the heat introduced by these intrusions will be discussed below in terms of the petroleum system implications.
Figure 12: (A) Map of amplitudes on a Megasequence 4 surface showing the regional polygonal faulting pattern. (B) Map of a smaller region of the surface showing polygonal fault pattern. (C) Uninterpreted vertical profile through polygonal faults in Megasequence 4. (D) Interpreted vertical profile with faults annotated.
Figure 13: (A) Uninterpreted (B) Interpreted profile through topsets in Megasequences 1 and 2. This is one of two common types of faulting that presents an interpretation challenge.
Megasequences 1 and 2.

Figure 14: (A) Regional uninterpreted seismic profile in the center of the dataset. (B) The same profile with two interpretation challenges annotated. Shallow gas accumulations and variable degrees of associated data deterioration most commonly affect Megasequences 3-5. Intrusive volcanics are high amplitude, cross-cutting reflections that mostly affect the interpretation of Megasequences 1 and 2. Intrusive volcanics are high amplitude, cross-cutting reflections that mostly affect the interpretation of Megasequences 3-5. Shallow gas accumulations and variable degrees of associated data deterioration most commonly affect Megasequences 3-5.
Megasequence 1: Berriasian (?)

Key Surfaces

Megasequence 1 is composed of two sequences: 1a and 1b. The lower sequence boundary is defined by the first identifiable clinoform that overlies and downlaps onto the underlying parallel reflections. (Figures 10, 15, 16, 17). The sequence boundary itself is erosional in the slope and basin-floor across much of the study area. Overlying the sequence boundary, a distinct external bank form develops associated with the southeastern progradation. The upper sequence boundary is identified by onlap of the overlying megasequence onto the final clinoform (Figures 15, 16, 17). Little to no clear erosional truncation is seen along the upper boundary. Sequences 1a and 1b are separated by a sequence boundary that can be imaged in most places in the study area (Figures 15, 16). However, this sequence boundary has been deformed or eroded and cannot be reliably correlated through the entire data set (Figure 17). Hence, the two sequences (1a and 1b) are treated as one package here due to their genetic similarity and the lack of resolution of the boundary between them.

In the depocenter, where Megasequence 1 is thickest, an additional sequence may be resolved within Sequence 1b (Figure 15). However, laterally, the decrease in seismic resolution due a lack of stratal thickness makes this sequence difficult to define. Consequently, the naming approach does not differentiate it; instead, it is included in Sequence 1b.

Time Structure Maps

The basal sequence boundary of Megasequence 1 has a largely homoclinal dip to the southeast (Figure 18). The surface marks the top of a series of parallel reflections in the underlying Jurassic sedimentary fill (Figure 15). The upper sequence boundary of Sequence 1b
Figure 15: (a) Uninterpreted (B) Interpreted profile showing Megasequence 1 is subdivided into 1a and 1b. This profile is an example of where the merged SB/MFS separating 1a and 1b is clearly imaged. Onlap, downlap, and erosional truncations are noted with arrows. Systems tracts are labeled where recognizable. A third sequence at the base of 1a is a possible alternate interpretation to the systems tract. SB/MFS=merged sequence boundary and maximum flooding surface, HST=highstand systems tract, TST=transgressive systems tract, LST=lowstand systems tract.
and volcanic intrusions. Note that the lowstand of 1b is uplifted by the intrusions.

Figure 16: Dip profile through the shelf edge in the southwestern half of the dataset. (A) Uninterpreted (B) Interpreted to show the impact of volcanic intrusions on the interpretation of Megasequence 1. Sequences 1a and 1b are annotated with sequence boundaries, the merged sequence boundary/maximum flooding surface that separates 1a and 1b, seismic facies, systems tracts, volcanic intrusions, volcanic dikes, etc. Note that the lowstand of 1b is uplifted by the intrusions.
By chaotic facies at the shelf edge.

Hooing surfaces, systems tracks, and seismic facies. The sequence boundary separating Sequence 1a from 1b is masked.

**Figure 17**: (A) Uninterpreted (B) Interpreted profile showing Megasequence 1 with sequence boundaries, maximum flooding surfaces (MFS), and sub-parallel offset chaotic clinoforms.

1a
1b
HST
LST
MFS/SB

(A) (B)

Berriasian?
Figure 18: Time structure map (twt) of the base Megasequence 1 sequence boundary. Contour interval is 500 ms. The sequence boundary has homoclinal dip to the southeast.
Figure 19: Time structure map (twt) of the top Megasequence 1 sequence boundary. Contour interval is 500 ms. The surface dips most steeply on the slope between 4.5 and 5.5 sec twt. Slight offsets of the sequence boundary are present creating a rugose pattern reflected in some of the contours.
(Hauterivian) has a slight increase in gradient in the area that corresponds to the foreset of the clinoform (Figure 19).

The southern portion of the two time-structure maps is uninterpreted due to deformation caused by the pervasive igneous dikes and sills. To the south, these intrusions cut entirely across Megasequence 1 (Figure 16). In some areas, they only penetrate Sequence 1a, and uplift the basin-floor portion of Sequence 1b in the process by ~200 ms (Figure 16).

Isochron Map

The isochron map shows two-way time values that vary from 0.25 to 1.5 seconds. Most of the sequence is between 0.75 to 1.2 seconds twt. Two isothicks and one isothin are present. The greatest time-thickness is in the north, and trends northeast and has values between 1.20 to 1.50 sec twt (A on Figure 20). This thick is associated with the clinoforms in the shallower sequence 1b, such that the final shelf edge is aligned with the basinward edge of the thick (Figure 20).

An apparent time thick is present in the east (B on Figure 20). Values vary from 1.2-1.4 seconds. A seismic profile through the area illustrates the presence of local dikes and sills (Figure 21). The apparent thick is an artifact of these intrusions, and where the base of Sequence 1a is picked. This area may be an isothick, but it is difficult to determine without use of depth migrated seismic data.

Megasequence 1 thins on the shelf from an average of 1.0 sec twt to the northeast to 0.5 sec twt to the southwest (Figure 22). Where the sequence is thickest to the northeast, distinguishing between 1a and 1b is not possible due to the chaotic seismic facies along the shelf
Figure 20: Isochron map (twt thickness) of Megasequence 1. Isochron thick (A, B) and thins (C) are shown. Megasequence 1 is thickest at the shelf edge (A) in the northeastern half of the seismic volume. The position the final shelf edges of sequences 1a and 1b are shown. Intrusive volcanics mask the sequences to the south.
Figure 21: Arbitrary seismic profile through isochron thicks on the basin floor. (A) Uninterpreted (B) Interpreted showing the upper and lower sequence boundaries of Megasequence 1 and the merged sequence boundary/maximum flooding surface that separates 1a and 1b. Notice the pervasive volcanic intrusions that cross cut and deform the megasequence.
Figure 22: Strike line through Megasequence 1 at shelf edge. (A) Uninterpreted (B) Interpreted profile showing the upper and lower sequence boundaries of Megasequence 1. The merged sequence boundary/maximum sequence boundary is masked locally by chaotic, low amplitude facies. The megasequence thins from 1500 ms in the northeast to 1000 ms in the southwest.
(Figures 17, 22). Therefore, the increased thickness cannot be attributed to one sequence or the other.

**Seismic Facies**

Five seismic and geologic facies are present in this sequence (Figure 23). All facies trend to the northeast, i.e. parallel to the paleo shelf edge (Figure 23). To the west, Facies 1 is a series of parallel to sub-parallel, discontinuous reflections with variable amplitude. These have been offset by a series of high angle normal faults (Figure 12). Facies 2, which is southwest of Facies 1 along the paleo-shelf edge, are chaotic reflections with low amplitude (Figure 17). The chaotic reflections are likely due to post-depositional slumps and slides, and the low amplitude may be attributed to deeper gas chimneys. Facies 3 consists of moderate amplitude, semi-continuous, oblique clinoforms that are present in the lower and upper sequences that largely stack on one another. In Sequence 1a, the clinoforms are eroded by the overlying sequence boundary (Figure 16). Facies 4 are a series of divergent, high amplitude reflections that thin and onlap the slope to the northwest (Figures 15, 16, 17). These reflections change basinward (southeast) to Facies 5, which consists of subparallel to chaotic, discontinuous, variable amplitude reflections between igneous intrusions.

**Geologic Interpretation**

The systems tracts and general sedimentary environments for Sequence 1b, and for portions of Sequence 1a, can be defined based on the geometry of reflections and the presence of onlap and downlap surfaces (Figures 15, 16, 17). In Sequence 1b, seismic facies 4 and 5 onlap onto the sequence boundary and are interpreted as submarine fans. The sequence boundary can be traced updip to a topset reflection; clinforms downlap onto this surface, indicating the
Figure 23: Seismic facies map of Megasequence 1. Locations of Figures 15, 16, 17, 21, and 22 are shown.
sequence boundary and maximum flooding surface have merged here (within the resolution of the seismic). The prograding clinoforms, therefore, are a portion of the early highstand systems tract and downlap onto lowstand systems tract to the southeast (basinward). The transgressive systems tract is included within one reflection (Figure 15).

The interpretation of the systems tracts in Sequence 1a are more speculative than for 1b due to the lower seismic resolution. To the southwest, a basal onlapping package corresponds to the lowstand systems tract (Figures 16). To the northeast, thick topset reflections aggrade (Figure 17). In some places, a possible downlap surface is present, indicative of a maximum flooding surface and overlying highstand systems tract. Sequence 1a is eroded along the slope by the overlying Sequence 1b. Reconstruction of the volume of upper slope that was eroded is difficult. The strata that were eroded would be a part of the highstand systems tract (Figure 17).

The final shelf edges of Sequences 1a and 1b are stacked sub-vertically, but change position slightly relative to one another across the study area. To the southwest, the final 1a shelf edge is basinward of the final 1b shelf edge. In the center of the data set, they cross each other and the final 1b shelf edge is more basinward. To the northeast, the two shelf edges switch back to 1a being basinward of 1b (Figure 20). The basinward limit of the maximum thickness at the shelf edge corresponds to the final Sequence 1b shelf-slope break (A on Figure 20).

Note that the aggradational form of this megasequence can be created by either a carbonate or a siliciclastic margin. However, due to the regional setting and rock types in the source area, this sequence is interpreted to be composed of siliciclastic strata (Figure 4). The basin must have subsided during the Berriasian as fast as sediment was supplied to the basin to generate the accommodation necessary for the shelf to aggrade.
The entirety of Megasequence 1 represents a balance between basin subsidence and sediment supply from the Falkland Platform as indicated by its overall aggradational stratal architecture. The generally similar seismic character throughout Megasequence 1, and the sub-parallel, stacked positions of their shelf edges suggests that the depositional system did not change dramatically between sequences 1a and 1b. Instead, the sequence boundary that separates them likely represents a pulse of increased sediment supply or a short-lived fall in relative sea level punctuating an otherwise balanced system.

The lateral variability within Megasequence 1 is primarily controlled by shelf edge and slope instability. Where instability is greatest, internal deformation including slump/slides and associated basin-floor, mass-transport deposits dominate the depositional system (Figure 24 A). Where the shelf edge is more stable, continuous clinoforms extend across the shelf and into deepwater without significant internal deformation (Figure 24 D). Gas chimneys are visible below Megasequence 1 (Figure 24 B); therefore, trapped gas may account for some, but not all, of the observed decrease in seismic reflectivity in chaotic areas (Figure 24 A).

The depocenter for Megasequence 1 was present in the northeast half of the study area. In this location, the megasequence is thickest and has the highest degree of internal deformation. The strata near the final shelf edges of sequences 1a and 1b are characterized by chaotic reflections that are interpreted as soft sediment deformation associated with late stage highstand shelf instability (Figure 24 A). The slope and basin-floor deposits here are similarly chaotic, and are interpreted to be debris flow and mass-failure deposits (Figure 24 A). The combination of increased thickness and increased instability is evidence of higher rates of sedimentation in the
depocenter of Megasequence 1. Additional factors that may contribute to this instability are the presence of muddy and overpressured sediments.

In the central part of the study area, Megasequence 1 is less internally deformed than to the northeast. The shelf deposits in Sequence 1a are mostly parallel topsets and few preserved foresets. These clinoforms are typically truncated by the overlying sequence boundary. The basin-floor deposits associated with this dominantly aggradational shelf setting are relatively thin and comprise interbedded chaotic and continuous strata. These slope and basin-floor strata are interpreted as interbedded turbidites and debris flows (Figure 24 B). In Sequence 1b, prograding and aggrading clinoforms are identifiable on the shelf. The basinward deposits in 1b can be subdivided into an onlapping wedge and overlying downlapping units (Figure 24 C). The lowstand wedge at the base of Sequence 1b does not appear to be coeval with any updip strata, indicating that there was bypass on the shelf and slope during the early lowstand. The wedge has high amplitude, continuous reflections and varies in thickness across the study area. The lowstand deposits that downlap onto this wedge are coeval with updip the shelf edge delta clinoforms. This package of basin-floor strata thins basinward, tends to have internal wavy reflections, and is interpreted as slope-front turbidites. Slope failure that is present in the center of the study area, is manifested as large slumps that maintain some internal reflection continuity (Figure 24 C).

To the southwest, away from the main depocenter, Megasequence 1 has continuous internal reflections that can be correlated from the shelf to basin floor. The megasequence is thinner in this location and has negligible evidence of internal deformation or erosion. The pattern of thick highstand and thin lowstand in Sequence 1a, as described in the central and
northeastern locations, is also present to the southwest (Figure 24 D). The shelf edge in Sequence 1b is particularly interesting here. Due to the lack of shelf edge failure, the geometry of the prograding shelf edge delta is preserved (Figure 24 D). Clinoforms change from mostly aggradation to mostly progradation as they approach the shelf edge. The trajectory of the shelf edge is falling basinward, indicating that these strata were deposited during the late highstand during a relative fall in sea level. Thickened foresets here indicate deposition primarily at the upper slope; the coveal basin-floor deposits are thin (Figure 24 D).

**Shallow-Deepwater Linkage**

The overall depositional patterns identified in Megasequence 1 are: (1) outer shelf and slope instability are most prevalent where rates of sedimentation are high; (2) failures of shelf and slope are directly correlated to chaotic mass-transport deposits on the basin floor; (3) where shelf deposits are thick and aggradational, associated basinward deposits are thin; and (4) the largest volume of sediment was deposited on the basin floor during shelf and slope bypass.
Figure 24: Seismic profiles through Megasequence 1 showing the variation across the study area and the relationship between shallow and deepwater strata.
Megasequence 2: Valanginian

Key Surfaces

The basal sequence boundary of Megasequence 2 is defined by onlapping reflections of the lowstand systems tract (Figure 25). The upper sequence boundary is similarly defined by erosional truncations at the top of the Megasequence 2 highstand systems tract and onlapping reflection truncation of the Megasequence 3 lowstand systems tract (Figure 26).

Megasequence 2 consists of at least two and possibly more sequences. To the northeast, where the megasequence is thicker, at least two sequences can be identified (Figure 27). In the center of the study area, smaller, possible higher frequency sequences may be present (Figure 26). Similar to Megasequence 1, correlation of the sequences within Megasequence 2 across the study area is difficult.

Time Structure

There is an embayment in the time structure contours of the upper Megasequence 2 boundary in the center of the data (Figure 28). This indicates erosion into the upper portion of Megasequence 2 (Figure 30), and affects the thickness of Megasequence 3. The gradient of the upper sequence boundary is more steeply dipping in the center of the data set than at the either the northeast or southwest edges (Figure 28).

Isochron

Megasequence 2 varies in time thickness from 0.25 to 1.50 seconds twt (Figure 29). Three distinct areas of thickness are present. To the west, a northeast trending area of 0.25-0.60 sec twt is the thinnest part of the megasequence. The upper sequence boundary erodes to within
Figure 25: (A) Uninterpreted (B) Interpreted seismic profile to the southwest displaying Megasequence 2.
Figure 26: (A) Uninterpreted (B) Interpreted profile through the center of Megasequence 2 where the upper sequence boundary erodes into the highstand systems tract.
Identified in the basinward strata. Poor seismic resolution and erosion makes correlation difficult in the looser strata. Thickens to the northeast where multiple sequences can be interpreted. There are two sequence boundaries that are Berriasian?

Figure 27: (A) Uninterpreted (B) Interpreted seismic profile in the northeast part of the study area. Megasequence 2.
Figure 28: Time structure map of the top Megasequence 2 sequence boundary. Contour interval is 500 ms. The surface dips to the southwest and has a depression in the center of the dataset. This is surface erodes the top of Megasequence 2 and accommodates the thickest lowstand of portion of Megasequence 3.
Figure 29: Isochron map of Megasequence 2. Contour interval is 25 ms. The thickest area is at the northwest edge of the study area. The thinnest area is in the west.
Figure 30: (A) Uninterpreted (B) Interpreted profile through the center of Megasequence 2 where the Upper Valanginian sequence boundary erodes into the highstand systems tract.
250 ms of the lower sequence boundary, leaving Megasequence 2 especially thin in that area (Figures 29, 30). The thickest area is to the northeast, ranging from 1.10-1.50 sec twt. This corresponds to the area where multiple sequences are identifiable within the megasequence (Figure 27). The remaining area is between 0.60 and 1.1 sec twt.

**Seismic Facies**

Five seismic facies are present in Megasequence 2 (Figure 31). Facies 1 are parallel, discontinuous, low amplitude reflections on the shelf (Figures 25-27). There is significant erosion within and at the top of Megasequence 2 on the shelf, particularly to the northeast. Facies 2 are semi-continuous, moderate amplitude clinoform reflections that are part of highstand or prograding complex systems tracts (Figure 26). Facies 3 are onlapping continuous, moderate amplitude reflections (Figures 25, 26, 27). The lowstand systems tracts in the southeastern half of the study area is thick and has continuous internal seismic facies (Figures 25, 26, 27, 30). Facies 4 are chaotic to semi-continuous, high amplitude reflections (Figure 27). The megasequence thickens to the northeast, where it can be subdivided into multiple sequences. Therefore, the seismic facies are stacked vertically in this area. Facies 5 are chaotic, variable amplitude reflections punctuated by continuous, high amplitude reflections. Within this facies, one reflection with greater continuity is interpreted to be transgressive systems tracts and maximum flooding surfaces between distal highstand and lowstand systems tracts (Figures 27, 30).

**Geologic Interpretation**

All systems tracts are preserved in Megasequence 2 in spite of the small time thickness to the southeast. The thick lowstand systems tract (slope and basin-floor fans) is characterized
Figure 31: Seismic facies map of Megasequence 2. Locations of Figures 25, 26, 27, and 30 are shown.
by onlap against the basal sequence boundary. Then, the prograding complex developed across the lowstand wedge. The transgressive systems tract is thin, and represents a backstep of 8-15 km as evidenced by the position of the prograding clinoforms in the highstand systems tract. Where multiple sequences are interpreted to be present to the northeast, a similar pattern is observed, albeit with a higher degree of internal erosion. All systems tracts are identifiable, indicating that at least one full relative cycle of sea level took place during deposition.

The megasequence is thin to the southwest, which is likely indicative of low accommodation during deposition and/or the location of the depocenter (Figure 25). To the northeast, the increase in thickness may be due to a local sediment source and possibly increased subsidence in this area (Figure 27). This variation in thickness is compensational with overlying sequence 3, such that the basinward thickness of Sequence 2 and Sequence 3 are controlled primarily by the structure of the Barremian sequence boundary between them.

The extensive erosion along the upper sequence boundary is a bit atypical for third-order sequences because, normally, they have less erosion. This sequence boundary may be second-order, which means, (1) the sequences within Megasequence 2 are third- or fourth-order, and (2) this impacts the prospectivity of the base-of-slope strata in Megasequence 3 in terms of the volume of sand delivered. Brown et al. (1996) observed that, in the Bredasdorp Basin in South Africa, volumetrically more sand overlies the second-order than the third-order sequence boundaries.

The influence of the igneous intrusions in Megasequence 2 are present in the center and to the southwest part of the study area. The igneous intrusions uplift areas of the basin-floor sediments by up to 200 ms (Figures 26, 27). Additionally, the northern extent of the intrusion is
a prominent dike that cuts up through the lowstand systems tract strata. Directly west and adjacent to the dike, a syncline appears to have formed by the upward inflation of the basin-floor strata (Figure 30). The thickness of Megasequence 2 is consistent throughout the syncline, indicating that the deformation was post-depositional. This syncline, however, appears to create the accommodation for thick lowstand fans in the lowest portion of Megasequence 3, indicating that the folding took place between the deposition of Megasequences 2 and 3 (Figure 30).

The stratal architecture within Megasequence 2 varies significantly across the study due to the increased thickness and erosion in the depocenter. The presence of incised valleys on the shelf correlates to thicker deepwater strata and vice versa. The deepwater strata are composed of alternating lowstand and highstand systems tracts on the basin floor.

There are 3-4 identifiable depositional sequences in the deepwater strata depending on the location relative to the depocenter. The lower two sequences have lower amplitude, more continuous reflections. The upper two sequences have higher amplitude and more discontinuous reflections (Figure 32 A). The upper two sequences on the basin floor thicken dramatically downdip of the shelfal depocenter. In contrast, the lower two sequences on the basin floor vary only slightly across the study area in thickness and seismic facies (Figure 32 A, B, C). This means that most of the variation in deepwater strata is accounted for during the latter part of Megasequence 2 deposition.

At the depocenter to the northeast, Megasequence 2 is characterized by a thick unit of incised, prograding clinoforms on the shelf edge. The coeval strata on the slope and basin floor are a thick unit of alternating high-amplitude, continuous and chaotic reflections (Figure 32 A). The chaotic seismic facies are interpreted as mass-transport complexes associated with
shelf-edge failure and turbidity currents transported down incised channels. The uppermost sequence appears to consist of mostly stacked channel-levee systems (Figure 32 A). The overlying sequence boundary is highly erosive and appears to have removed a significant portion of the shelf edge.

In the center of the study area, the lowest basin-floor unit is a thick, onlapping lowstand wedge with no coeval shelf strata (Figure 32 B). This lowstand wedge is interpreted to have been deposited during the late lowstand when there was a high rate of subsidence and bypass of the shelf. This lowstand unit is overlain by a package of higher amplitude, variable continuity reflections that are coeval to shelf strata, indicating that they were deposited during a highstand (Figure 32 B). The upper half of Megasequence 2 has prograding and aggrading clinoforms on the shelf with high-amplitude, continuous and chaotic reflections on the slope and basin floor (Figure 32 B). These strata are interpreted as a shelf edge delta that is partially eroded by the overlying sequence boundary in the northeast. Sediment supply outpaced subsidence at this time resulting in progradation of the delta across the shelf.

In the southwestern part of the study area, farthest from the depocenter, shelfal deposits are thin. The basal, onlapping, lowstand wedge that is visible across the study area dominates the lowstand package here (Figure 32 C). The topsets in the upper part of of the megasequence are faulted, making truncation by the overlying sequence boundary difficult to identify (Figure 32 C). In general, there is little erosion within the megasequence in this area. The megasequence is cut by igneous intrusions here that uplift the basin-floor strata (Figure 32 C).
Figure 32: Seismic profiles through Megasequence 2 showing variation across the study area and the relationship between shallow and deepwater strata.
Shallow-Deepwater Linkage

The overall depositional patterns identified in Megasequence 2 show a correlation between increased thickness of the lowstand units and either bypass on the shelf or increased incision in upper Megasequence 2 shelf strata. In the case of shelf sediment bypass, the lowstand deposits onlap and have internally consistent seismic facies indicating little change in the depositional system. In the case of incised valleys on the shelf, there is variability in the lowstand between chaotic and continuous units, indicating that sediment delivery to the slope and basin floor alternated between debris flows and sediment-gravity flows. Additionally, there is a correlation between relatively thin deepwater units in the center of the study area and a stable, aggradational shelf edge delta. This relationship indicates that, in the upper part of the megasequence outside the depocenter, the majority of sediment accumulated at the delta front with relatively little downslope deposition. Alternating lowstand and highstand systems tract strata in deepwater indicate the confluence of a unique set of circumstances required for large volumes of sediment to be deposited on the basin floor during a highstand. This was likely a high net-gross system with high rates of sedimentation when accommodation was low such that deltas prograde to the shelf edge and spill into deepwater, effectively overriding changes in relative sea level.
Megasequence 3: Upper Valanginian to Mid-Albian

Key Surfaces

The lower sequence boundary is defined by extensive erosional truncation of the underlying highstand reflections and the onlapping reflections onto the lower slope clinoform (Figures 30, 33). The upper sequence boundary is defined by erosional truncation of Megasequence 3 highstand reflections and has a well-defined paleo shelf edge and a strong oblique clinoform morphology (Figures 33, 34).

Within Megasequence 3, at least two major depositional sequences are present, and possibly more (Figure 33). The lower sequence comprises thick, base-of-slope deposits that onlap the lower boundary (Figures 37, 38). The upper sequence sits 20-30 km to the northwest and overlies the topset reflections of Megasequence 2 (Figure 33). Clearly, a significant merged sequence boundary and flooding surface separates the two sequences (Figure 33).

Time Structure

The upper sequence boundary (Mid-Albian) corresponds to an oblique clinoform (Figures 33, 34). The shelf and basin-floor portions of the surface have similar, shallow dips to the southeast. The slope is more steeply dipping (Figure 34). The final paleo shelf is between 1.89 and 2.5 sec twt. The basin floor is between 3.0 and 5.0 sec twt. The slope dips steeply from 2.5 to 3.0 sec twt (Figure 34).

Isochron Map

Most of Megasequence 3 varies from 500-800 msec in two discrete, northeast trending areas. Two local time-thicks, up to 100 ms twt, are present on the shelf and at the base-of-slope.
Figure 33: (A) Uninterpreted (B) Interpreted regional profile through Megasequence 3 with lower and upper sequence boundaries and the prominent merged sequence boundary and maximum flooding surface labeled. Apparent downlap surfaces within the upper depositional sequence are also annotated. Note the significant erosion and onlap associated with the lower sequence boundary.
Figure 34: Time structure map of the top Megasequence 3 sequence boundary. The margin is oriented NE-SW and there is a distinctive shelf edge at 2.5 seconds twt. The base of slope is at 3.0 seconds twt. The basin floor slopes off gradually to the SE to a maximum of 5.0 seconds twt.
**Figure 35:** Isochron map of Megasequence 3. Contour interval is 25 ms. The thickest part of the megasequence is at the base of slope in the center of the study area. The thinnest part of the megasequence is the slope where the upper sequence boundary is highly erosional. The remaining shelf and basin floor have consistent isochron values of 0.5 to 0.75 seconds TWT.
where its basal strata are thickest (Figure 35). A prominent thin, trending NE, is present along
the northwestern portion of the data set (Figure 35). Values range from 0.25-0.50 sec twt. This
thin corresponds to the area where the Mid-Albian sequence boundary erodes the upper part of
Megasequence 3 (Figure 33).

Seismic Facies

Five seismic facies are present in Megasequence 3 (Figure 36). Facies 1 are parallel,
continuous, high amplitude reflections that represent the aggradational topsets on the pre-existing
shelf of Megasequence 2 (Figure 33). Facies 2 are chaotic, low amplitude reflections to the north.
This facies consists of a series of erosional surfaces (incised valleys) that cut into one another;
multiple erosional remnants are present (Figure 44). Facies 3 are subparallel, semi-continuous,
high amplitude reflections that constitute thin slope deposits in the upper portion of
Megasequence 3 (Figure 33). These reflections may represent condensed section(s).

Facies 4 are overall mounded, continuous, high amplitude reflections at the base-of-slope
in the center of the data set. This facies corresponds with the thickest part of Megasequence 3
(Figure 35) and represents submarine fans (Figures 37, 38). Facies 4 can be subdivided into 3-6
discrete packages of strata, which are interpreted as individual fans. These fans have an
offsetting distribution in both strike and in views (Figures 37, 38). The fans are separated by
laterally continuous reflections, which are onlapped by the overlying fan. The lower package in
Facies 4 overlies an irregular erosional surface, presumably associated with sequence boundary
formation (Figure 38). This fan (Fan 1) filled in the erosional bathymetry, and then began to
aggrade (Figure 38). Fan 2 is areally more widespread, extending basinward (southeast) of the
lower package and onlaps the slope to the west (Figure 37, 38, 39). Fan 3 is areally limited and
Figure 36: Seismic facies map of Megasequence 3. The locations of Figures 33, 37, 38, and 44 are shown.
Figure 37: (A) Uninterpreted (B) Interpreted transgressive, onlapping stacking pattern of Megasequence 3 submarine fans in the center of the study area. (C) Packages labelled as Fans 1-3 where Fan 1 is deepest and most areally restricted, Fan 2 thickest and most extensive, and Fan 3 downlaps onto the upper surface of Fan 2.
Figure 38: (A) Uninterpreted (B) Interpreted strike line through the basin floor fans identified in Megasequence 3. Note that Fan 1 has the highest amplitude reflections and the compensational nature of Fan 3.
partially overlies the middle package; it onlaps farther updip onto the slope (Figure 42). Up to three more fans, that are identifiable in strike-view, have similar offset, onlapping patterns (Figure strike profile).

Facies 5 are onlapping to sub-parallel, semi-continuous, moderate to high amplitude reflections in the basinward part of the study area. This facies includes more deepwater turbidite fans capped by basinal transgressive systems tract sediments (Figure 33).

Seismic Attribute Analysis

The base-of-slope turbidite systems in Facies 4 are the most prospective reservoir targets in the study area. The fans are sufficiently thick with minimal faulting that seismic attributes can be used to generate meaningful depositional maps. Attribute analysis on fans of Facies 4 shows that they are channelized (Figures 40, 41, 42).

The fans are interpreted as channel-levee systems. Amplitude maps generated on seismic troughs show dendritic and meandering patterns of anomalously low amplitudes on the surfaces of the fans. The elongated amplitude patterns are slightly different in each fan. Fan 1 appears to have three main channel fairways (Figure 40). The easternmost grouping of amplitudes in Fan 1 appear to branch into a fan, unlike the middle and western channels. Fan 2 is more areally extensive and has a more elongated morphology. The amplitudes mapped extend lengthwise down the crest of the largest extremity of the fan (Figure 41). These anomalous amplitudes appear to originate at a common point and have a braided pattern. The anomalous amplitudes in Fan 3 are restricted to the thickest part of the fan and have a meandering pattern (Figure 42).

In addition to channel forms, Fan 2 has large slide blocks at its base (Figure 43), likely indicating the presence of a mass-transport complexes. The mass-transport complexes and
Figure 39: Isochron map of Fans 1 and 2 combined. This is the time thickness between the top of Fan 2 and the base of Megasequence 3. Note the anomalous thick in the center of the study area; this is the extent of Fan 1.
Figure 40: Amplitude map of Fan 1 with channel forms interpreted. Fan 1 is the deepest of the Megasequence 3 lowstand elements. The extent of this fan is controlled by the depression in the underlying sequence boundary.
Figure 41: Amplitude map on the surface of Fan 2 interpreted as channels. The anomalous amplitudes may indicate sand or hydrocarbon-filled channels.
Figure 42: (A) Isochron of Fan 3 between the surface of Fan 2 and the surface of Fan 3. The fan is oriented approximately north-south and stacks against the western flank of Fan 2. (B) An amplitude extraction on the surface of the thickest portion of Fan 3 interpreted as a channel.
Figure 43: (A) Uninterpreted (B) Interpreted profile showing slide blocks and thrusts in the lowstand fans in Megasequence 3.
channel-levees in the fan are the product of a rapid fall in relative sea level and high energy, high sediment load depositional events scouring the shelf and slope before settling on the basin floor as mounded fans.

**Geologic Interpretation**

The two major sequences in Megasequence 3 have different spatial distributions (lower to the southeast, upper to the northwest), and are the product of distinctly different settings. In the lower sequence, the thick, base-of-slope deposits overlie a significant erosional sequence boundary. The upper sequence overlies a major transgression, which resulted in a backstep of the shelf edge of 20-40 km. The subsequent progradation in the upper sequence did not advance as far as the shelf in the underlying Megasequence 2. On the megasequence scale, these lower and upper sequences correspond to third-order lowstand and highstand systems tracts, respectively. Both sequences and their associated boundaries are likely second-order events (Upper Valanginian-Top Aptian and Top Aptian-Mid-Albian).

The lower, basinward portion of Megasequence 3 consists almost exclusively of lowstand systems tract strata. The basin-floor strata have maximum two-way-time thicknesses of 700-1300 ms with almost no associated shelf deposits (Figure 45). This relationship of thick deepwater sediments with little to no shallow marine deposits indicates that the lower part of Megasequence 3 was deposited during a period of extended sediment bypass of the shelf and slope.

The primary variation within the basin-floor strata are overall mounded deposits that are present only in the center of the study area (Figure 45 B). The location of the mounded submarine fans corresponds to a syncline in the basal sequence boundary that appears to have formed as a response to intrusion of an underlying igneous dike. The upper surfaces of each of
the submarine fans are downlap or onlap surfaces due to their paleobathymetry (Figure 45 B). To the northeast and southwest of these fans, the basin-floor strata change to more parallel reflections that onlap and backstep (Figure 45 A, D). Unlike the underlying megasequences, there are no prograding clinoforms (i.e. prograding complex) that overlie the basin-floor deposits in this megasequence. Therefore, these strata are interpreted to have been deposited after a significant relative fall in sea level, and during a period of slowly rising relative sea level.

Within the basin-floor deposits, there are between four and six packages that can be defined and correlated (Figure 45). The basin-floor wedge tends to comprise parallel, high-amplitude, continuous, onlapping seismic reflections; however, evidence of mass-transport deposits and channel-levee systems are also present. The presence of each of these depositional systems indicates that the energy and style of sedimentation varied during the deposition of this sequence. Both of these types of deposits tend to be mud-rich; however, the lack of any coeval sediment on the shelf implies that these basin-floor strata consist of both sand and mud-rich sediments transported from updip.

Between the lower and upper sequences of Megasequence 3, there is a 20-40 km backstep of the margin. The maximum flooding surface (green on Figure 45) and transgressive systems tract associated with this major transgression are not well-resolved in the seismic data, particularly in the thin area between the final shelf edge of Megasequence 2 and the final shelf edge of Megasequence 3. However, in some locations, there is clearly downlap of the overlying strata onto a semi-continuous surface, which is interpreted to be the maximum flooding surface. To the northeast and southwest, the maximum flooding surface appears to merge with the underlying sequence boundary (Figure 45 D). The timing of this backstep is estimated to be
Aptian, which is consistent with the age of observed source rocks in DSDP wells 330 and 551, indicating that it corresponds to a regional transgression, rather than a local tectonic event in the Fitzroy sub-basin. This regional transgression is interpreted to be caused by the Aptian Ocean Anoxia Event, a global eustatic highstand.

The upper sequence within Megasequence 3 is northwest of the lower package and overlies the topsets of Megasequence 2. This upper sequence consists of highly aggradational shelf strata (topsets), both steep and gently dipping prograding clinoforms, and multiple erosional surfaces that are indicative of an incised valley complex (Figure 44, 46).

The upper portion of the megasequence consists of 4-5 depositional sequences that can be differentiated based intervening downlap and erosional surfaces in the southwestern half of the study area, where they are not obscured by incised valleys (Figure 46 D). These sequences are strongly aggradational on the shelf and comprise mostly flat-lying topsets and some shallowly dipping, prograding clinoforms. The progradation within depositional sequences is interpreted as deltas advancing basinward across the pre-existing shelf. In some cases, the deltas prograde into and fill incised valleys on the shelf. One depositional sequence, which appears to be second youngest package, progrades past the basinward edge of the underlying sequences (yellow on Figure 46 D). The clinoform foresets in this sequence extends past the underlying shelf edge and form a prograding slope front. These foresets downlap onto the maximum flooding surface at the base of the upper package.

Compound incised valleys dominate the upper sequence of Megasequence 3 in the northeastern half of the study area (Figure 46 B). These valleys are clearly formed by multiple, non-contemporaneous erosional events. In some locations, the basal erosional surface incises
into the underlying megasequence. Seaward dipping clinoforms or lateral accretion surfaces infill
the eroded valleys. The valley-fill clinoforms appear to be coeval with the slope-front
clinoforms of the second youngest depositional package mentioned above (Figure 46 A). This
suggests that the erosional surfaces are representative of a long-lived submarine canyon that was
subsequently filled by prograding deltaic and related sediments.

Interestingly, there are little coeval deepwater deposits associated with the upper
Megasequence 3 package. Generally, a thin layer (100-250 ms twt) of basin-floor strata is
present across the study area. These strata appear to be the same in most locations regardless of
the presence or absence of incised valleys. In spite of the extensive updip erosion, no significant
increase in thickness of strata is observed on the basin floor. This enigma leads to the hypothesis
that perhaps the expected basin floor sediments are preserved outside the study area.

Shallow-Deepwater Linkage

The lower sequence in Megasequence 3 consists almost exclusively of lowstand,
basin-floor strata with no coeval shelf deposits. This relationship is interpreted to be the result of
an extended period of shelf and slope bypass during superposed second and third-order
lowstands.

There are three possible interpretations for the lack of basin-floor strata in the upper
sequence: (1) the vast majority of sediment transported in the area during this period was trapped
on the shelf due to a balanced rate of sediment supply, sea level fluctuations, and basin
subsidence; (2) the overlying sequence boundary is highly erosive and these strata were removed
post-depositionally; and/or (3) the these strata were deposited more than 50 km basinward of the
final shelf edge (i.e. outside the study area). Based on the presence of erosional truncation of the
uppermost shelf-edge strata, the overlying sequence boundary is likely an erosional surface. However, it is more likely to have eroded the shelf edge and slope than the basin-floor deposits.

The shallow and deepwater strata in this upper sequence are interpreted to represent the inverse relationship of those in the lower sequence of Megasequence 3. In both cases, large volumes of sediment are being transported into the basin and deposited almost exclusively in either the basin floor or shelf setting.
Figure 44: (a) Time structure map of the base of the compound incised valley in the upper part of Megasequence 3.

(b) Strike line through incised valleys on the shelf in the upper part of Megasequence 3.
**Figure 45:** Seismic profiles through the lower part of Megasequence 3 showing variation of lowstand deposits across the study area and the lack of coeval shelf strata.
Figure 46: Seismic profiles through upper Megasequence 3 showing variation of shelf strata across the study area and the lack of coeval downdip strata.
Megasequence 4: Mid-Albian to Santonian

Key Surfaces

Megasequence 4 progrades significantly basinward of the underlying Mid-Albian shelf edge at the top of Megasequence 3. Megasequence 4 is the first Cretaceous sequence that records an overall regression; the previous three sequences are on an overall transgression. The lower sequence boundary (Mid-Albian) is defined by erosional truncation of upper part of the underlying of Megasequence 3 and prominent stratal onlap along the base of Megasequence 4 (Figure 47). The upper sequence boundary (Santonian) is defined by onlapping reflections in the overlying Megasequence and does not appear to be strongly erosional (Figure 47). No erosional truncation of the underlying highstand is observed. Both the lower and upper sequence boundaries are highly deformed by small faults. (Figures 11, 47, 48)

Time structure map

The regional dip on the lower sequence boundary is more east-southeast than the underlying sequence boundaries (Figures 18, 19, 28, 34, 49). Its structural position ranges from 1.5 sec twt on the shelf to 4.5 sec twt on the basin floor. The surface is shallowest in the west and deepest in the east. In contrast to the base of Megasequence 4, the upper sequence boundary has smoother, more gradual shelf edge and toe-of-slope transitions (Figure 47, 48, 49).

Isochron map

Megasequence 4 ranges from 0.25 to 1.5 sec twt thickness. The thickest part of the sequence corresponds to the prograding clinoforms where the shelf edge has migrated up to 40 km basinward (Figure 50). The megasequence is thickest in the southwest, with values ranging from 1.2 to 1.5 sec twt. The megasequence thins to the northeast, which is parallel to the
surfaces and seismic facies are annotated.

Figure 47: (A) Uninterpreted (B) Megasequence 4 interpreted in the southwest half of the study area. Systems tracts, internal

(A) parallel discontinuous

(B) chaotic clinoforms

(c) parallel high amplitude

Mid-Albian

Santonian

PGC?
Figure 48: (A) Uninterpreted (B) Interpreted regional profile through Megasequence 4. The interpretation of internal boundaries and systems tracts is more difficult in the NE than the SW due to the decreased thickness of the megasequence.
Figure 49: Time structure map of the top Megasequence 4 sequence boundary. The structural trend of the sequence boundary is oriented more SSW-NNE than previous shelf edges. Locations of Figures 47, 48, and 51 are shown.
Figure 50: Isochron map of Megasequence 4. Contour interval is 25 ms. The thickest part of the megasequence is a trend from southwest to northeast, parallel to the paleo shelf edge.
Figure 51: (A) Uninterpreted (B) Interpreted strike line through Megasequence 4 showing the decrease in thickness and definition of internal surfaces from southwest to northeast.
orientation of the paleo shelf edge (Figure 50, 51). This thickness appears to compensate for the change to a more eastward trending orientation of the margin. The megasequence is thin (0.50-1.0 ms twt) on the shelf (west) and basin floor (east). Where the megasequence is thick, at least one internal sequence boundary is identifiable (Figures 47, 51).

Seismic facies

The external stratigraphic form of Megasequence 4 is sigmoidal, which is a marked change from the underlying megasequences (Figures 47, 48). Three seismic facies are present, which are associated with the shelf, slope/prograding complex, and basin floor, respectively (Figure 52). Each facies is highly deformed by pervasive polygonal faulting (Figure faults). Facies 1 consists of parallel, discontinuous, moderate amplitude reflections where flat-lying topset beds (lower coastal plain to shelf strata) are offset by subvertical normal faults. Facies 2 is southeast of Facies 1, and comprises the bulk of the sequence (Figure 47, 51). Facies 2 are chaotic to discontinuous, variable amplitude sigmoidal clinforms. The strata are pervasively deformed by polygonal faulting (Figure 11). The distribution of Facies 2 is similar to that of the isochron thick (Figures 50, 52). This facies is inclusive of much of the lowstand, transgressive, and highstand systems tracts. Facies 3 is southeast of Facies 1 and 2 at the basinward (southeastern) edge of the study area. Facies 3 consists of subparallel, semi-continuous to continuous, high amplitude reflections (Figure 47, 48). The thin, basin-floor strata display the highest continuity and amplitude of reflections within this megasequence. These strata are as faulted as the surrounding area, but due to the increased thickness and amplitude of the reflections, they appear less deformed within the resolution of the seismic data.
Figure 52: Seismic facies map of Megasequence 4. There are three seismic facies, which are associated with the shelf, slope, and basin floor strata. Locations of Figures 47 and 48 are shown.
Geologic Interpretation

Megasequence 4 records the only major overall regression in the Cretaceous strata in this study area. The overall trend of the isochron is different than Megasequence 1-3 in that its isothick is located to the southwest (Figures 20, 29, 35, 50). This change in location of isothick is likely caused by a shift in the location of the marginal marine depocenter from the older megasequences. In addition, the final Santonian shelf edge is 10-40 km basinward of the shelf edge at the base of the sequence (Figures 47, 48). The greatest amount of progradation is to the southwest and decreases to the northwest. This change in the orientation of the margin during the deposition of Megasequence 4 is likely due to the switch in the shallow-marine depocenter. The shelf edge of the upper sequence boundary trends more SSW-NNE than all the previous shelf edges, which trend SW-NE.

The greatest fraction of sediment in Megasequence 4 is in the foresets, and the clinoforms have a clear sigmoidal configuration (Figure 53). As a result, the associated margin is both progradational and aggradational, and the shelf-slope break in Megasequence 4 is significantly more gradual and gently dipping than the final shelf edge in Megasequences 1, 2, and 3.

The basal sequence boundary appears to be erosional in the shelf and slope setting, indicating a relative fall sea level, followed by the deposition of the lowstand wedge, and then strong progradation. This change is interpreted to be the result of a high rate of sedimentation combined with a decrease in basin subsidence during the deposition of Megasequence 4.

The depocenter during the deposition of Megasequence 4 shifted to the southwest such that the megasequence is as much as twice as thick in that area than to the northeast (Figure 53). This shift in depocenter appears to be a compensational with respect to the underlying
megasequences, which have depocenters that are concentrated in the northeast part of the study area. Multiple depositional sequences can be identified within Megasequence 4, particularly in the southwest where the strata are thickest (Figure 53 B).

The pervasive polygonal faulting in Sequence 4 provides insight into its geologic conditions. Polygonal faults are thought to form due to volume-driven contraction resulting from compaction-driven vertical fluid expulsion. These polygonal fault patterns are most common in fine-grained or interbedded finer-to-coarser grained sediments, and their origin is not attributed to regional tectonic stresses. The development of these dewatering faults in Megasequence 4 may record a shift to high rates of deposition of fine-grained sediments from a reoriented margin.

Interpreting the stratigraphy within Megasequence 4 in detail is challenging due to the pervasive polygonal faulting throughout the interval (Figure 12). However, some reflection patterns can be identified. At the base, there is a lowstand wedge of strata that onlaps the underlying sequence boundary and does not appear to have any coeval shelf deposits. That depositional unit is overlain by a prograding complex that has minor aggradation within the topsets, thickened foresets, and downlapping bottomsets (Figure 53). This prograding complex may consist of multiple higher frequency sequences. In the depocenter to the southwest, there is a thick aggradational topset unit overlying the clinoforms (Figure 53 B). These strata may be highstand systems tract deposits, or they may be transgressive systems tract deposits with apparent truncation beneath the overlying sequence boundary. In the latter case, no highstand was developed. The coeval basin-floor strata do not increase in thickness to the same degree that the slope and shelf strata do toward the depocenter.
Figure 53: Seismic profiles through Megasequence 4 showing variation across the study area and the relationship between shallow and deepwater strata.
Shallow-Deepwater Linkage

The relationship between shallow and deepwater sedimentation shows that high sediment supply does not necessarily result in thick basin-floor deposits. Rather, the majority of accumulated strata in this megasequence are concentrated on the slope. Another consideration that is relevant to petroleum systems element distribution is overall shingled pattern, and therefore the lack of vertically stacked elements, in such a strongly prograding system.

The strongly progradational nature of the clinoforms, particularly in the prograding complex, indicates that rate of sedimentation significantly outpaced the rate of basin subsidence. This may indicate that subsidence in the Fitzroy sub-basin had decreased due to a tectonic forcing or the end of thermal subsidence on the Falkland Plateau. Alternatively, it may reflect an increase in sediment supply as the result of higher erosion rates on the Falkland Platform.
Megasequence 5: Campanian to Mid-Maastrichtian

Key Surfaces

Megasequence 5 is the uppermost Cretaceous sequence and has a divergent external form, unlike the underlying megasequences (Figure 54). The lower sequence boundary is a prominent regional onlap surface extending from base-of-slope to the shelf edge (Figure 54). The biostratigraphy indicates that there is an unconformity between Santonian and Campanian strata. The upper boundary is identified as the top of the seismic facies package and has good continuity and high amplitude. There are subtle onlapping reflections overlying the upper boundary.

Time structure map

The upper sequence boundary (Maastrichtian) has a homoclinal structural dip to the east-southeast (Figure 55). Although there is no well-defined shelf edge, the orientation of the surface is consistent with the top of Sequence 4 (Figure 49). The surface is shallowest at the western corner of the study area at 1.0 sec twt and deepest at the eastern corner of the data set at 3.5 sec twt. This trend can be applied to the overlying Cenozoic strata as well, indicating that the basin was likely in its final orientation by the Late Cretaceous.

Isochron map

Megasequence 5 ranges from <0.25 sec twt on the shelf (northwest) to a maximum of 1.00 sec twt (southeast). The increase in thickness is present in a 20 km wide zone parallel to the orientation of the margin (Figure 56). To the northwest and southeast of this transitional area, the
Cretaceous sequences because it comprises no clinoforms due a shift in sediment source direction.

Figure 54: (A) Uninterpreted (B) Megasequence 5 interpreted on a regional profile. The sequence is unique among the treatments.
**Figure 55:** Time structure map of top of Megasequence 5. Contour interval is 500 ms. Locations of Figures 54 and 58 are shown.
**Figure 56:** Isochron map of Megasequence 5. Contour interval is 25 ms. The thickest part of the megasequence is at the southeastern edge of the study area on the basin floor. Locations of Figures 54 and 58 are shown.
isochron values are very consistent across the data set. Part of the increased thickness in the basinward strata is due to an onlapping wedge at the base of the sequence (Figure 58).

Seismic facies

Megasequence 5 is composed of three seismic facies (Figure 57). Facies 1 are parallel, semi-continuous, variable amplitude, onlapping reflections that are part of a very thin topset succession along the western portion of the study area (Figure 54). Facies 2 are chaotic, discontinuous, low amplitude, divergent reflections (Figure 54). Facies 2 is southeast of Facies 1 and extends to the southern corner of the study area. Facies 3 is present at the southeastern edge of the study area, and is surrounded by Facies 2. Facies 3 has higher amplitude and a higher degree of reflection continuity than Facies 2. There is more clear onlapping in the deepest portion of the sequence where Facies 3 is present (Figure 58). Facies 2 and 3 are extremely deformed by polygonal faulting (Figure 12).

Geologic Interpretation

Megasequence 5 represents a distinct change in the overall stratigraphic architecture of the basin. Almost all of the strata were deposited basinward of the pre-existing shelf edge (top Megasequence 4). The shallow marine to coastal plain deposits (topsets) are extremely thin, and in some places, almost nonexistent. Sequence 5 does not have a well-defined shelf edge or any identifiable clinforms within the study area. It is possible that the sediment source shifted between Sequences 4 and 5, changing the position and orientation of the shelf edge. This hypothesis requires a tectonic event in which the source area to the northwest changed, and a depositional fairway into the basin was established.
Figure 57: Seismic facies map of Megasequence 5. Locations of Figures 54 and 58 are shown.
Figure 5B: (A) Uninterpreted (B) Interpreted seismic profile displaying the onlapping wedge at the base of Megasequence 5.
A prominent lowstand wedge is present in the base-of slope (Figure 58). The top of this wedge has a horizontal or slightly dipping upper surface with better reflection continuity than the rest of the sequence (Figures 54, 58). High amplitude reflections within the wedge may be condensed sections. If so, it may be interpreted as a regional seal, providing a key petroleum systems element.

An analysis of the relationship between shelf, slope, and basin floor deposits is not done for Megasequence 5 because the sediment is not sourced from a local shallow marine depocenter. The strata are virtually identical across the study area, and are interpreted to be distally onlapping sediments eroded from a land mass outside the study area.
DISCUSSION

Variability in shallow to deepwater linkage

The nature of the linkage of sedimentation from the shallow marine to deepwater settings varies considerably both within and between megasequences. These differences are likely caused by changing rates of sedimentation, subsidence, shifts in the shallow marine depocenter, and relative change in sea level. Three distinctly different patterns of shelf to basin-floor stratal relationships are recorded in the lower four megasequences.

Megasequences 1 and 2, which comprise at least six depositional sequences, have similar shallow to deepwater stratal relationships. The stratal architecture in both megasequences appears to be controlled primarily by location of shallow marine depocenter (i.e. the sediment source). Within the shallow marine depocenters (to the northeast for both megasequences), there is increased incision on the shelf and increased thickness of basin floor strata.

In contrast, Megasequence 3 has a completely different stratal architecture, consisting of thick basin floor deposits lacking coeval shelf strata (lower sequence) and thick shelf strata lacking coeval basin-floor deposits (upper sequence). Interestingly, the location of major incised valleys in upper 3 is similar to the location of the depocenters megasequences 1 and 2, which are likely controlled by the location of the updip drainage outside the study area.

Megasequence 4 also has a depositional pattern that is unique within the basin. The megasequence consists of sigmoidal clinoforms with strong progradation, accumulation of sediment on the slope, and similar stratal geometries across the study area, despite dramatic thickness change. The depocenter shifted to the southwest, apparently filling in topographically
low area created by the concentration of preceding depocenters to the northeast; however, there is no evidence of a point source in the marginal marine strata that deliver sediment to the slope and deep basin. With this shift in depocenter, the orientation of final shelf edge of Megasequence 4 is rotated ~15 degrees counterclockwise compared to the final shelf edges in underlying megasequences.

The implication of this variability in stratal architecture between megasequences is that the relative influences of sediment supply, basin subsidence, and relative changes in sea level differ to form each of these patterns. Within Megasequences 1 and 2, there is a relative balance between the three variables. In contrast, in Megasequence 3, deposition of the thick lower base-of-slope unit is the result of an extended relative lowstand in sea level, and the regional backstep is controlled by an extended relative transgression and early highstand. Megasequence 4 is may be primarily controlled by a tectonic event due to the dramatic change in depocenter, stratal geometry, and onset of internal polygonal faulting.

**Depocenter shifts**

In general, the marginal marine depocenters of Megasequences 1-3 were concentrated in the northeast, resulting in more extensive erosion both within and between megasequences than to the southwest. Then, the depocenter for Megasequence 4 shifted to the southwest, and strata filled the accommodation space created by the stacking of thin portions of the underlying megasequences. Megasequence 5 onlaps and is thickest where Megasequence 4 is thin on the basin floor along the basinward edge of the study area.

In more detail, the depocenters of each megasequence are compensationally stacked and
shift in both strike and dip directions. For example, the basin-floor thick in Megasequence 2 compensates for the basin-floor thin in Megasequence 1. The basin-floor thicks in Megasequences 2 and 3 overlap, which is the only instance where consecutive local depocenters are not offset. Due to the overlap, there is increased internal erosion in these strata, and potentially amalgamated sands with reservoir prospectivity.

Relationship between Falkland Plateau Basin and Atlantic margins

Previous authors have discussed the affinity of Falkland Islands geology to South America versus South Africa, based on the paleogeographic and modern geographic positions of the Falkland Plateau. Understanding the link between the Falkland Plateau Basin and other Atlantic divergent-margin basins is necessary to ascertain which, if any, well-documented tectonic events that are recorded in those basins can also be recognized in the study area. In terms of petroleum potential, a key understanding is how similar the Falkland Plateau Basin is to the prolific South Atlantic oil and gas basins of western South America and eastern Africa.

The Falkland Plateau Basin had a different evolution compared to those on the Atlantic margins due to its unique tectonic history. The Falkland Plateau is isolated to the south of the Agulhas Fracture zone from the Atlantic rifting that the other basins on the margin experienced. The extension that formed the Falkland Plateau Basin developed during the Jurassic, is associated with the breakup of Gondwana, and is not related to the Cretaceous spreading of the South Atlantic. Additionally, the Falkland Plateau Basin is not underlain by oceanic crust like other basins along the Atlantic margin. However, regional stresses throughout the Cretaceous likely influenced the Falkland Plateau Basin during the deposition of the five megasequences. For example, igneous intrusions that cut Megasequences 1 and 2 disrupt Valanginian strata. Both
Jurassic and Cretaceous intrusions have been dated on the Falkland Islands, but assuming these subsurface intrusions are the latter, they were contemporaneous with the rifting of the nearby Mid-Atlantic Ridge.

The sedimentary source area for the Fitzroy sub-basin shifted from the Outeniqua Basin (offshore South Africa) to the Falkland Platform at the beginning of the Cretaceous. This change in source area is defined on seismic data as the oldest clinoforms that prograded from northwest to southeast. The change is source terrane likely records the time when the Falkland Plateau had moved too far from the African continent for deltas to reach the basin. The change may also represent a contemporaneous uplift of the Falkland Islands that generated sediment supply for the basin. At the end of the Santonian, another shift in sedimentary source area is identified and attributed to an unknown tectonic event (start of Megasequence 5).

Isolating the tectonic events that impacted stratigraphy in the Falkland Plateau Basin is tenuous, at best, because the basin has undergone stresses associated with the break-up of Gondwana, the spreading of the South Atlantic, and most recently, the opening of the Scotia Sea. Each of these major regional tectonic events is overprinted by more local events due to the relative movements of the Falkland Platform, Maurice Ewing Bank, and any other microplates or land masses that have since been eroded or subducted. Therefore, the primary comparisons that can be drawn are: (1) the source terrane for sedimentary basin fill is lithologically the same as some South African basins, (2) like most divergent basins on the Atlantic margins, the Falkland Plateau Basin is extensional and shows no evidence of structural inversion, and (3) the stratal patterns in the Falkland Plateau Basin are consistent with passive margin-style deposition. To
Figure 59: Continental reconstruction at 135 Ma, immediately prior to South Atlantic opening, illustrating that the line of continental separation and the position of the principal failed rifts in the region were controlled by both the position of boundaries between different ages of basement and the structural grain of the basement. Data from the Exxon Tectonic Map of the World (1985), Good and de Wit (1997), Lawver et al. (1999), Unrug (1996).
draw more specific ties between the Falkland Plateau Basin and other basins in the region using the data available for this study would be highly speculative.

**Cretaceous Transgression and Regression**

Overall, the stratigraphic trend in the Fitzroy sub-basin is one of transgression during the Early Cretaceous, followed by regression during the Late Cretaceous, which is consistent with the eustatic sea level curve. The locations of the final shelf edges define the major stratigraphic trends. The trend of these four Lower Cretaceous shelf edges is transgressive. The final shelf edges of the two sequences in Megasequence 1 (approximately Berriasian) are aggradational and overlap in map view. This character represents a balanced state between sediment supply and subsidence for 6 million years during the earliest Cretaceous. The basin was likely undergoing thermal subsidence during this time such that accommodation kept pace with sediment supply into the basin. The shelf edge that defines the top of Megasequence 2 (uppermost Valanginian) is at the same position as the final shelf edges of Sequence 1a and 1b at the southwest edge of the data set, and diverges landward to the northeast. This separation represents an approximately 10 km backstep. The final Megasequence 3 shelf edge (mid-Albian) is sub-parallel to and sits approximately 20 km landward from the lower package of Megasequence 3, due to the intervening Aptian transgression. In contrast to Megasequences 1-3, the top of Megasequence 4 (Santonian) shelf edge is 10-40 km basinward of Megasequence 3. This is the first megasequence that progrades basinward of the previous shelf edge. The orientation of the Santonian shelf edge is different from those in the Early Cretaceous; the Santonian is oriented SSW to NNE as opposed to SW to NE. This change in shoreline/shelf edge orientation may
indicate that the Falkland Plateau Basin had rotated slightly counterclockwise to realign the margin or that the sediment supply shifted toward the southwest during the Late Cretaceous.

The biostratigraphic ages of major surfaces provide insight into the orders of megasequences and provide a reference point to compare with global eustatic sea level. A major unconformity at the Valanginian-Aptian lies in the lowest part of Megasequence 3. This boundary approximately corresponds to a significant change in stratal architecture between Megasequences 2 and 3. At the top of Megasequence 4, there is a condensed section comprising stacked unconformities between the Albian, Cenomanian, Turonian, and Santonian. This boundary corresponds to a major shift in the sediment source area away from the Falkland Platform. Interestingly, based on the biostratigraphic ages, the top Albian (which is the end of the global transgression) lies within Megasequence 4 as opposed to the top of Megasequence 3. This means that the onset of progradation in the Fitzroy sub-basin is earlier than would be expected from eustatic changes alone.

Petroleum System Elements

Source Rocks

The petroleum potential of the Falkland Plateau Basin is contingent on the presence of mature source rocks. Organic-rich mudstones have been penetrated in DSDP wells on the Falkland Plateau 600 km to the east. Gas chimneys and shallow gas accumulations, identified as high anomalous amplitude reflections above vertical data washout zones, are apparent in the Fitzroy sub-basin. They are not clearly associated with fault migration pathways, so the source of the gas is unclear. From a sequence stratigraphic perspective, transgressive systems tracts are the most likely candidates for source rocks. There are identifiable transgressive systems tracts in
Figure 60: Map of the positions of final shelf edges for each megasequence. Note an overall transgressive trend during the Lower Cretaceous, followed by Santonian progradation and a change in orientation. The upper sequence boundary of Megasequence 5 (Maastrichtian) is not shown, because it does not have a defined shelf edge.
the Cretaceous sequences, however, they are typically thin and poorly preserved in the northeastern part of the study area.

Analysis of the regional distribution of source rocks, including cores from the DSDP sites 511 & 330 on the Maurice Ewing Bank, indicates widespread occurrences of Aptian organic rich rocks (Figure 61). Aptian-Barremian source rocks are ~50 m thick, Type II-III kerogen, 2-6% TOC, with HI of 200-500. The Aptian source interval corresponds to the transgressive systems tracts in Megasequence 3 in the study area. The DSDP cores also indicate the presence of organic-rich source rocks in the Upper Jurassic stata. The Kimmeridgian-Oxfordian source rocks are ~50-100 km thick, Type II-III kerogen, 3-7% TOC, with HI of 350-550.

These data are promising, but the significant distance (~600 km) between these cores and the study area increases the risk factor for source rock presence. Based on the seismic data in the study area alone, it appears more likely that any source rocks present are gas-prone and/or overmature. Marginal marine deltas prograding to the shelf edge are present throughout the Cretaceous section suggesting that much of the organic material in the sub-basin may be terrigenous. Therefore, gas-prone Type III kerogen might be expected in any source rocks that develop. In addition, shallow gas accumulations are a direct indicator that gas is being generated; however, it is unclear whether that generation is in Jurassic or Cretaceous strata.

**Reservoirs**

Channelized lowstand submarine fans in Megasequences 2 and 3 may comprise reservoir quality sand. The sediments are interpreted to be sourced from a quartzitic source area on the Falkland Platform and transported to the basin floor via turbidity currents in channel-levee systems. Reservoir quality sands are expected in sand-filled channels and possible basin-floor
fans (depositional lobes). Additionally, the Toroa-1 well encountered thick, quartzose sands in a similar depositional environment approximately 100 km southwest of the study area (Figure 3).

However, these potential reservoirs are in close proximity to intrusive volcanic dikes and sills that introduced additional local heat into the basin. The possible consequence of this increased heat flow is cementation of siliciclastic reservoir sands that may decrease porosity and permeability in these sandstones, particularly in the Lower Cretaceous basin-floor sediments.

Seals

The identifiable transgressive systems tracts and flooding surfaces throughout the Cretaceous sequences are good candidates for seals. These intervals appear to be more well preserved in the southwest than the northeast where there is increased internal erosion. Regional onlapping packages are likely marine shales, such as the Megasequence 5 wedge that onlaps the Santonian slope, and may act as regional seals for the underlying petroleum system.

In addition, previous work has found that potential sandstone reservoirs in all of the basins surrounding the Falkland Islands are likely to be capped by thick argillaceous sequences, and may, therefore, be adequately sealed (Richards, 2001). Specifically, the lowstand fan wedges developed in the Falkland Plateau Basin are likely to be encased in pelagic mudstones, and these may form adequate sealing horizons (Richards, 2001). Although there are many small faults, the general lack of large-offset suggests that sealing horizons are unlikely to be vertically breached.

Traps

Most potential traps in the Fitzroy sub-basin are stratigraphic, of which three types have been identified. Updip pinchouts of submarine fans against the slope, anomalously
Figure 61: Diagram illustrating the variation in timing of early anoxia across Gondwana land masses, including the Maurice Ewing Bank on the Falkland Plateau. Time scale from Harland et al. (1990); numbers at the heads of columns refer to DSDP/ODP well sites. (Macdonald, 2003)
high-amplitude channels that fed the lowstand fans, and lateral facies changes (e.g. proximal to
distal levees) all may be traps.

There are fewer opportunities for structural traps in the Fitzroy sub-basin, which is a
limitation on the variety of play concepts that may be explored. It is possible that some faults,
particularly in the topsets, have sufficient offset to create a 3-way closure. The igneous intrusions
on the basin floor may also have associated structural traps including 3-way closure against a
dike or 4-way compactional drape above and intrusion. These traps are not well-documented in
the seismic data and are considered speculative. The lack of ideal structural traps is not
necessarily problematic assuming the stratigraphic closures are well-sealed and large enough to
be commercial.

Uncertainties

The most significant uncertainties arise from a lack of well data in proximity to the study
area. Source-rock intervals described from DSDP sites 330 and 551 must be projected from over
600 km east on the edge of the Maurice Ewing Bank. Additionally, there is lack of lithologic
information in the basin, making interpretations solely dependant on identified stratal
relationships. However, oil and gas discoveries in the basins surrounding the Falkland Islands
are promising, and leveraging a sequence stratigraphic interpretation in the Fitzroy sub-basin is a
logical step toward finding a commercial discovery.
Figure 62: Map of the Falkland Plateau showing major tectonic elements and the locations of DSDP Wells 330 and 311.

---

on the Maurice Ewing Bank. These wells are approximately 600 km east of the data set used in this study. (Marshall, 1994)
CONCLUSIONS

1. The Fitzroy sub-basin has five second-order Cretaceous megasequences; each consist of 2-8 higher frequency (likely third-order) sequences. Extensive faulting and gas chimneys obscure the seismic data to the point that regional correlation of individual higher frequency sequences is not possible.

   Although four of the megasequences have a well developed topset-foreset-bottomset geometry, each megasequence records different stacking patterns and stratal architecture. The changing depositional system throughout the Cretaceous is the result of a complex balance between sediment supply, basin subsidence, and changes in relative sea level.

2. Overall, Megasequences 1-3 (Berriasian-mid-Albian) are transgressive, although individual third-order sequences are progradational. The overall backstepping trend is consistent with eustatic sea level rise in during the Early Cretaceous. Megasequence 4 (mid-Albian-Santonian) progrades significantly basinward of the underlying megasequences, which approximately aligns with the onset of eustatic sea level fall during the Late Cretaceous.

3. Megasequence 1 (approximately Berriasian) comprises two sequences that show extensive shelf edge and upper slope syndepositional deformation and instability in response to increased sediment supply in the depocenter (northeast). In contrast, the shelf, slope, and basin-floor strata are undeformed and well-preserved to the southwest.

   Megasequence 2 (approximately Valanginian) comprises up to four sequences, and shows the greatest lateral variability in depositional systems of all the megasequences. In the depocenter to the northeast, thick basinal deposits, consisting of channel levee complexes, mass-transport deposits, and sheet-like deposits, are coeval with updip stacked incised valleys in
the continental to shallow marine strata. To the southwest, the basinal deposits are primarily parallel, onlapping reflections coeval to thin topset beds that are not incised.

Megasequence 3 (uppermost Valanginian to mid-Albian) comprises two major upper and lower sequences. The lower sequence sits almost entirely in a basinal setting and consists of multiple (up to six) offsetting submarine fans (channel-levee systems), each possibly being a third-order sequence. There are little to no coeval shelf sediments present. A significant landward shift in the depocenter (20-40 km) then occurred, such that the upper sequence was deposited overlying the pre-existing shelf strata of Megasequence 2. The upper sequence consists of up to five sequences, is strongly aggradational overall with internal progradation, and contains significant compound incised valleys to the northeast.

Megasequence 4 (mid-Albian-Santonian) has a markedly different geometry than the underlying megasequences, and is the only megasequence where the depocenter shifts to the southwest. The stratigraphic architecture is dominated by sigmoidal clinoforms and is consistent across the study area despite a significant increase in thickness to the southwest.

Megasequence 5 (Santonian-mid-Maastrichtian) is unique because it consists solely of onlapping strata, and represents a shift in the sediment source area away from the Falkland Platform. The basal sequence boundary likely marks a significant tectonic shift in the region.

4. The most consistent stratal pattern identified from correlations of shelf, slope, and basin-floor strata is that, during any given depositional sequence, sediments are preferentially deposited in either shallow or deepwater. Often, there are some strata preserved across the entire depositional profile, however, one setting typically accumulates most of the available sediment at the expense of the other. The implication is that deepwater features including basin-floor fans are
most likely to form during periods of extended lowstand shelf incision and/or bypass. Conversely, the basin floor is likely starved of sediment during periods of shelf aggradation.

In addition, the character of basin-floor sediments corresponds to the degree of incision and instability updip. Mass-flow deposits and channel-levee systems preferentially developed on the basin floor where the coeval updip sediments are more chaotic. Basin-floor wedges of sheet-like onlapping strata preferentially develop where there are no preserved coeval updip strata, and where the updip shelf and upper slope are relatively undeformed. The depocenters for Megasequences 1-3 are concentrated in the northeast half of the study area; therefore, most erosion and deformation is isolated to that area.

5. The most prospective intervals from a petroleum systems perspective are the basin-floor deposits in the downdip depocenters of Megasequences 2 and 3. The lowstand mounded submarine fans and channel-levee systems are potential reservoir intervals. Their geometry and channelized nature provide ample opportunities to form stratigraphic traps. The overlying Aptian transgression in Megasequence 3 likely provides a seal for these units. High amplitude channel forms identified in seismic profiles and attribute maps may be sand-filled and/or hydrocarbon saturated.

The presence of source rock is the highest risk in the petroleum system. Although organic-rich rocks have been documented on the Falkland Plateau, from DSDP cores and hydrocarbon discoveries, their occurrences are far from this study area. The identification of shallow marine deltas throughout the Cretaceous implies that much of the organic material in these sediments is terrigenous, which would generate gas-prone Type III kerogen. The maturation of these source rocks is also a risk, as we do not have heat-flow data in this basin.
The active tectonic setting and intrusive volcanism in the subsurface increases the local risk of overmatureations. Gas accumulations in the shallow subsurface may be evidence of Type III kerogen and/or overmatureation, however, the source of that gas is unknown and may be from deeper rocks.
REFERENCES


