SEISMIC, STRUCTURAL AND STRATIGRAPHIC EVOLUTION OF THE CRETACEOUS SEQUENCES OF THE ORPHAN BASIN, OFFSHORE NEWFOUNDLAND AND LABRADOR

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by

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Abstract

The continental margin of Newfoundland is made up of a series of interconnected, deep, Mesozoic sedimentary basins. Between the Cumberland Belt Transform Zone and the Charlie Gibbs Transform Zone the Avalon terrane is dissected into a 450 km wide track of extensional ridges and grabens collectively known as the Orphan Basin. From both a tectonic and a petroleum potential point of view the basin can be divided into an older (Late Triassic – Early Jurassic) sub-basin known as the East Orphan Basin and a younger (Cretaceous) sub-basin known as the West Orphan Basin. The Orphan Basin is an underexplored area and few studies have been completed on the structural, tectonic and stratigraphic framework of the area.

Seismic stratigraphic analysis of the basin identified six major sequence boundaries ranging in age from pre-Mesozoic (Seismic Basement) to present (Water Bottom) and four Cretaceous sequences were identified, mapped and described. Four fault families were defined within the study area on the basis of their regionality, timing and duration of movement and depths of detachment: the Basin Bounding Fault Family, the Basement Involved Fault Family, the Sedimentary Fault Family and the Transfer Fault Family.

Based on the mapping of the Cretaceous sequences and the orientations of major faults seen in the study area, the Orphan Basin can be divided into three distinct tectonostratigraphic regions. From west to east they are Areas A, B, and C. Areas B and C were affected by the Late Triassic – Early Jurassic Tethys Rift and the Late Jurassic – Early Cretaceous Atlantic Rift. Area B was reactivated for a third time with the Aptian – Albian Labrador rift that caused uplift and inversion of large structures in this area. Area A was predominantly affected by the Aptian – Albian Labrador rift and has Early and Late Cretaceous basin fill. The orientation of the major basement involved and basin bounding faults in the basin show a counterclockwise rotation from east to west as the rift propagated landward. The oldest faults (located in Area C) have a NE-SW orientation in line with the Tethys rift while those faults in the younger Area A have an approximate N-S to NNW-SSE orientation in line with the Labrador rift.

A proven petroleum system has not been identified in the Orphan basin; however, due to the timing of rifting, two different petroleum systems are proposed for the East Orphan and the West Orphan basins. Considering all the elements and processes required for a working hydrocarbon system, the most likely plays within the East Orphan Basin are: an oil prone source rock equivalent to the Egret Member of the Rankin Formation; reservoirs of Early Cretaceous stacked sandstones, a seal of Late Cretaceous and Tertiary shales; large structural traps in the form of drape over horst blocks, extensional anticlines and rotated fault blocks of Late Jurassic – Early Cretaceous age. The petroleum system for the East Orphan Basin is likely analogous to that of the Jeanne d'Arc Basin. In the West Orphan Basin the most likely plays are: Late Cretaceous and early Tertiary organic rich shales equivalent to the Bjarni and Markland Formations in the Labrador basins; reservoirs made up of Late Cretaceous and early Tertiary sands; seals of thick Nautilus or Banquereau equivalent shales; structural, stratigraphic and combination traps, most likely basin margin fans pinched out updip or draped over some form of structure. The petroleum system for the West Orphan Basin is likely analogous to that of the Labrador basins.

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Dedication

This thesis is dedicated to the
memory of my grandparents;

To Poppy, a man of few words,
to Nanny, a woman of many,
and to Granny, who's strength was an inspiration

You were with me every step of the way

Table of Contents

Title Page i
Abstract ii
Acknowledgements iii
Dedication v
List of Figures viii
List of Tables xiv

Chapter 1: Introduction 1

1.1 Introduction to the Orphan Basin 1
1.2 Background and Previous Work 5
1.2.1 Potential Field Data 5
1.2.2 Vintage Industry Reflection Data 7
1.2.3 Exploration Wells 7
1.2.4 Deep Seismic Reflection Data 9
1.2.5 Wide Angle Refraction Seismic Data 10
1.3 Purpose 11
1.4 Research Objectives 12
1.5 Data and Methods 13

Chapter 2: Geography, Stratigraphy and Basin Structure 17

2.1 Geography 17
2.2 Regional Geology 19
2.3 Stratigraphy and Mesozoic Basin Development 24
2.3.1 Orphan Basin 25
2.3.2 Jeanne d'Arc Basin 33
2.3.3 Porcupine Basin 36
2.4 Structure and Basinal Features 39

Chapter 3: Seismic Stratigraphy 42

3.1 Introduction 42
3.2 Well Control 42
3.2.1 Well Information 44
3.2.2 Time-Depth Information 45
3.3.3 Well Picks and Seismic Markers 47
3.3 Seismic Stratigraphy 52
3.3.1 Cretaceous Structural Regions 52
3.3.2 Bsm Sequence Boundary 55
3.3.3 Seismic Sequence S1 58
3.3.4 K1 Sequence Boundary 62
3.3.5 Seismic Sequence S2 66
3.3.6 K2 Sequence Boundary 70

3.3.7 Seismic Sequence S3 74
3.3.8 K3 Sequence Boundary 79
3.3.9 Seismic Sequence S4 84
3.3.10 T Sequence Boundary 88
3.3.11 Seismic Sequence S5 93
3.3.12 Water Bottom 95
3.3.13 Volcanics 97

Chapter 4: Tectonics 98

4.1 Introduction to West and East Orphan Sub-Basins 98
4.2 East Orphan Basin Fault Families 100
4.2.1 Basin Bounding Fault Family 100
4.2.2 Basement Involved Fault Family 102
4.2.3 Cretaceous Faults 103
4.3 West Orphan Basin Fault Families 106
4.3.1 Basin Bounding Fault Family 106
4.3.2 Basement Involved Fault Family 107
4.3.3 Cretaceous Faults 109
4.4 Transfer Fault Family 111
4.5 Tectonostratigraphic Evolution 112
4.5.1 Late Triassic – Early Jurassic 114
4.5.2 Late Jurassic – Early Cretaceous 117
4.5.3 Aptian – Albian 124
4.5.4 Late Cretaceous – Paleocene 126

Chapter 5: Implications for Petroleum Systems 135

5.1 Introduction 135
5.2 Potential for Source Rocks 136
5.3 Potential for Reservoirs 146
5.4 Traps 150
5.5 Hydrocarbon Indicators 157
5.6 The Potential Hydrocarbon System 159

Chapter 6: Conclusions and Recommendations for Future Work 161

6.1 Justification of Study 161
6.2 Conclusions 162
6.3 Recommendations for Future Work 169

References 170

Appendices

Appendix A (in pocket)

List of Figures (Short Titles)

1.1	Bathymetry, basin location, exploration lease blocks and study area, offshore Newfoundland	4
1.2	Basemap of Orphan Basin study area showing GSI seismic grid, current exploration license blocks and well locations	14
1.3	Example of GSI 2000-2003 2D seismic dip line	15
2.1	Orphan Basin location map and basin boundaries	18
2.2	Composite chart showing tectonic and structural stages, deformation style and simplified stratigraphy for the Newfoundland continental margin	21
2.3	Earliest Cretaceous North Atlantic reconstruction prior to onset of sea floor spreading	24
2.4	Reconstruction of the North Atlantic Ocean between Africa, Iberia and North America at chron M0 with respect to Eurasia	29
2.5	Location of Jeanne d'Arc Basin	33
2.6	Lithostratigraphy of the Jeanne d'Arc Basin	34
2.7	Location of Porcupine Basin	37
2.8	Generalized stratigraphy, lithology and tectonic history of the Porcupine Basin	38
3.1	Basemap of the Orphan Basin showing 2D seismic grid and well locations	43
3.2	Time-depth curves for wells in the Orphan, northern Jeanne d'Arc and Flemish Pass basins	46
3.3	Simplified geological cross-section through Orphan Basin wells	50
3.4	Schematic diagram depicting age, formation names, lithology, horizon name, seismic sequence name and quality of each seismic marker	51
3.5	Time structure map of the basement depicting three distinct Cretaceous depocenters of the Orphan Basin	54
3.6	Seismic dip section showing seismic horizons tie at the Blue H-28 well	56

3.7 Seismic dip section across Orphan Basin showing structural setting and seismic character of the basement 57

3.8 NW-SE seismic dip line through Area B showing the seismic character of seismic sequence S1 59

3.9 NW-SE seismic dip line through Area C showing the seismic character of seismic sequence S1 60

3.10 Compilation of Figures 3.8 and 3.9 for side-by-side comparison of seismic sequence S1 61

3.11 S-N seismic profile showing correlation of K1 sequence boundary at Baccalieu I-78 62

3.12 NW-SE seismic dip line through Area B showing K1 sequence boundary 63

3.13 NW-SE seismic dip line through Area C showing K1 sequence boundary 64

3.14 Compilation of Figures 3.12 and 3.13 for side-by-side comparison of K1 sequence boundary 65

3.15 SW-NE seismic strike line through Area B showing the seismic character of seismic sequence S2 67

3.16 NW-SE seismic dip line through Area C showing the seismic character of seismic sequence S2 68

3.17 Compilation of Figures 3.15 and 3.16 for side-by-side comparison of seismic sequence S2 69

3.18 NW-SE seismic dip line through Area B showing K2 sequence boundary 71

3.19 NW-SE seismic dip line through Area C showing K2 sequence boundary 72

3.20 Compilation of Figures 3.18 and 3.19 for side-by-side comparison of K2 sequence boundary 73

3.21 NW-SE seismic dip line through Area A showing the seismic character of seismic sequence S3 75

3.22 NW-SE seismic dip line through Area B showing the seismic character of seismic sequence S3 76

3.23 NW-SE seismic dip line through Area C showing the seismic character of seismic sequence S3 77

3.24 Compilation of Figures 3.21, 3.22 and 3.32 for side-by-side comparison of seismic sequence S3 78

3.25 NW-SE seismic dip line through Area A showing K3 sequence boundary 80

3.26 NW-SE seismic dip line through Area B showing K3 sequence boundary 81

3.27 NW-SE seismic dip line through Area C showing K3 sequence boundary 82

3.28 Compilation of Figures 3.25, 3.26 and 3.37 for side-by-side comparison of K3 sequence boundary 83

3.29 NW-SE seismic dip line through Area A showing the seismic character of seismic sequence S4 84

3.30 NW-SE seismic dip line through Area B showing the seismic character of seismic sequence S4 85

3.31 NW-SE seismic dip line through Area A showing the seismic character of seismic sequence S4 86

3.32 Compilation of Figures 3.29, 3.30 and 3.31 for side-by-side comparison of seismic sequence S4 87

3.33 NW-SE seismic dip line through Area A showing T sequence boundary 89

3.34 NW-SE seismic dip line through Area B showing T sequence boundary 90

3.35 NW-SE seismic dip line through Area C showing T sequence boundary 91

3.36 Compilation of Figures 3.33, 3.34 and 3.35 for side-by-side comparison of T sequence boundary 92

3.37 NW-SE dip seismic section showing seismic sequence S5 through Areas A, B and C 94

3.38 Time structure map of Water Bottom sequence boundary 96

3.39 N-S seismic section through northern part of Area B showing strong amplitude anomalies, which may be interpreted as volcanic in origin 97

4.1 Time structure map of basement showing the West and East Orphan basins overlain by basin bounding and major basement involved faults 99

4.2 NW-SE dip profile through East Orphan Basin showing White Sail Basin bounding fault 101

4.3 NW-SE dip seismic section through East Orphan Basin showing White Sail basin bounding fault, basement involved faults and sedimentary faults 105

4.4 NW-SE dip seismic profile through the West Orphan Basin showing basin bounding Bonavista Fault 107

4.5 NW-SE dip profile through the West Orphan Basin showing Bonavista basin bounding fault and basement involved faults 110

4.6 Basement time structure map of the seismic basement showing major basement involved faults and Areas A, B and C 113

4.7 NW-SE dip profile through Area B (east of the White Sail Fault) showing Jurassic and older sediments 116

4.8 Time structure map of the K1 Sequence Boundary 118

4.9 NW-SE dip profile through Area C of the East Orphan Basin showing highly reflective Early Cretaceous S2 synrift sequence and synrift sedimentary faults 120

4.10 NW-SE dip profile through Area B showing large scale antiform of Early Cretaceous age 121

4.11 Time structure map of K2 sequence boundary 122

4.12 NW-SE seismic dip profile through Area B showing late movement along sedimentary faults 123

4.13 Extensional anticline in Area B that has been modified and inverted due to transtension and ridge push 125

4.14 NW-SE dip profile through Area B of the Orphan Basin showing the K3 (Santonian) erosional/channelized unconformity 128

4.15 Time structure map of the K2 (Santonian) sequence boundary with outline of mapped channel 129

4.16 W-E seismic profile through Area A of the Orphan Basin showing eroded top of a basement block at the Base Tertiary Unconformity 130

4.17 Time structure map of T sequence boundary 131

4.18 Summary of Lithostratigraphy of Jeanne d'Arc Basin, sequence boundaries and seismic sequences and structural styles in the Orphan Basin 133

4.19 Schematic structural map of Orphan Basin showing ages and areas affected by rifting events 134

5.1 North Atlantic Oxfordian-Kimmeridgian paleo-oceanography 138

5.2 Isochron map of Kimmeridgian Horizon to Water Bottom 140

5.3 Results from drilling at IODP site 1276 showing lithostratigraphy and laminated black shales 142

5.4 Isochron map of Tertiary sequence (Water Bottom to Base Tertiary Unconformity) 145

5.5 Schematic diagram showing provenance for predominantly Late Jurassic – Early Cretaceous and Aptian - Late Cretaceous reservoir sands 147

5.6 Seismic profile through Area B showing highly reflective Early Cretaceous sequence 148

5.7 W-E seismic profile through West Orphan Basin showing interpreted Tertiary and Late Cretaceous sedimentary fans 149

5.8 Time Structure map of K2 sequence boundary (interpreted top of potential reservoir) showing areas of closure 151

5.9 NW-SE profile through Area B of Orphan Basin showing large extensional anticline 152

5.10 S-N strike profile through extensional anticline shown in Figure 5.9 153

5.11 NW-SE seismic profile through Area B of Orphan Basin showing 2 potential structural traps 154

5.12 SW-NE strike profile through the SE anticline shown in Figure 5.11 155

5.13 NW-SE seismic dip profile through the Orphan Basin showing basement high with thin Mesozoic cover 156

5.14 SW-NE seismic profile through the East Orphan Basin showing expression of gas chimneys 157

5.15 NW-SE strike profile through Area B showing bright spot and gas chimneys 158

List of Tables

3.1 List of wells in Orphan, Northern Jeanne d'Arc and Flemish Pass basins showing location, elevation and total depth 45

3.2 List of wells and formation tops in Orphan Basin 48

3.3 List of wells and formation tops in Northern Jeanne d'Arc and Flemish Pass basins 49

Chapter 1

Introduction

1.1 Introduction to Orphan Basin

The Orphan Basin has once again become an area of active frontier exploration as seen by the December, 2003 offshore land sale of $672 Million in exploration work commitments. Current exploration work consists of a 5000 km 3D seismic program on behalf of Chevron Canada Resources (C-NLOPB weekly reports, 2006) and a recently completed Geological Survey of Canada – Atlantic research cruise on geo-hazards. Discoveries of large reserves in the nearby Jeanne d'Arc Basin, new geological understanding of deepwater basins and advances in deepwater development technology has brought renewed interest to the basin. With an area of over 160,000 square kilometers, the Orphan Basin represents an immense exploration region with petroleum potential (Figure 1.1). The present exploration focus is on the East Orphan Basin. To date seven unsuccessful wells have been drilled in the West Orphan Basin; however, an exploration well was drilled by Chevron Canada Resources in the East Orphan Basin during the fall of 2006 to spring of 2007.

The passive continental margin of Eastern Canada is characterized by a series of deep sedimentary basins above a wide zone of significantly thinned continental crust. Faulting style and basin geometry vary laterally along the margin. According to previous studies, the East Orphan Basin contains a complete Jurassic sequence and probably older sediments, indicating that this part of the margin evolved subsequent to the initial Late

Triassic-Early Jurassic rifting of the Pangean super-continent and Atlantic Ocean opening (Enachescu, 1987b; Tankard and Balkwill, 1989; Enachescu *et al.*, 2005). Late Triassic-Early Jurassic (Tethys), Late Jurassic-Early Cretaceous (North Atlantic) and the Late Cretaceous (Labrador) extensional phases dissected the Avalon terrane, between the Grand Banks and the Charlie Gibbs Fracture Zone, into a 450 km wide tract of extensional ridges and grabens that collectively form the broad Orphan Basin (Enachescu, 1987b and 1988; Tankard and Welsink, 1989; Enachescu *et al.*, 2004a). During basin development and sediment accumulation conditions suitable for the generation and preservation of source and reservoir rocks were created (Koning *et al.*, 1988; Smee, 2003; and Enachescu *et al.*, 2004b).

The Orphan Basin was subjected to two major intra-continental rift stages (Enachescu *et al.*, 2005). Initially the basin was a Paleozoic sedimentary platform that was affected by Permo-Triassic rifting in only the eastern part. During this early Tethys rift the West Orphan Basin formed the western rift shoulder and together with intra-basinal ridges, were the provenance areas for most of the continental red bed sediments deposited in the alluvial and lacustrine settings. Rifting was followed by thermal subsidence, marine invasion and deposition of shallow marine deposits including stratified evaporites and massive carbonate beds. The evaporite interval has been interpreted seismically based on regional basin correlations and has different characteristics than the coeval Argo salt sequence of the Scotian and Grand Banks basins (Enachescu *et al.*, 2005).

Reactivation of the Orphan Basin during the Late Jurassic to Early Cretaceous Atlantic rift phase caused deepening and expansion of the basin with local highs and

elevated shoulders supplying the sediment sources. Synrift Mesozoic rocks drilled in the basin include mid Jurassic aged alluvial sandstones on the Orphan Knoll (Laughton *et al.*, 1972; van Hinte and Ruffman *et al.*, 1995). During the Kimmeridgian, a shallow epeiric sea extended from Nova Scotia to northern Europe and organic rich shales were deposited.

With each phase of rifting, the locus of extension moved westward and resulted in the formation of two asynchronous main basins and younging of synrift sedimentary fill in the landward direction (Enachescu *et al.* 2005). Basement blocks in the east have a thick Mesozoic cover, while those in the west are sediment poor or entirely devoid of sediment. Extreme erosion took place during the middle to Late Cretaceous – Early Tertiary, marked by the Avalon and Base Tertiary unconformities, which are mappable across the basin. The Base Tertiary Unconformity marks a time when the entire Orphan Basin underwent a period of subaerial exposure.

Since the early Tertiary the Orphan Basin and the Orphan Knoll have undergone rapid subsidence and foundering in the deeper Atlantic waters (Enachescu *et al.*, 2004). The East Orphan Basin remains under-filled with sediment during the Tertiary to present, while the West Orphan Basin has a thick section of post-Paleocene sediments including shelf progradation and marginal slope fan sequences related to the postrift subsidence (Enachescu *et al.*, 2005).

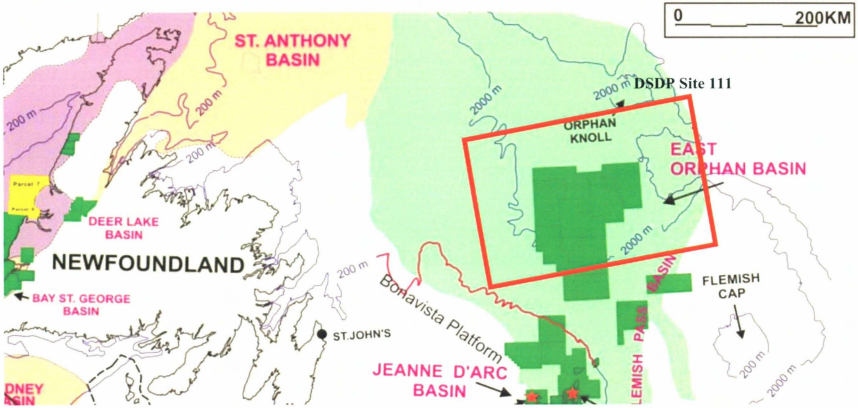

Figure 1.1: Bathymetry, basin location, exploration lease blocks and study area, offshore Newfoundland. Approximate location of study area outlined in red, exploration blocks shown in dark green. Light green shaded area is Mesozoic, pink shaded area is Carboniferous and purple shaded area is Early Paleozoic. Figure modified from the C-NLOPB and Geological Survey of Canada (2005)

1.2 Background and Previous Work

The Orphan Basin is Canada's most recently explored frontier basin and is one of the least-researched, least drilled areas of the Canadian Atlantic margin. While a short-lived exploration phase occurred in the 1970s, the basin's northerly location, deep water setting, poor quality of early vintage seismic data, lack of hydrocarbon discoveries, or presence of Jurassic source rocks in the earliest wells led to basin abandonment and cessation of exploration-drilling. This exploration phase left a legacy of geophysical methods, including drilling, seismic profiling and a dense grid of gravity and magnetic data that have extensively surveyed the area offshore Newfoundland. Exploration interest in the adjacent Flemish Pass Basin in the late 1990's – early 2000's saw two key wells drilled in the area adjacent to the Orphan Basin. One of these wells, Mizzen L-11, established the presence of Kimmeridgian source rock and Late Jurassic – Early Cretaceous reservoir rocks in the area.

1.2.1 Potential Field Data

Scientific investigations and petroleum exploration in the Orphan Basin began in the 1960s with bathymetric and potential field surveys. Natural Resources Canada provides publicly available free-air gravity and total magnetic field data on their website (http://gdcinfo. agg.nrcan.gc.ca/gdr/index_e.html).

Verhoef and Srivastava (1989) used this data to correlate sedimentary basins across the North Atlantic in order to determine the early evolution of the North Atlantic

Ocean. The digital geophysical data were used to create bathymetric, magnetic anomaly and Bouguer anomaly paleo-reconstructions for closure and their reconstructions provide the framework in which the signatures of the potential field data over the Newfoundland and Labrador sedimentary basins could be compared. They used the horizontal derivatives of the magnetic and Bouguer anomalies to delineate the outlines of the Mesozoic basins. Trends seen in the Orphan Basin match the initial direction of motion between North America and Eurasia (Verhoef and Srivastava, 1989). Keen and Dehler (1997) noted that the Orphan Basin margin has the largest and broadest gravity high in their study area. Kearsey and Enachescu (2005a) created a first derivative map using the gravity data to track major structural and tectonic lineaments within the basin. Potential field maps and modeling were used extensively to investigate ridges, discriminate between basement fault blocks and to investigate the possibility of salt diapirism in the basin (Kearsey and Enachescu, 2005a).

The free-air gravity map is dominated by distinct positive anomalies associated with the continental slope, Flemish Cap and Orphan Knoll, while the deep-water basin is correlated with a gravity low (Enachescu *et al.*, 2005). An areally extensive gravity high is mapped in the central part of the East Orphan Basin. This anomaly was interpreted as a central failed rift zone by Skogseid *et al.* (2004) and as a mantle upwelling by Sibuet *et al.* (2005) and Kearsey and Enachescu (2005b). This anomaly was modeled and it was concluded that mantle upwelling remains in the lower crust with no large quantities of volcanic material intruding the sedimentary fill of the Orphan Basin (Kearsey and Enachescu, 2005b).

1.2.2 Vintage Industry Reflection Data

A large amount of 2D seismic data was acquired primarily over the western portion of the basin during initial exploration phase in the 1970's and early 1980's. Several regional papers and maps were published by the Geological Survey of Canada-Atlantic using this pre-1985 industry reflection data. The seismic data was recorded with a short streamer and lacked deep penetration. Processing was hampered by severe multiples, the great majority of the lines were not migrated and imaging below the Base Tertiary unconformity and in shelf break areas was quite poor (Smee *et al.*, 2003; Smee, 2003; Enachescu *et al.*, 2005; Enachescu and Fagan, 2005).

Regional maps created by GSC (2005), Welsink *et al.* (1989) and Grant and McAlpine (1990) show a bounding-fault zone on the west side of the basin and several elongated ridges and alternating troughs. Dehler and Keen (1993) used the vintage seismic data set to derive estimates of the amounts of subsidence in order to create a model of lithospheric extension in the Orphan Basin. This model is used to determine the deformation and thermal history of the Atlantic margin. They concluded that the basin has undergone multiple extensional events and that there are thermally mature zones suitable for oil or gas generation in the West Orphan Basin.

1.2.3 Exploration Wells

Drilling in the Orphan Basin began with the Deep Sea Drilling Joides Site 111 on the Orphan Knoll in 1970 (Figure 1.1). The core hole was drilled in 1797m of water on

the crest of the Orphan Knoll and did not encounter basement rocks. Drilled to a total depth of 128 m the well did drill 20 m of Pleiocene strata overlying a series of unconformities between which lower Miocene, Eocene and Mesozoic sediments were encountered (Laughton *et al.*, 1972). The lower Cretaceous section consisted of approximately 55m of carbonate sands and shaley limestones deposited within an interpreted shallow water marine environment (Ruffman and van Hinte, 1973; van Hinte and Ruffman *et al.*, 1995; Enachescu *et al.*, 2004). Geological correlation to the DSDP 111 hole also identified the presence of a Jurassic (Bajorcian) sequence which is thick in the half grabens and contains continental clastics and marine shales.

Late 1960's to early 1970's vintage regional seismic data indicated the presence of a number of very large structures in the deep water areas of the Orphan Basin. Based on this seismic data, exploration licenses and permits were obtained and exploration concentrated on the shallower West Orphan Basin. Seven wells were drilled, Bonavista C-99 (1974), Cumberland B-55 (1975), Blue H-28 (1979), Hare Bay E-21 (1979), Sheridan J-87 (1981), Linnet E-63 (1982) and Baie Verte J-57 (1985). All were unsuccessful in terms of hydrocarbon discoveries and future drilling programs were abandoned. Good to excellent Cretaceous reservoirs were encountered in the Bonavista C-99, Linnet E-63 and Blue H-28 wells (Koning *et al.*, 1988; Smee *et al.*, 2003).

Exploration continued in neighboring basins and wells drilled in the Flemish Pass Basin (i.e. Baccalieu I-78 and Mizzen L-11) and in the Jeanne d'Arc Basin (i.e. Panther P-52) provide important geological information that can be jump-correlated to the Orphan Basin (Enachescu *et al.*, 2005). In particular, Mizzen L-11, one of the most recent wells drilled by Petro-Canada in the Flemish Pass Basin, provides proof of the

existence of Kimmeridgian source rocks (Egret Member) north of the Jeanne d'Arc Basin and that oil was generated and migrated into porous Cretaceous reservoirs (Enachescu and Hogg, 2005).

1.2.4 Deep Seismic Reflection Data

Since 1984 approximately 5170 km of deep seismic reflection data have been acquired offshore Newfoundland and Nova Scotia to examine intracrustal structures and processes affecting basin formation. The 84-3 LITHOPROBE East seismic line traverses the Orphan Basin complex extending from the continental shelf off Newfoundland, across the basin and almost to the first seafloor spreading magnetic anomaly (Chron 34N), sampling the continent-ocean transition. The line is oriented SW-NE, parallel to the direction of tectonic transport and defines the major crustal structures within the basin (Tankard and Welsink, 1989).

This 600 km transect was first interpreted by Keen *et al.* (1987) who identified a subhorizontal mid-crustal detachment zone, separating the brittle upper crust from the more ductile lower crust at the seven to eight second (two way time) range. Most of the faults terminate at the level of this decollement. Basement highs and lows are distinct features of the seismic profile and the topography is generally interpreted as being due to high angle normal faulting associated with crustal extension (Keen *et al.*, 1987).

1.2.5 Wide Angle Refraction Seismic Data

In 1986 a 400 km long wide-angle seismic reflection/refraction survey was shot in two segments (86-6 and 86-8) along the existing LITHOPROBE 84-3 refraction line and across the northeast continental margin of Newfoundland. The data from 15 ocean bottom seismometers were modeled by Chian *et al.* (2001) in order to derive a seismic velocity model for most of the Orphan Basin and the underlying continental crust. The profile was complemented by the existing multichannel reflection data, petroleum exploration well information from Blue H-28, Bonavista C-99 and DSDP Site 111, gravity data and other deep seismic reflection and refraction lines.

They concluded that prerift metasedimentary rocks are made up of a sequence of siliciclastic and carbonate strata dated as Cenozoic to upper Paleozoic, have a topographic relief of up to 5 km and velocities increasing with depth from ~5.2 km/s to 5.9 km/s. Unaltered crystalline crust below the metasedimentary section has a velocity range of 6.1-6.5 km/s. Most of the lower crust landward of the Orphan Knoll has a velocity of 6.8-7.0 km/s, typical of continental lower crust velocities i.e. those of the Avalon crust seen on land (Miller *et al.*, 1985). The model suggests that continental stretching persisted from 180 Ma to 101 Ma (Chron 34N) when final breakup between Canada and western Europe occurred, leaving a 400 km wide zone of thinned continental crust underneath the shelf and deep water area of the Orphan Basin (Chian *et al.*, 2001). The thinned continental crust stretches 360 km seaward without evidence of magmatic underplating, indicating that the northeast Newfoundland margin underwent non-volcanic rifting.

1.3 Purpose

There have been few academic studies of the Orphan Basin. Previous work has focused on tectonic and structural evolution of the entire Atlantic Margin with descriptions of the Orphan Basin relegated to a paragraph or two. Exploration has historically focused on the relatively shallow shelfal regions of the West Orphan Basin where drilling occurred on large structural closures that could be recognized on the seismic data available at that time. Drilling proved unsuccessful and the large structures were in fact rotated basement blocks with little to no Mesozoic sedimentary cover.

Renewed interest in the basin is now focusing on the deep to ultra deep East Orphan Basin where new seismic data shows a complete sequence of Late Triassic (or earlier) to Tertiary sediments. Kimmeridgian aged source rocks in the Flemish Pass can be correlated into the Orphan Basin, and previous wells prove the existence of good to excellent Cretaceous reservoirs in the West Orphan Basin (Smee *et al.*, 2003; Enachescu *et al.*, 2004 and 2005). The proximity of the gas rich Hopedale Basin, Labrador, gives hope for a potential type III, gas prone, kerogen source in the West Orphan Basin as the thick (2000m) succession of Tertiary sediments indicates burial depth in that area is sufficient for hydrocarbon generation (Hardy and Enachescu, 2005 and 2007; Enachescu *et al.*, 2005).

Improving the understanding of the regional petroleum system of the Orphan Basin requires a detailed analysis of the Cretaceous structural setting, depositional history and a complete understanding of the tectonic history of the East and West Orphan Basins. The purpose of this study is to gain an understanding of the regional geology, tectonic

history and petroleum systems of the basin and to use this information to create regional maps, reconstruct the Cretaceous evolution and isolate potential hydrocarbon plays associated with Cretaceous structural and stratigraphic trapping mechanisms.

1.4 Research Objectives

The main objectives of this study are to:

1. Complete a seismic stratigraphic analysis of the Cretaceous interval, define seismic sequences, tie these sequences to available well data and publicly available information and develop a framework for the description and interpretation of the depositional history of the Orphan Basin
2. Develop the structural and tectonic history of the basin. This involves regional and detailed mapping of structural and tectonic features and associate seismic stratigraphic sequences to various stages of rift evolution.
3. Map and describe main rift elements such as basin bounding faults, transfer faults, major thick and thin skin faults, ridges and troughs, and characterize principle structural features.
4. Research the possibility of Cretaceous and Tertiary source rocks
5. Identify and illustrate hydrocarbon play types

1.5 Data and Methods

GSI of Calgary has donated over 20,000 km of 2D seismic lines to Memorial University and Pan Atlantic Petroleum Systems Consortium (PPSC) to be used for regional research studies of the Orphan Basin (Figure 1.2). These lines were recorded between 2000 and 2003 using a 6 kilometer streamer, 12.5 m hydrophone group interval, a two millisecond sample interval and 12 second record length. A tuned acoustic source array with a 3,000 cu in volume and operating at 2,000 psi was used in all of the GSI surveys. The processed seismic data is 96 fold and includes pre-stack time migration and modern, multiple suppression algorithms (Radon transform).

The resolution in 2,000 m water depth and in very shallow sediments below the water bottom is on the order of 10-15 m. The resolution in the deeper water (3,000 m) is approximately 25-30 m. The seismic resolution is based on the measurement of frequency of reflections and estimation of interval velocities (Enachescu *et al.*, 2005). The overall quality of the data is fair to excellent; however, a zone of signal deterioration exists at the slope break, where primaries are obscured by cross-cutting multiples (Figure 1.3). Due to a low impedance contrast and its great depth, the basement interface is not always mappable. Due to the proprietary nature of this donated seismic data, shot point locations cannot be shown.

Seismic stratigraphic principles (e.g. Vail *et al.*, 1977a and b) were used to define major seismic surfaces and events based on termination patterns. Interpretation of the 2D data set and all mapping was done using Landmark® software. Mapping was based on time migrated seismic data; therefore, thicknesses are described as isochronous and are

measured in two way travel time (ms). In order to accurately image geometries, depths and thicknesses, the data must be converted to depth and migrated using velocity information from wells. Due to a lack of well information in the deepwater Orphan Basin, creating and using a generalized velocity function would likely introduce errors and as such this processing was not attempted. The use of time migrated seismic is a standard in academia and the petroleum industry. Limitations of this data are noted and as such, is an acceptable means of interpretation.

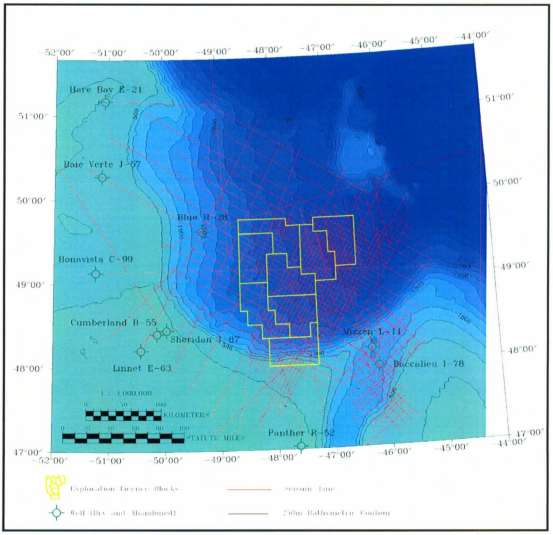

Figure 1.2: Basemap of Orphan Basin study area showing GSI seismic grid, current exploration license blocks and well locations. Bathymetric data courtesy of the Government of Canada.

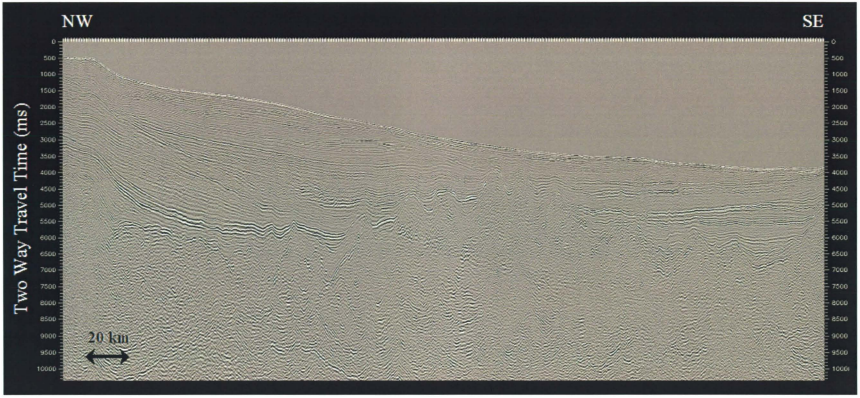

Figure 1.3: Example of GSI 2000-2003 2D seismic dip line. Vertical scale is two way travel time (ms).

The results of the study and particulars of research undertaken are presented in Chapters 3, 4 and 5. Conclusions and recommendations for further work are presented in and 6. Chapter 2 contains a review of the published regional geological knowledge and structural and stratigraphic understanding of the Orphan, Jeanne d'Arc and Porcupine basins. This review provides the necessary framework for the original geoscience work done during the study.

Chapter 2

Geography, Stratigraphy and Basin Structure

2.1 Geography

The Orphan Basin is an Atlantic-type rifted area that is part of the intracontinental network of basins formed during the Mesozoic within northern Pangea. The basin is a highly attenuated Precambrian/Paleozoic area containing Mesozoic to Tertiary sedimentary infill and situated north and northeast of the Grand Banks of Newfoundland (Fig 2.1).

The basin is located 370 kilometers northeast of St. John's and covers an area of approximately 160,000 square kilometers, extending from the continental shelf of the Bonavista Platform in the west to the lower slope in the east. Water depths range from <500 m in the west to 3,000 m near the continent-ocean boundary. The gradient of the upper slope in the West Orphan Basin is 3-4° and gradually shallows to 1-2° in the deep water East Orphan Basin. The basinal area includes the southern and southwestern sides of the Orphan Knoll, a large elevated block, which rises steeply from 3,000m to 1,800m water depths in the northeastern section of the basin (Enachescu *et al.*, 2005).

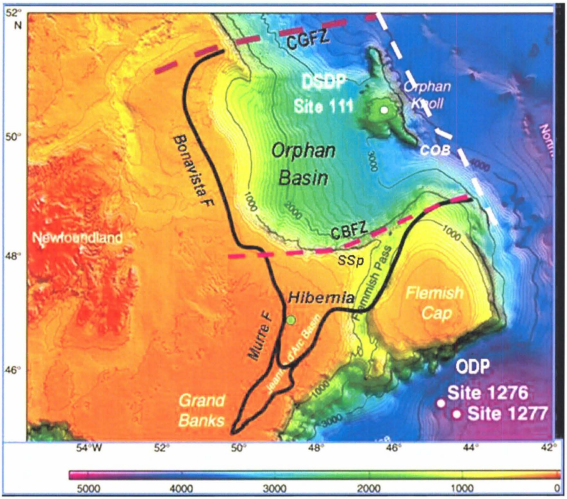

Figure 2.1: Orphan Basin location map and basin boundaries. Bathymetry and 2003 ODP Sites 1276 and 1277, Leg 210, after Tucholke, Sibuet *et al*., 2004. Tectonic framework from Enachescu *et al*., 2004 a. Annotations are CBFZ = Cumberland Belt fault zone, CGFZ = Charlie-Gibbs fracture zone, COB = interpreted Continent-Ocean boundary, SSp = Sackville Spur. Bathymetric highs are Grand Banks, Newfoundland's shelf, Flemish Cap, and Orphan Knoll as indicated by the colour bar. Water depth is in meters.

The Orphan Basin is bounded to the north by the Charlie Gibbs Fracture Zone and its landward extension, the Dover Fault (Haworth, 1977). To the south lie the continental shelf areas of the Flemish Cap and Grand Banks, which are dissected by elongate rift basins (Chian *et al.*, 2001) and the Cumberland Belt Transfer Zone. The basin is situated east of the Bonavista Platform and a fault-induced hinge zone.

The Bonavista Platform is part of the terranes of the Appalachian Orogen and, based on tectonostratigraphic boundaries, most of the Orphan Basin is situated within the Avalon Zone (Keen *et al.*, 1986). At the eastern edge of the basin lie the southern and southwestern sides of a large elevated block known as the Orphan Knoll and the Continent Ocean Boundary (COB) approximately marked by the 4,000m bathymetric contour (Figure 2.2 and Enachescu *et al.*, 2004 a). The large basinal area is located just north of the oil-prolific Jeanne d'Arc Basin (Enachescu, 1987; Tankard and Welsink, 1987 and 1989; McAlpine, 1990).

2.2 Regional Geology

The continental crust underlying the Grand Banks has undergone a long and complex history of construction, which began in the Proterozoic and includes the accretion of a series of exotic terranes onto the North American Craton (Grant and McAlpine, 1990). Some of the Mesozoic rift basins on the Grand Banks may be related to reactivated Paleozoic structures because they are approximately parallel to structural trends of the Appalachian Orogen exposed onshore in Newfoundland (Grant and

McAlpine, 1990) and the distribution of these basins was largely controlled by failure along pre-existing planes of weakness (Tankard and Welsink, 1989).

The East Coast of Canada is generally divided into three regions: the Nova Scotian margin in the south, the Newfoundland margin in the centre and east and the Labrador margin in the north (Louden, 2002). The Grand Banks and adjacent areas evolved as a result of three main rifting events which greatly influenced the configuration of the margin and the evolution of related rift basins (Enachescu, 1987a and b and 1988). Prior to the onset of rifting, eastern Canada lay in the middle of the supercontinent Pangea (Keen *et al*., 1990). The initial phase of Pangea breakup spanned the late Permian to Middle Jurassic and culminated in the development of a new divergent/transform margin between Gondwana and Laurasia (Ziegler, 1989).

A widespread volcanic pulse (CAMP event) at 200 Ma marked the onset of rifting in Late Triassic to Early Jurassic (Marzoli, 1999). It was during late Early Jurassic to Mid Jurassic when Nova Scotia and northern Africa began to separate. The East Coast Magnetic Anomaly (ECMA), a narrow, linear, high magnetic trend of interpreted subaerial extrusive volcanics, defines the eastern limit of the rift and, according to Dehler and Keen (2001 and 2002), marks the boundary between continental and oceanic crust. Starting in the Mid-Jurassic the initial rift (Tethys stage) became a successful oceanic rift south of the Newfoundland Transform Zone but was abandoned north of it and the Grand Banks experienced only thermal subsidence from mid- into the Late Jurassic.

The tectonic history of the Newfoundland margin is marked by four periods of subsidence and two main periods of regional uplift (Figure 2.2 from Enachescu, 1987).

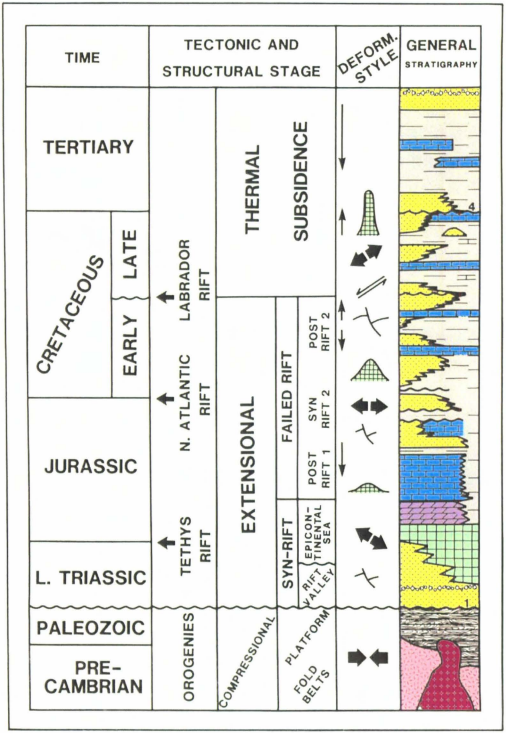

Figure 2.2: Composite chart showing relationship between geological time, tectonic and structural stages, deformation style and simplified stratigraphy for the Newfoundland continental margin. Modified from Enachescu (1987).

Initial rifting with extension in the NW-SE direction began in Late Triassic to Early Jurassic and was followed by a period of subsidence in the Early to Middle Jurassic. A second phase of rifting in the Late Jurassic to Early Cretaceous was initiated by updoming of the Grand Banks and had a NE-SW direction of extension, causing oblique slip and local transpression on the earlier faults (Louden, 2002). Mid Cretaceous unconformities are related to the breakup of the Grand Banks first from Iberia and then from the Irish margin. East of Newfoundland the trend of basement structures swings from the NE-SW to N-S expressing mid-Cretaceous separation of Europe from North America (Grant and McAlpine, 1990).

The Labrador Sea is a northwestward extension of the North Atlantic Ocean, from the Charlie-Gibbs fracture zone in the south, to the Davis Strait in the north. Rifting and breakup of these margins began in the Early Cretaceous and ended during the Late Cretaceous (Louden, 2002). During Late Cretaceous crustal separation was achieved between the Labrador Shelf and Greenland. The North Atlantic spreading axis rapidly propagated into the Labrador Sea, causing the rotation of Greenland relative to the North American Craton (Ziegler, 1989). Rifting occurred during early Cretaceous with deposition of the synrift Bjarni Formation. Active rifting ended with the deposition of marine shales of the postrift Markland Formation in the Late Cretaceous. Seafloor spreading in the Labrador Sea began in the Early Tertiary and continued to the Late Eocene at which time the syndrift sediments of the Gudrid Member (sandstone), Cartwright Formation (shale), Kenamu Formation (shale) and the Leif Member (sandstone) were deposited. The Labrador arm of the north Atlantic failed in the Late Eocene-Early Oligocene and the spreading axis shifted to the Greenland-European

margin. The postdrift sediments in the Labrador basins were deposited at the time of rift extinction from the Eocene to present and are made up the Mokami Formation and the Saglek Formation (Martin *et al.*, 2006).

Between the Grand Banks and the Charlie Gibbs fracture zone the Avalon terrane is dissected into a 450 km wide tract of rift basins that collectively form the broad Orphan Basin (Tankard and Welsink, 1989). The Orphan Basin has undergone repeated extensional episodes, each followed by a period of thermal subsidence. The final postrift stage is marked by rapid subsidence since the Eocene (Enachescu *et al.*, 2005). With each new stage, rifting moved landward and re-mobilized previously formed structural and tectonic features of the basin. Based on the age of the main rifting stages, the Orphan Basin can be divided into two sub-basins: the East Orphan and West Orphan basins. The upper crust of the basin was stretched by brittle extension on numerous regional and local basement involved faults and on several crustal penetrating detachments. The basin represents and area of thinned and foundered continental crust with stretch factors greater than 0.5 over most of the area (Keen and Dehler, 1993; Chian *et al.*, 2001). Long lasting extension with multiple slow rifting stages may explain the extremely thinned upper crust of the basin, the large area affected, the striking succession of ridges and troughs, a lack of volcanic features, the decrease in depth to the mantle due to lithospheric thinning by extension, and the great amount and rapid rate of thermal subsidence during the final (Tertiary) postrift stage. Strike slip in a transtensional regime and oblique reactivation of successive rift structures also caused the structural complexity with the East Orphan Basin.

2.3 Stratigraphy and Mesozoic Basin Development

The areas comprising the continental shelves of Norway, UK, Ireland, Greenland and Newfoundland were connected from the Late Paleozoic through to Early Cretaceous times (Ziegler, 1988) (Figure 2.3).

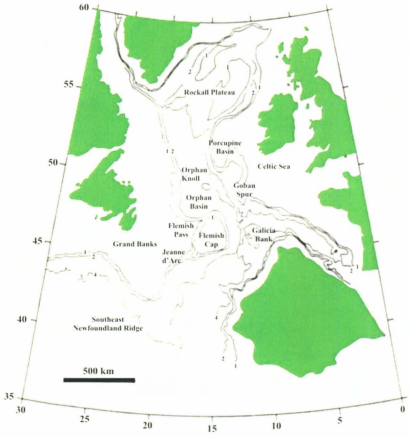

Figure 2.3: Earliest Cretaceous North Atlantic reconstruction illustrating relative positions of North Atlantic sedimentary basins immediately prior to onset of sea floor spreading. Bathymetric contours in kilometers. (Modified from Masson and Miles, 1986).

The rifting stages, occurring in the Permo-Triassic, Late Jurassic-Early Cretaceous and mid Cretaceous, affected the Jeanne d'Arc, Orphan and Porcupine basins and a broadly common lithofacies pattern occurs with and between the basins (Williams *et al.*, 1999). Paleogeographical reconstructions (Masson and Miles, 1986) show that these basins were in the same vicinity during the Late Jurassic and Early Cretaceous times prior to the final Atlantic breakup in the mid Cretaceous (Figure 2.3).

2.3.1 Orphan Basin

The geologic evolution of the Orphan Basin is similar to that of the adjacent Jeanne d'Arc and Flemish Pass basins, and that of the Porcupine Basin, which lies off the west coast of Ireland (Smee *et al.*, 2003).

A formal stratigraphic characterization of the Orphan Basin has not been compiled as very few wells have penetrated a full Cretaceous and Jurassic section, and as such, the Jeanne d'Arc stratigraphy is often used in describing the stratigraphy of the Orphan Basin. Based on seismic stratigraphic analysis, Enachescu *et al.* (2005) concluded that the Orphan Basin was subjected to four major intra-continental rifting stages lasting over 160 Ma (Figure 2.2). The basin fill started with an initial lacustrine stage and followed by a marine stage with reduced evaporite deposition. Intra-continental rift fill and intervening thermal subsidence was coeval with the stepped opening of the North Atlantic Ocean and rifting during the two phased detachment of Greenland from its continent-size neighbours (Enachescu *et al.*, 2005).

The basin was initially a Paleozoic sedimentary platform (Avalon Terrane). The prerift basement of the platform is composed of Precambrian metamorphic, Paleozoic meta-sedimentary and igneous rocks. The Precambrian rocks are a component of the Avalon Terrane of the Appalachian Orogen (Williams and Hatcher, 1983). The Paleozoic rocks, which range in age from Cambrian to Devonian are 5 to 8 km thick (King *et al*, 1985 and King *et al*., 1986). This Paleozoic sedimentary platform was subjected to Triassic rifting only in its eastern side, East Orphan Basin (Enachescu *et al*., 2004 a, and Enachescu *et al*., 2004b). The initial narrow rift projected northeastward from the Jeanne d'Arc Basin, expanded during the Late Triassic – Early Jurassic and deepened during the Mid Jurassic. A new extensional stage started in the Late Jurassic. To the south the East Orphan Basin was connected to the Jeanne d'Arc and Flemish Pass basins of the Grand Banks, while to the north it was attached to the Porcupine Basin and the south-eastern sectors of the Rockall Trough (Enachescu *et al.*, 2005; Kearsey and Enachescu, 2005b). The rifted area was bordered landward by the White Sail Fault, a likely continuation to the north of the Jeanne d'Arc Basin's Murre-Flying Foam Fault lineament (Enachescu *et al*., 2004 a). This fault and its imbricates had a critical role in the initiation of the Late Triassic rifting and developed into the basin bounding fault for the East Orphan basin. The future West Orphan Basin was still an elevated part of the continent, forming the western rift shoulder, and was the likely provenance for the alluvial and lacustrine sediments deposited during the early rift phase. Additional sediments were supplied locally from the erosion of the numerous rotated basement highs. It is possible that several polarity changes of the bounding fault occurred during this stage; however, they have been modified and obscured by later rift stages (Enachescu *et al*., 2005).

Rifting was followed by thermal subsidence, marine invasion and the deposition of a mixed evaporite sequence with intercalations of clastic beds. The stratified evaporite interval is seismically interpreted based on regional basin correlations and has different characteristics when compared to the coeval, Argo Salt sequence of the Scotian and Grand Banks basins (Enachescu *et al.*, 2005). During the Late Triassic to Early Jurassic, several lateral and parallel rift branches existed alongside the main Jeanne d'Arc-East Orphan-Porcupine rift zone connected to the southern European basins.

After a long thermal subsidence stage, the newly formed Orphan rift basin was reactivated, enlarged and developed during the Late Jurassic-Early Cretaceous Atlantic rift phase (Enachescu *et al.*, 2005). During this time the Grand Banks basins and the East Orphan Basin continued to deepen and expand. New faults formed and syn-tectonic deformation occurred. Transtension due to rotation of the extensional vector from a NW-SE to an E-W direction took place (Enachescu *et al.*, 2005). The basins on the future Canadian continental margin were still connected to basins that would form part of the European margin (Porcupine, Rockall and Lusitania basins). Some local highs within the larger basinal area were already emergent and developed into proximal sediment sources as proven by the sampling of Bajocian-aged alluvial sands on the Orphan Knoll by DSDP site 111 (van Hinte *et al.*, 1995). After the termination of early intracontinental rifting which fragmented the area into connected subbasins bounded by major faults, a period of regional thermal subsidence followed (Enachescu, 1987b and 1988).

During the Kimmeridgian, a broad but shallow epicontinental sea extended from Nova Scotia into northern Europe and developed beyond the boundaries of the initial rift basins (Sinclair *et al.*, 1992). The organic rich sediments deposited in this sea are the

most significant oil source rocks in the basins and are the source for the oil found in the Hibernia, Terra Nova and White Rose Fields in the Jeanne d'Arc Basin and the Connemara field in the Porcupine Basin. The quality of the marine, oil-prone source rock may differ with the size, shape and depth of the individual basins and subbasins and with their location relative to the developing Atlantic (Enachescu *et al.*, 2005). It is possible that arms of this Late Jurassic sea occasionally extended to the northwest into the proto-Labrador sear rift (Sonderholm *et al.*, 2003; Enachescu, 2006a).

The Grand Banks separated from Iberia starting in the Berriasian. Separation was likely completed on three different segments, advancing from south to north. This last rift stage, which occurred in the Aptian, separated the Flemish Cap from the Galicia Bank (Enachescu *et al.*, 2005). In the Early Cretaceous a major triple junction was active northeast of the Flemish Cap (Figure 2.4). The three rift branches were, south (Grand Banks/Iberia branch), east (Bay of Biscay branch) and northwest (Flemish Cap-Labrador branch) (Verhoef and Srivastava, 1992; Sibuet *et al.*, 2007).

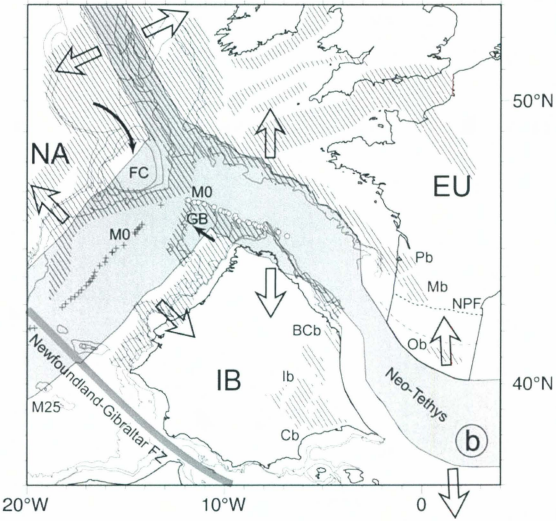

Figure 2.4. Reconstruction of the North Atlantic Ocean between Africa, Iberia (IB) and North America (NA) at chron M0 with respect to Eurasia (EU). Calculated amount of extension between M25 and M0 (Late Jurassic-Early Aptian) in gray. The parameters used are those from Verhoef and Srivastava (1992) for M25 and from Srivastava *et al.*, (2000) for M0. Transparent arrows show M25-M0 directions of plate motions. Hachured lines show continental shelf basins and continental margins. Black arrows indicate rotation of Galicia Bank (GB) and Flemish Cap (FC) during this period. BCb = Basque-Cantabrian basins, Cb = Catalan basin, Ib = Iberian basin, Mb = Mauléon basin, NPF = North Pyrenean fault, Ob = Organyà basin, Pb = Parentis basin. Reproduced from Srivastava *et al.* (2000).

Extension and minor transtension continued during the Labrador rift stage in the Orphan Basin. During this extensional stage, Greenland separated from Labrador, Cretaceous basins took shape on both the Canadian and European continental margins, and the Orphan Basin began to separate from its Irish conjugate basins (Rockall and Porcupine basins). During the Cretaceous, the western rift shoulder migrated westward beyond the White Sail Fault, as a new sector of the Bonavista Platform was involved in rifting and an incipient Early Cretaceous basin, West Orphan Basin, developed (Enachescu *et al*., 2004). As rifting progressed westward, several successive Early Cretaceous sedimentary troughs were formed, dissecting the stretched Paleozoic platform. This area, lying just east of the Blue H-28 well, became the older part of the West Orphan Basin.

At this time, the Orphan Knoll, Central Orphan High and main intra-basinal ridges began to emerge as elevated basinal features provided local sediment sources. A widespread Albian-Aptian erosional unconformity (Southern Grand Banks Avalon/mid-Cretaceous unconformity) is also interpreted across the Orphan Basin (Enachescu *et al*., 2005). In the Orphan Basin this unconformity marks the end of the Aptian-Albian Labrador rift stage. This extensive erosional event occurred as a result of regional uplift associated with the final continental breakup around the Grand Banks and the onset of continental drift in this North American segment (Enachescu *et al*., 2005). To the north, several intra-continental rift basins were present between the future Labrador and Greenland continental masses.

The Orphan Basin began to separate from the West Ireland basins at the end of the Albian and continued thoughout the early Late Cretaceous. The West Orphan Basin, west

of Blue H-28, formed during this stage and was connected with the newly formed basins on the Labrador shelf. Numerous parallel ridges and troughs were formed throughout the West Orphan Basin. The troughs deepened as a result of thermal subsidence and were filled with mainly siliciclastic sediments. Local strike-slip movement caused significant deformation of earlier Mesozoic structures and probably of older Paleozoic erosional remnants present in the East Orphan Basin as the Flemish Cap continued to move away from the basin in a southeast direction (Enachescu *et al.*, 2005).

A renewed episode of extension occurred during the Late Cretaceous-Early Tertiary (Enachescu *et al.*, 2005). The locus of this extension was the region between Labrador and Greenland and Greenland and northern Europe, which was also affected by the west Greenland volcanic event and the formation of the Iceland hot spot. On the Grand Banks, rifting was mainly focused in the westernmost part of the West Orphan Basin (Enachescu *et al.*, 2005). Certain basin structural highs were strongly reactivated with Jurassic and Cretaceous sedimentary successions and probably older beds being strained by transtensional movements and forced to move upward on the reactivated fault planes from the subbasins on top of rotated basement blocks.

Block movements and rift reactivation continued in the Orphan Basin at least to Paleocene time, principally influenced by the continuing separation of Greenland from Labrador and by the separation of Greenland from northern Europe (Enachescu *et al.*, 2005). In the West Orphan Basin, extension caused several rotated blocks to form during this stage. Typically these have no preserved Mesozoic sediments, or only a thin, condensed, Late Cretaceous cover as intersected by wells drilled in the area (i.e. Blue H-28, Bonavista C-99, Baie Verte J-57, Cumberland B-55, Hare Bay E-21, Linnet E-63 and

Sheridan J-87). Extreme erosion of these blocks took place during the middle to Late Cretaceous-Early Tertiary. Since the Early Tertiary, the entire basin and its outer ridge, the Orphan Knoll, have undergone rapid subsidence and foundering in the deeper Atlantic waters. The East Orphan Basin remains, to a great extent, under-filled with sediment during the Tertiary to recent time; however, the Late Cretaceous to Late Tertiary sedimentary cover should provide sufficient seal for older structures if comprised of marine shales (Enachescu *et al.*, 2004, Hardy and Enachescu, 2004 and 2007). In contrast, the West Orphan Basin has a thick section of post-Paleocene sediments including shelf-prograding and marginal-fan sequences related to the postrift subsidence.

The synrift sedimentary fill becomes younger in a landward direction (Enachescu *et al.*, 2005). In the west large, north-south trending basement ridges are sediment poor or devoid of sediment. Intervening deep troughs were identified on seismic data and clearly correlated with their respective potential field signatures (Kearsey and Enachescu, 2005b). Based only on evaluated the tectonic extension, with no correction applied for fault-plane erosion, the Orphan Basin has an average stretching factor of 2.5 from the Late Triassic to Early Tertiary (Enachescu *et al.*, 2004). Many of the uplifted blocks in the western part of the basin have flat tops, indicating large-scale erosion during the Late Cretaceous-Early Tertiary, when they were sub-aerially exposed. A higher average stretching factor, greater than 4, is computed only if the older East Orphan Basin is considered (Enachescu *et al.*, 2005). As a result, the upper continental crust under the Orphan Basin is more than double its length in the dip direction (west-northwest/east-southeast) compared with the initial prerift Appalachian crust. Many of the major faults are believed to penetrate deep into the crust; however, this cannot be reliably interpreted

on the 2D seismic grid. There are significant variations in the Moho's position along the margin indicating that the lower crust has probably been extended by a combination of ductile and brittle extension (Keen *et al*., 1987; Keen and Dehler, 1997; Louden, 2002).

2.3.2 Jeanne d'Arc Basin

The Jeanne d'Arc Basin is bounded by the Murre and Mercury listric normal faults to the west, the Avalon Uplift to the south, the Bonavista Platform to the west and the Cumberland Transform Zone to the north (Figure 2.5).

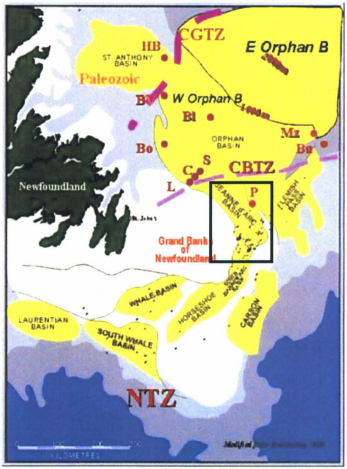

Figure 2.5: Location of Jeanne d'Arc Basin (black box). Annotations CGTZ – Charlie Gibbs Transform Zone, CBTZ – Cumberland Belt Transform Zone, NTZ – Newfoundland Transform Zone. Modified from Enachescu (2000).

The structural and stratigraphic development of the Jeanne d'Arc Basin has been discussed by a number of authors (Enachescu, 1986 and 1987; Keen *et al*., 1987; Tankard and Welsink, 1989; Driscoll *et al*., 1995) and a summary of the stratigraphy, with specific focus on the Late Jurassic and Cretaceous sequences as they relate to rift episodes, is presented. The lithostratigraphic chart presented here is in use by the CNLOPB and its nomenclature is based on that of Deptuck *et al*., (2003), McAlpine (1990) and Sinclair (1988) (Figure 2.6).

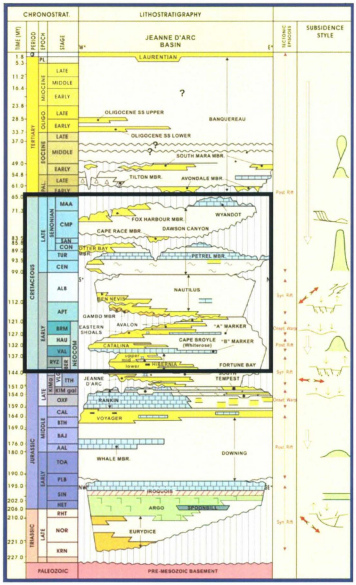

Figure 2.6: Lithostratigraphy of the Jeanne d'Arc Basin. Cretaceous stratigraphy outlined in black box. Reproduced from the C-NLOPB Call for Bids (2004), after Deptuck *et al*., (2003), McAlpine (1990) and Sinclair (1988).

The Jeanne d'Arc Basin is a Mesozoic sedimentary basin which represents 3 failed rifts related to the opening of the present North Atlantic Ocean (Enachescu, 1987; Grant and McAlpine, 1990) followed by late Cretaceous and Tertiary thermal subsidence. The Cretaceous sequences were deposited during the synrift and postrift phases of the Early Cretaceous Atlantic rift and during the onset warp, synrift and early postrift phases of the mid to Late Cretaceous Labrador rift.

East-west extension of the Early Cretaceous rift event formed north-south grabens and half grabens in which sandstones, conglomerates and shales of the Upper Jurassic Jeanne d'Arc Formation were deposited (Sinclair, 1988). These sandstones were transgressed and capped by the shales of the Early Cretaceous Fortune Bay Formation during a flooding event at the end of the Tithonian. Renewed uplift of the clastic source area caused the deltaic progradation of the Hibernia sandstones. The lower Hibernia Formation consists of stacked delta channels which prograded across the southern Jeanne d'Arc Basin in the Berriasian, while the upper Hibernia Formation represents a second cycle of deltaic sedimentation sourced from the southeast (Sinclair, 1988). The postrift sediments consist of the B Marker limestone of the Whiterose Formation followed by a minor interval of thinly interbedded shales and calcareous progradational sandstones the Catalina Member. These sediments were then covered by the thick Hauterivian shales of the Whiterose Formation (Sinclair, 1988).

Uplift at the beginning of the third rift episode (Late Cretaceous) produced the Late Barremian/Early Aptian unconformity. The Barremian A Marker member of the Avalon Formation consists of thick limestones overlain by shales and coarsening upward sandstones of the Avalon Formation, deposited during the regression related to this uplift

(Sinclair, 1988). Fine-grained rift sediments deposited by a fluvial system deposited the fining upward, transgressive Aptian-Albian Ben Nevis Formation. Syn-depositional growth on listric and low angle faults occurred during this rift period, creating northwest-southeast trends and resulted in the tilting of fault blocks that created most of the structures that contain hydrocarbons in the Jeanne d'Arc Basin (Sinclair, 1988). The postrift is marked by the Cenomanian unconformity whereby flat-lying Cenomanian to Turonian marls and Petrel Member limestones overlie tilted lower Cretaceous Hibernia Sandstones (Sinclair, 1988). Coarse grained Otter Bay and Fox Harbour sandstones prograded eastward off the Bonavista Platform and are overlain by the Upper Cretaceous limestone and chalk Wyandot Member and Dawson Canyon shales (Sinclair, 1988).

2.3.3 Porcupine Basin

The Porcupine Basin is a north-south oriented Mesozoic to Cenozoic sedimentary basin on the continental shelf, 200 km west of Ireland (Robinson and Canham, 2001). It is one of a series of Atlantic borderland basins that developed with a tectonostratigraphic framework related to the opening of the North Atlantic Ocean. The basin is bounded on three sides by relatively shallow shelf platforms: to the north by the Slyne High, to the west by the Porcupine High, to the east by the Irish Mainland Shelf and merges with the Goban Spur to the south (Smith and Higgs, 2001) (Figure 2.7). These platform areas underwent long periods of uplift and erosion throughout the Mesozoic and are likely to have provided a significant source for clastic sediment deposition into the basin (Robinson and Canham, 2001). The stratigraphy of the Porcupine Basin has been

discussed by numerous authors and a stratigraphic chart from Robertson and Canham (2001) is shown in Figure 2.8.

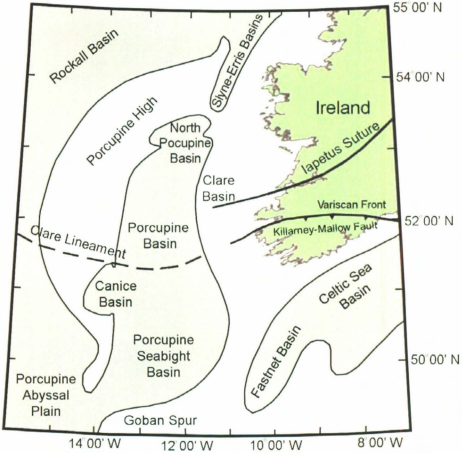

Figure 2.7: Location of Porcupine Basin. Grey areas represent sedimentary basins. Map modified from Johnson *et al.* (2001).

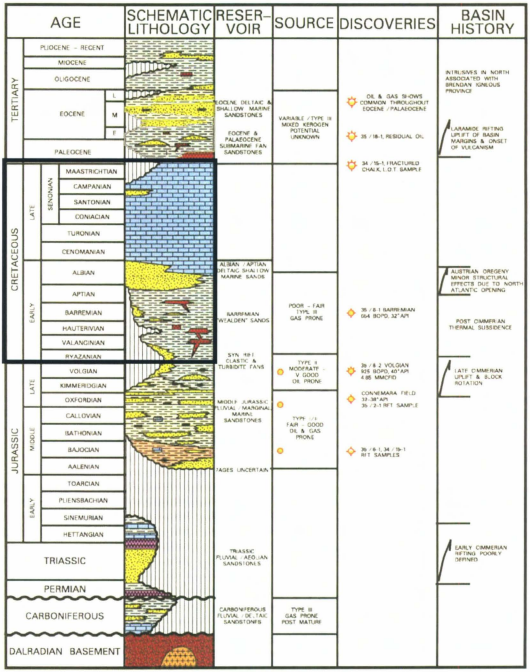

Figure 2.8: Generalized stratigraphy, lithology and tectonic history of the Porcupine Basin, indicating major unconformities, reservoir and source rock intervals and hydrocarbon discoveries. Cretaceous stratigraphy outlined with black box. Reproduced from Robinson and Canham (2001).

The base of the Late Jurassic-Early Cretaceous rift succession is generally marked by an unconformity overlain by fluvial to marine clastics and occasional carbonates which provide an important set of reservoirs and the richest source rocks in the basin. The thermal subsidence phase is marked by Valanginian to Early Aptian shales which drape the fault topography (Williams *et al*., 1999).

The mid Cretaceous rift succession is characterized by deltaic, shoreface and marine strata. A thick, regressive succession of mid Aptian to Albian sandstones occurs within the Porcupine Basin. This succession overlies a thin paralic to shallow marine sequence of progradational delta plain, distributary mouth bar and shoreface sandstones. Thermal subsidence resumed in earliest Cenomanian times and relative sea level rise was enhanced by the onset of seafloor spreading between Newfoundland and the European continental shelves (Hubbard *et al*., 1985; Sinclair, 1988). A thick succession of Upper Cretaceous deep marine limestones and marls onlapped and covered the residual fault block topography and overstepped the basin margins.

2.4 Structure and Basinal Features

The structural architecture of the Orphan basin is dominated by elongated ridges and subbasins formed by large normal faults (Enachescu *et al*., 2005). These ridges are oriented northeast-southwest in the East Orphan Basin and north-south in the West Orphan Basin. Several of these ridges are comparable in size to the Central Ridge and the associated sub-basins are as large, or larger than the Jeanne d'Arc Basin (Enachescu,

1987; Enachescu *et al.*, 2004 c). The Base Tertiary Unconformity truncates some of these ridges, while others rise above it.

In the West Orphan Basin and western side of the East Orphan Basin many of the basement ridges are capped by interpreted Paleozoic meta-sediments and some blocks are overlain by thin Mesozoic units (i.e. Blue H-28). These basement blocks are large, between tens and hundreds of kilometers long, some with structural closures of 200-400 km^2 (Enachescu *et al.*, 2005). The tops of the rotated basement blocks have been intensely eroded by the Base Tertiary Unconformity and a peneplain surface can be reconstructed by connecting the Bonavista Platform and eroded tops of the ridges, indicating subaerial erosion took place in this basin during the Labrador rift stage (Early Cretaceous-Late Early Cretaceous). Significant uplift of the West Orphan Basin took place during this rift stage. Block rotation and erosional periods, followed by subsidence and tilting have affected the tops of these blocks (Enachescu *et al.*, 2005). The troughs separating these large basement ridges are shallower near the Bonavista Platform and become increasingly deeper towards the east. Troughs adjacent to the Orphan High have 5-7 km of sediments, likely preserving a complete Cretaceous sedimentary record (Enachescu *et al.*, 2005).

In the East Orphan Basin, some of the basement ridges (and their basinal flanks) have a thick, sedimentary cover containing thick Cretaceous and Jurassic sequences. These sequences are frequently folded in the downthrown direction of major extensional faults, forming large, anticlinal structures and drape folds in the overlying Paleocene strata (Enachescu *et al.*, 2005). Most of these extensional anticlines were modified by inversion due to transtension. The Cretaceous sequences are intensely segmented by

dense, normal faulting. While salt relationships are extremely important on the Scotian Margin and in the Jeanne d'Arc Basin, there is no clear diapirism observed north of the Cumberland Belt Fault Zone. If there is salt present in the East Orphan Basin, it is likely in a stratified form, similar to evaporite and salt sequences observed in the Porcupine Basin (Enachescu *et al.*, 2005). This early synrift evaporite sequence creates an important detachment surface for the overlying sedimentary sequences in the East Orphan Basin.

Minor volcanic activity is identified on the 2D seismic data set. Several strong-amplitude anomalies, interpreted as sills or lava flows, are seen at the mid to Late Cretaceous level in the East Orphan Basin. The absence of widespread volcanic features confirms the non-volcanic origin of the Orphan Basin (Keen *et al.*, 1987; Chian *et al.*, 2001; Louden, 2002; Enachescu *et al.*, 2004c).

Chapter 3

Seismic Stratigraphy

3.1 Introduction

Within the study area six seismic sequence boundaries were identified and defined using well control, regional correlations and seismic stratigraphic principles. These boundaries have been labeled: Bsm, K1, K2, K3, T and WB and delineate five seismic sequences: S1, S2, S3, S4 and S5. The sequence boundaries were defined and mapped in time (TWT) using the 2D seismic grid.

This chapter contains a seismic stratigraphic analysis of the six sequence boundaries and the five seismic stratigraphic sequences, with a detailed account of the Cretaceous sequences within the basin (S1-S4).

3.2 Well Control

Well control in the Orphan Basin is extremely sparse with six wells located on the shelf in the West Orphan Basin and one, Blue H-28, located in the deepwater, eastern part of the West Orphan Basin. Blue H-28 is the critical well for the central-eastern part of the Orphan Basin (Koning *et al.*, 1988; Enachescu *et al.*, 2005 and 2006). There were no wells drilled in the ultra-deep water; however, at the time of this thesis submission, Great Barasway F-66 was finished drilling in the East Orphan Basin in 2340m water depth (Enachescu *et al.*, 2006 and Figure 3.1). No results from this well will be public until 2009. There are three other wells of interest located in adjacent areas to the basin,

including Mizzen L-11, Baccalieu I-78 in the Flemish Pass Basin and Panther P-52 in the northern Jeanne d'Arc Basin.

The lack of wells in the deep water makes correlation of events from the West Orphan Basin wells into the East Orphan Basin extremely difficult and jump correlations had to be made from neighbouring Flemish Pass and northern Jeanne d'Arc wells.

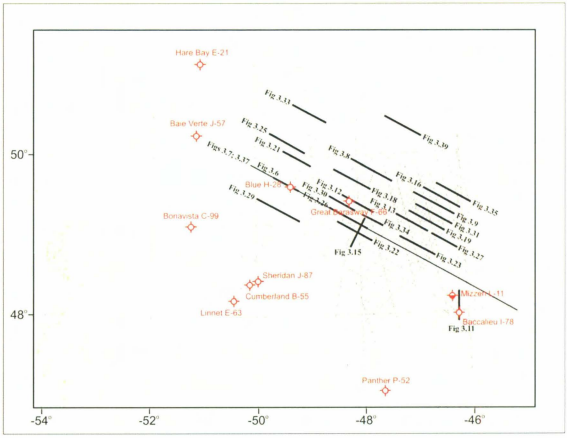

Figure 3.1: Basemap of the Orphan Basin showing 2D seismic grid, well and figure locations. Additional wells used in this study are Mizzen L-11 and Baccalieu I-78 located in the Flemish Pass Basin and Panther P-52 located in the northern Jeanne d'Arc Basin. At the time of thesis submission the Great Barasway F-66 well was drilled but no data is publicly available. Coordinates are in NAD 83.

Early exploration targets in the 1970s and 1980s were large structural highs identified by mapping of the Base Tertiary Unconformity, the deepest resolvable event at that time (Smee *et al*., 2003; Enachescu *et al*., 2004 a and b). Some of the drilled highs were seismically interpreted as large reefs, but all of the early Orphan Basin wells were drilled into rotated basement blocks and encountered thin Mesozoic cover. In contrast, the Flemish Pass Basin (Mizzen L-11 and Baccalieu I-78) and the northern Jeanne d'Arc Basin (Panther P-52) wells penetrated significant thicknesses of Cretaceous sandstones and shales as well as Kimmeridgian source rocks.

The C-NLOPB (http://www.cnlopb.nl.ca) and the GSC Atlantic BASIN (www.gsca.nrcan.gc.ca/BASIN) provide information on all publicly available wells in the Newfoundland offshore area. The information includes: Spud Date, Location (NAD83), classification, datum, total depth and current status. Also available are the casing depths, conventional cores, tests and geological tops. For consistency, the C-NLOPB geological tops were loaded into the Landmark® system and were used in this study.

3.2.1 Well Information

For each well in the study area, the well header, well location, elevation datum and total depth information were obtained from the Canadian Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) Schedule of Wells (2003) and were loaded into Seisworks®. Table 3.1. is a summary of the information used.

Well Name	Location (NAD83)		Elevation (m)	Total Depth (m)
	Latitude	Longitude		
Bonavista C-99	49° 08′ 06.16″ N	51° 14′ 24.21″ W	12.2	3779.0
Cumberland B-55	48° 24′ 12.21″ N	50° 07′ 54.49″ W	29.9	4136.5
Blue H-28	49° 37′ 26.49″ N	49° 17′58.18″ W	14.7	6103.0
Hare Bay E-21	51° 10′ 21.80″ N	51° 04′ 23.30″ W	24.2	4874.0
Sheridan J-87	48° 26′ 39.56″ N	49° 57′ 35.30″ W	29.7	5486.4
Linnet E-63	48° 12′ 29.27″ N	50° 25′ 22.28″ W	27.1	4520.2
Baie Verte J-57	50° 16′ 43.58″ N	51° 07′ 49.77″ W	25.0	4911.0
Panther P-52	47° 01′ 53.01″ N	47° 37′ 39.81″ W	22.0	4203.2
Baccalieu I-78	47° 57′ 41.49″ N	46° 10′ 46.76″ W	23.7	5135.0
Mizzen L-11	48° 10′ 31.75″ N	46° 17′ 35.55″ W	23.8	3820.0

Table 3.1: List of wells in Orphan, northern Jeanne d'Arc and Flemish Pass basins. Location, elevation and total depth information obtained from the C-NLOPB Schedule of Wells (2003).

3.2.2 Time-Depth Information

Time-depth information was obtained from checkshot surveys and sonic logs, made available by the C-NLOPB. From north to south the wells used are: Hare Bay E-21, Blue H-28, Bonavista C-99, Sheridan J-87, Cumberland B-55, Linnet E-63, Baccalieu I-78 and Panther P-52 (Figure 3.1). There was no data available for Baie Verte J-57 or Mizzen L-11. The time-depth data for the available wells shown in Appendix A was plotted using Microsoft Excel® and a polynomial regression line was fitted to each data set (Figure 3.2). The graph shows two clusters of time depth curves. Those wells drilled on the Bonavista Platform in shallow water plot together and Blue H-28, drilled in deep water, and Mizzen L-11, drilled in the Flemish Pass plot together.

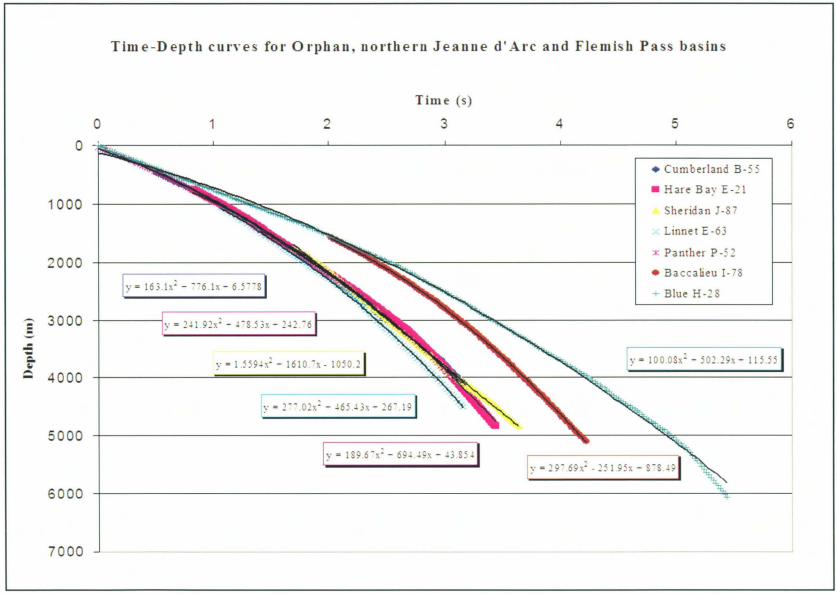

Figure 3.2: Time-depth curves for wells in the Orphan, northern Jeanne d'Arc and Flemish Pass basins. Derived from C-NLOPB checkshot and sonic (Blue H-28) data.

3.2.3 Well Picks and Seismic Markers

Several formation picks compiled by government research groups and individual researchers exist for the Orphan Basin. For consistency, the picks provided by the C-NLOPB Schedule of Wells (2003) were used in this study to correlate formation tops with seismic events. The formation tops were loaded into Landmark® and are listed in Table 3.2. A geological cross-section was created through the wells in the Orphan Basin (Figure 3.3) and has been modified from the C-NLOPB Call for Bids NF-01 (Smee, 2003).

In instances where no Orphan Basin well intersected a mapped horizon (as is the case with the Lower Cretaceous, Jurassic and Triassic markers) seismic markers were jump correlated from the Baccalieu I-78 well in the Flemish Pass Basin. Figure 3.4 is a schematic diagram summarizing the ages and lithostratigraphic affinities of each interpreted seismic event and the degree of confidence in the ability to regionally map these markers. The template for this figure was modified from Enachescu *et al*. (2000) and Young (2005) and the lithostratigraphy was reproduced from C-NLOPB (2003). No formal stratigraphic chart exists for the Orphan Basin, so the stratigraphy of the adjacent Jeanne d'Arc Basin (C-NLOPB, 2003) was used to interpret major sequence boundaries and unconformities. The criteria used to define seismic marker quality are as follows: Excellent – strong continuous event easily mappable across entire basin; Good – fairly strong, mainly continuous event, easily mapped in most parts of the basin; Fair – event is moderately strong in places, weak in others, fairly easily mapped in basinal areas, ambiguous over local highs; Poor – very weak, highly interpretive event.

Well	WD (m)	Formation	Tops (m)
Baie Verte J-57	303.2	Base Tertiary Unconformity Dawson Canyon Fm Fox Harbour/Otter Bay Mb	3964 3964 3964 - 4667
Blue H-28	1486.0	Base Tertiary Unconformity Dawson Canyon Fm Fox Harbour/Otter Bay Mb fault or unconformity Carboniferous	4910 4910 4910 - 5124 5281 5281
Bonavista C-99	329.2	Base Tertiary Unconformity Dawson Canyon Fm Fox Harbour/Otter Bay Mb limestone maroon shale Cenomanian Unconformity Basement (granite pegmatite)	3628.5 3628.5 3634.5 - ? 3652 3676 3679 3679
Cumberland B-55	194.8	Base Tertiary Unconformity Dawson Canyon Fm Fox Harbour/Otter Bay Mb Cenomanian Unconformity Weathered basement? Basement (metasediments)	3685 3685 3685 3706.5 3706.5 3728
Hare Bay E-21	239.1	Base Tertiary Unconformity Dawson Canyon Fm Fox Harbour/Otter Bay Mb Cenomanian Unconformity Barachois (Pennsylvanian)	3241 3241 3241 - 3362 3398 3398
Linnet E-63	160.0	Base Tertiary Unconformity Dawson Canyon Fm Fox Harbour/Otter Bay Mb Cenomanian Unconformity Nautilus? sandstone & shale shale Basement (metasediments)	2542 2542 2586 2913? 2913 3758 4084 4175
Sheridan J-87	215.8	Base Tertiary Unconformity Dawson Canyon Wyandot Member Petrel Member Cenomanian Unconformity Basement (metasediments)	4509 4509 4539 - 4573 4667 - 4678 ~4857 ~4857

Table 3.2: List of wells and formation tops in study area. Lithology picks from C-NLOPB Schedule of Wells (2003). These picks were loaded into Landmark® software for seismic sequence analysis.

Well	WD (m)	Formation	Tops (m)
Panther P-52	191.4	Base Tertiary Unconformity	2653
		Fortune Bay	2653
		Tithonian Unconformity	2835
		Rankin	2835
		Upper Tempest sandstones	2969
		Upper Kimmeridgian source rock	3256 - 3566
		Lower Tempest sandstones	3576 - 3758
		Lower Kimmeridgian source rock	3794 - 4003
Baccalieu I-78	1092.8	Base Tertiary Unconformity	1706
		Barremian shales and thin limestones	1706
		Avalon equiv.	2120
		Whiterose/Hibernia Upper zone equiv.	2257
		Hibernia Lower zone equiv.	3190
		Fortune Bay equiv.	3274
		Jeanne d'Arc equiv.	3727
		Tithonian Unconformity	3770
		Rankin	3770
		Upper Kimmeridgian source rock	4398 - 4804
		Lower Kimmeridgian source rock	4975
Mizzen L-11	1153	Base Tertiary	2474
		Petrel Equivalent	2501.5-2505.0
		Valanginian Marker	3146.5-3334.5
		Baccalieu	3334.5-3598.5
		Upper Jurassic	3508
		Jurassic SS No 1	3598.5-3742.5
		Jurassic SS No 2	3742.50-3825.0

Table 3.3: List of wells and formation tops in Northern Jeanne d'Arc Basin (Panther P-52) and Flemish Pass Basin (Baccalieu I-78 and Mizzen L-11). Lithology picks from C-NLOPB Schedule of Wells (2003). These picks were loaded into Landmark® software for seismic sequence analysis.

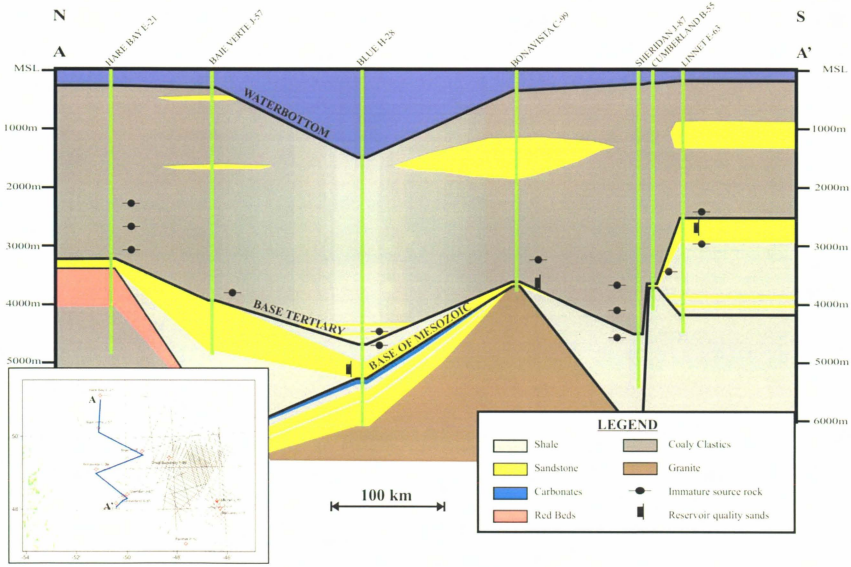

Figure 3.3: Simplified geological cross-section through Orphan Basin wells. Modified from C-NLOPB Call for Bids NF-01 (Smee, 2003).

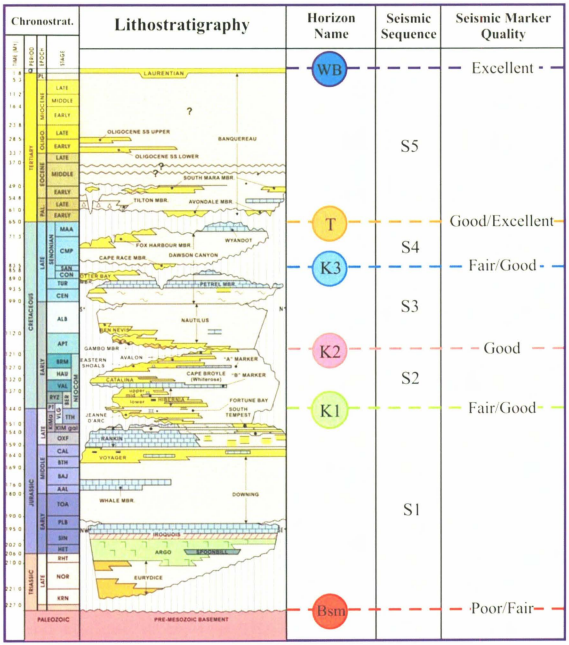

Figure 3.4: Schematic diagram depicting age, formation names, lithology, horizon name, seismic sequence name and quality of each seismic marker. Template modified after Young (2005); Jeanne d'Arc lithostratigraphy from Sinclair (1988) and reproduced from C-NLOPB (2003).

3.3 Seismic Stratigraphy

Seismic stratigraphy, as defined by Mitchum *et al.* (1977) is: "the study of stratigraphy and depositional facies as interpreted from seismic data". It involves the recognition of seismic facies and requires an ability to identify important surfaces (bounding discontinuities). Recognition of termination patterns, such as onlap, downlap, toplap and erosional truncation are critical for the identification of important surfaces that are needed to subdivide the seismically imaged stratigraphic record.

Seismic stratigraphy is made up of three elements: sequence analysis, facies analysis and attribute analysis. Sequence analysis involves subdividing the seismically imaged stratigraphic record based on bounding discontinuities. Facies analysis is focused on determining the specific lithologies of the subdivided units. Attribute analysis is concerned with identifying specific seismic attribute characteristics for each of the units.

Due to the high geological complexity, the regional character of this study and the low resolution of the seismic data displayed for convenience of interpretation at a very squeezed scale, this thesis will focus only on sequence analysis. The 2D nature of the data does not allow for confident horizon attribute analysis to be made.

3.3.1 Cretaceous Structural Regions

Seismic events were correlated over the entire basinal area wherever possible; however, due to complex tectonic and sedimentology histories of the two main sub-

basins (West and East Orphan basins) the quality, confidence and seismic character of these picks are highly variable throughout the study area.

The Cretaceous depocenters in the Orphan Basin were identified in three main areas (Figure 3.5). Area A is defined as the West Orphan Basin and includes the shelfal areas in the west and extends as far east as the Blue H-28 well. Area B is the central part of the Orphan Basin and belongs to the East Orphan Basin previously defined by Enachescu et al. (2004 a and b, 2005 a). Area C is the farther east region of the East Orphan Basin, adjacent to the Flemish Pass Basin and the Orphan Knoll.

Areas B and C were involved in the initial Late Triassic to Early Jurassic event to affect the Orphan Basin and contain complete Mesozoic to Tertiary sequences. Area B was strongly affected by the second rift event (Late Jurassic-Early Cretaceous) that caused reactivation along pre-existing faults, formation of new faults and the inversion of structures. It is the most tectonically complex region of the Orphan Basin. The sequences in this area have experienced multiple phases of faulting, subsidence and uplift and as such, confidence of mapping the main seismic horizons is low. Area A is the youngest area of the Orphan Basin and experienced rifting predominantly during the Late Cretaceous. Sequences mapped in this region include Late Cretaceous to Tertiary successions.

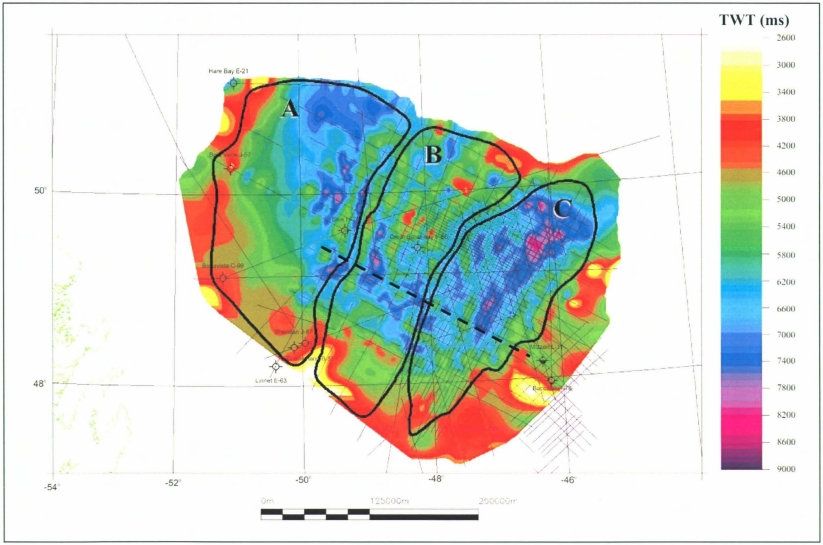

Figure 3.5: Basement time-structure map depicting three distinct Cretaceous depocenters of the Orphan Basin. Three Cretaceous depocenters are defined: A = West Orphan Basin, B = Central part of the basin, C = East Orphan Basin. Dashed black line shows location of Figure 3.7

3.3.2 Bsm Sequence Boundary: Top Basement Marker

For this study, the term seismic basement includes Paleozoic sedimentary and metasedimentary formations and underlying Precambrian metamorphic basement. Top basement is defined by the deepest resolvable event on the seismic data and is used to distinguish the prerift seismic basement from the sedimentary infill deposited during intracontinental rifting and following marine deposition. The basement marker is difficult to resolve due to complex faulting, large spacing between lines and the existence of zones of poor data quality. Paleozoic rocks exist locally but they cannot be easily distinguished from the underlying crystalline basement as the exact boundary between metasedimentary strata and crystalline crust is not associated with a large velocity contrast (Chian *et al.*, 2001; Enachescu *et al.*, 2005). Wherever possible the base of the Paleozoic rocks was picked as the top of the basement (Figure 3.6).

The seismic basement is highly dissected by faults and deepens dramatically from the continental shelf to the slope. The basement also rises gradually seaward toward the Orphan Knoll (Figure 3.6). Within the Orphan Basin all of the wells, with the exception of Baie Verte J-57, drilled into seismic basement. Hare Bay E-21, Blue H-28, Sheridan J-87, Cumberland B-55 and Linnet E-63 bottomed into Paleozoic metasediments, while Bonavista C-99 bottomed into granite pegmatite of the Avalon Terrane (Figure 3.6).

The quality of the Bsm horizon is variable throughout the seismic grid. It is fairly easily picked on the shelf and on basement highs, but difficult to resolve where it plunges at depth, in the intervening grabens or in the deep water (Figure 3.7). The horizon picking confidence is greatest on the basement highs and near well sites and decreases

where the seismic resolution deteriorates. Beneath the Bsm horizon there is little internal structure; however, there are strong events seen within the interpreted basement which may be faults or layers imaged from out of the plane. The Bsm sequence boundary has been dissected by numerous normal listric faults which caused the rotation of fault blocks and the formation of horst and graben structures. On the interpreted seismic sections the top of the Basement sequence boundary is denoted by Bsm and is displayed in red.

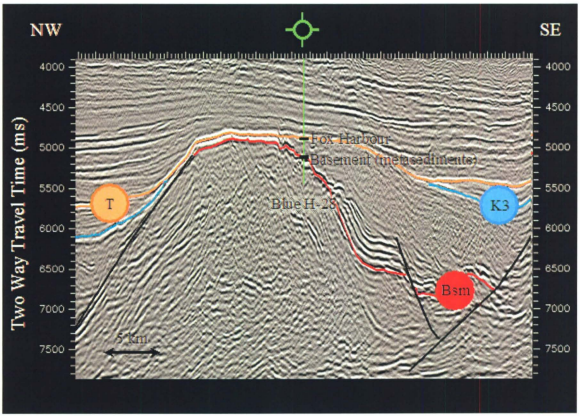

Figure 3.6: Seismic dip section showing seismic horizons tie at the Blue H-28 well. Stratigraphic picks are from the C-NLOPB Schedule of Wells (2003). T marker is the Base Tertiary unconformity (orange), K3 is an upper Cretaceous marker (blue) and Bsm marker is the Paleozoic seismic basement (red). Location shown on Figure 3.1.

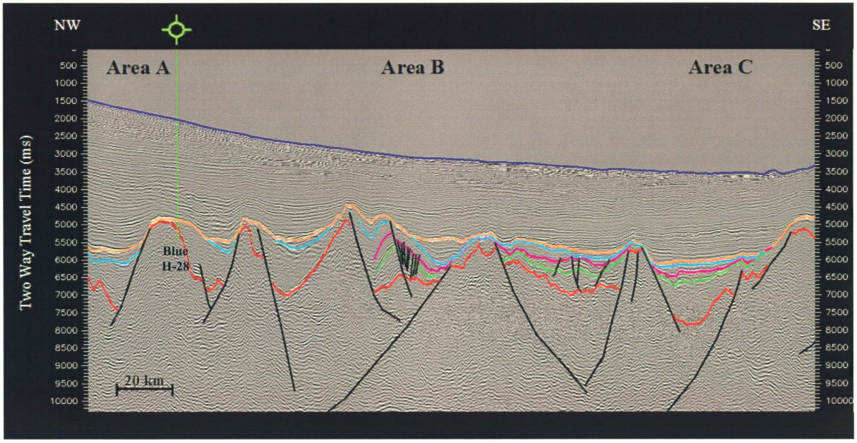

Figure 3.7: Seismic section (dip) across Orphan Basin showing structural setting and seismic character of the basement. Seismic markers are red: seismic basement; green: base Cretaceous; pink: mid Cretaceous unconformity; light blue: upper Cretaceous (Santonian) unconformity; orange: Base Tertiary unconformity, dark blue: Water Bottom. Areas A, B and C and line location are shown in Figures 3.1 and 3.5.

3.3.3 Seismic Sequence S1

Seismic sequence S1 is defined by the Bsm sequence boundary below and the K1 sequence boundary above and corresponds to the synrift basin fill that may contain Triassic and Jurassic aged sediments directly overlying the prerift basement. As the scope of this thesis focuses on describing the Cretaceous sequences, no attempt was made to distinguish or define pre-Cretaceous sequences. Redbed sandstones, shales and evaporites equivalent to the Eurydice, Osprey, Argo and Iroquois formations of the Jeanne d'Arc Basin, may overlie the basement in the deepest depocentres of the East Orphan Basin. No salt diapirs are seismically imaged in this basin; however, Triassic stratified evaporites have been suggested to be present in the East Orphan Basin (Enachescu *et al*., 2005).

The S1 sequence has limited areal extent and is restricted to the earlier part of the Mesozoic rifted area – the East Orphan Basin (Areas B and C). This sequence is not present in the West Orphan Basin (Area A), as this sub-basin was not involved in the Late Triassic-Early Jurassic rift event. At the time of S1 deposition, Area A made up the western shoulder of the East Orphan Basin and was likely a major sediment source area for the clastic deposits of the S1 sequence. The S1 sequence was not penetrated by any wells in the Orphan Basin.

The seismic character of S1 is highly variable. In Area B the sequence is strongly reflective near the K1 sequence boundary. The reflectors have strong amplitudes and are parallel to sub-parallel to K1. The seismic character becomes more chaotic with little internal structure towards the bottom of the sequence. In Area B the S1 sequence

thickens into numerous half grabens and onlaps rotated basement blocks. S1 is intensely faulted and has been affected and reactivated by subsequent rift events. The thickness of S1 varies significantly throughout the area. It is thickest in the depositional lows (upwards of 1200 ms (TWT)) and thinnest or non-existent on the tops of rotated basement blocks (Figure 3.8)

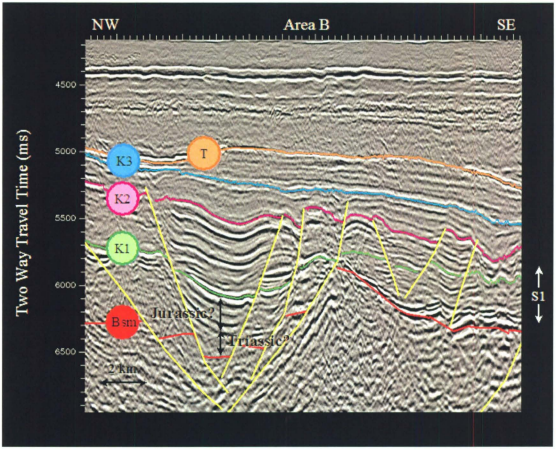

Figure 3.8: NW-SE seismic dip line through Area B. Yellow lines are faults. S1 bounded by seismic basement (Bsm) in red and K1 sequence boundary in green. Black arrows annotate inferred Jurassic and Triassic aged sediments. Also shown are overlying sequence boundaries. Location shown in Figure 3.1.

In Area C sequence S1 is chaotic with very few internal reflectors. This is likely due to the deep and distal nature of the sub-basin and the early Mesozoic sediments are

likely shale prone. The sequence is bounded at the top by a very strong amplitude event associated with the K1 sequence boundary (Figure 3.9). In this area S1 has experienced minor faulting related to the Late Triassic-Early Jurassic rift event. The thickness of this depositional sequence varies throughout the area. It is thickest in the central part of the area (upwards of 600ms) and thins or is not present on basement highs.

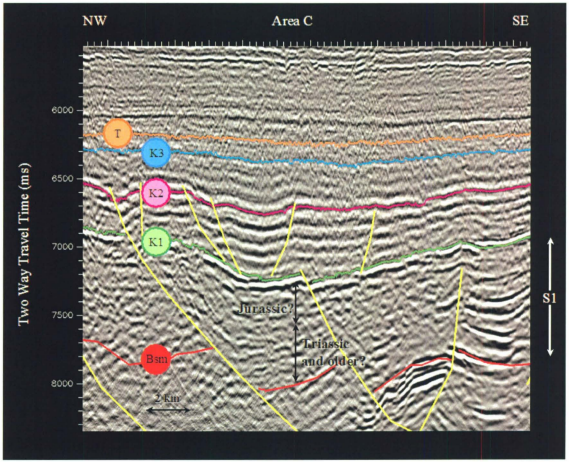

Figure 3.9: NW-SE seismic dip line through Area C showing characteristics of the S1 sequence. Yellow lines are faults and black arrows annotate inferred Jurassic and Triassic aged sediments. Also shown are overlying sequence boundaries. Location shown in Figure 3.1.

Figure 3.10 is a compilation of Figures 3.8 (through Area B) and 3.19 (Area C) for side-by-side comparison of the S1 sequence.

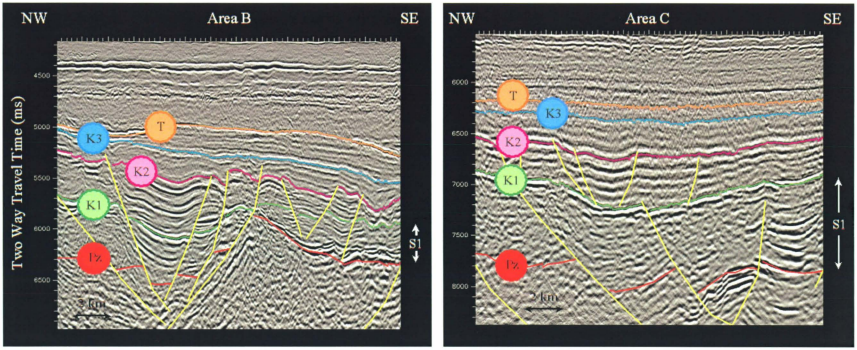

Figure 3.10: Figure 3.8 through Area B and Figure 3.9 through Area C displayed side-by-side for comparison of S1 seismic sequence character. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.4 K1 Sequence Boundary: Base Cretaceous Unconformity

Sequence boundary K1 is an unconformable surface in Areas B and C, as seen by the apparent downlap and onlap of the overlying Early Cretaceous reflectors. The quality of the K1 sequence boundary is good to excellent and is marked by a very strong positive peak. This sequence boundary is age equivalent to the Upper Jurassic unconformity (Tithonian Unconformity) seen in the Jeanne d'Arc and Flemish Pass basins. On interpreted seismic sections this horizon is coloured green.

This surface was picked only in the East Orphan Basin (Areas B and C), as it is absent in the West Orphan Basin. The sequence was not penetrated by any of the earlier Orphan Basin wells. Mizzen L-11 and Baccalieu I-78 wells in the Flemish Pass Basin

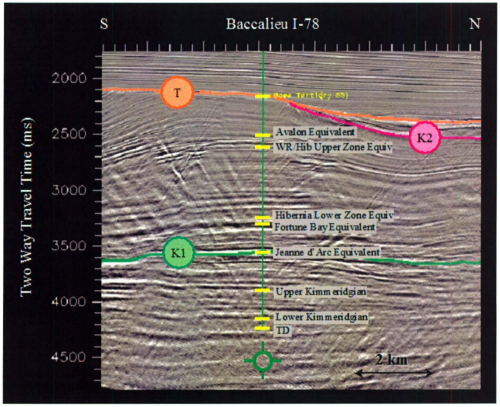

Figure 3.11: S-N seismic profile showing correlation of K1 sequence boundary at Baccalieu I-78 well location in Flemish Pass Basin. Location shown in Figure 3.1.

have drilled Upper Jurassic strata and a jump correlation from Baccalieu I-78 of the Upper Jurassic marker was made into Area C of the Orphan Basin. The top of the Jeanne d'Arc Formation equivalent strata coincides with sequence boundary K1 (Figure 3.11).

In Area B, K1 is a minor unconformity which marks a change in seismic character from high amplitude reflections above to lower amplitude reflectors of the upper S1 sequence below (Figure 3.12). It is a strong amplitude event marked locally by onlap of the overlying S2 sequence and low angle truncations of the underlying S2 sequence. The confidence in the seismic correlation of the K1 pick throughout Area B is fair to good.

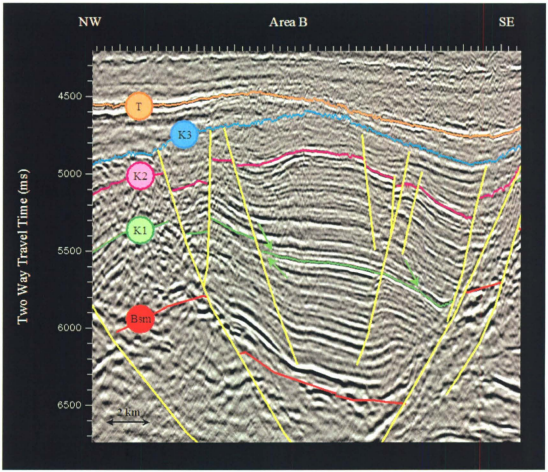

Figure 3.12: Seismic dip profile through Area B showing K1 sequence boundary. Yellow lines are faults. Green arrows show onlap of the upper reflectors and truncation of the lower reflectors. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

In Area C the K1 boundary is a major unconformity (Figure 3.13). It is marked by a very strong positive event produced by a high impedance contrast between the S1 and S2 sequences. It marks the change from the highly reflective, strong amplitude S2 sequence above to the very low amplitude, predominantly chaotic and transparent S2 sequence below. The K1 sequence boundary in Area C is marked by the onlap of the S2 reflectors and low angle truncation of S1 reflectors. The confidence in the seismic correlation of this pick is excellent. Figure 3.14 is a compilation of Figures 3.12 (Area B) and 3.13 (Area B) displayed side-by-side for comparison of K1 sequence boundary.

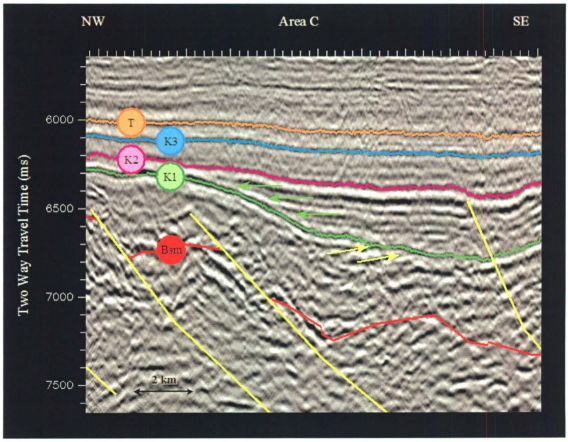

Figure 3.13: Seismic dip profile through Area C showing K1 sequence boundary. Yellow lines are faults. Green arrows show onlap of S2 sequence reflectors, yellow arrows show low angle truncation of S2 reflectors. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

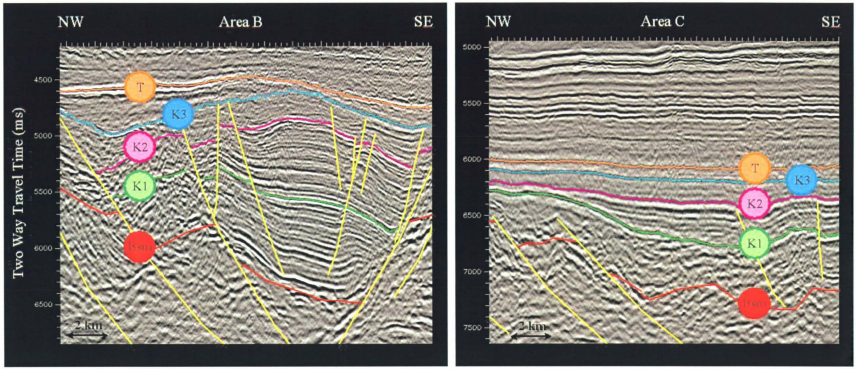

Figure 3.14: Figure 3.12 through Area B and Figure 3.13 through Area C displayed side-by-side for comparison of K1 sequence boundary. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.5 Seismic Sequence S2

Seismic sequence S2 is bounded at the base by the top Jurassic (Base Cretaceous) unconformity and at the base by the K2 Early Cretaceous unconformity. It is defined as Early Cretaceous and the lithostratigraphy is likely analogous to the Early Cretaceous sequences of the Jeanne d'Arc Basin. This sequence was mapped over Areas B and C; it is not present in Area A and was not penetrated by any of the Orphan Basin wells. The unconformity bounding the top of this sequence may be the Avalon or the Cenomanian unconformity.

The S2 sequence is structurally complex and dominated by highly reflective strong amplitude events (Figure 3.15). The seismic reflections are continuous and display parallel to sub-parallel events. In Area B this sequence is heavily faulted and reflectors have large offsets. Structures show inversion in places within this area likely due to repeated transtensional episodes related to a shift in rift orientation of the extensional main vector (NE-SW to N-S) which occurred during the Aptian-Albian Labrador rift phase. The thickness of S2 varies significantly throughout the area. It is thickest in the depositional lows (upwards of 1200ms) and is thinnest (<100ms) or non-existent on basement highs. In Area B the S2 sequence has been locally eroded by the K3 sequence boundary (erosional unconformity).

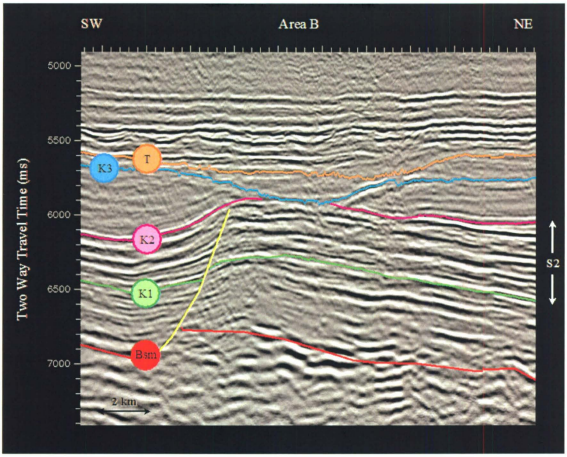

Figure 3.15: SW-NE seismic strike section through Area B showing the seismic character of the S2 sequence. Line shows erosion of S2 sequence by the K3 sequence boundary. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

In Area C the S2 sequence has relatively flat lying events, has few faults and is not structurally complex. The sequence is dominated by strong, continuous, parallel to sub-parallel reflectors which show evidence of onlap onto the K1 sequence boundary below (Figure 3.16). Reflections within the S1 sequence are commonly concordant with the K2 sequence boundary above. The sequence has an average time thickness of

approximately 500ms. It is thickest in the central region of Area C (upwards of 700ms) and thins towards the edges of the sub-basin. It onlaps basement highs and is very thin, or non-existent on the tops of rotated basement blocks.

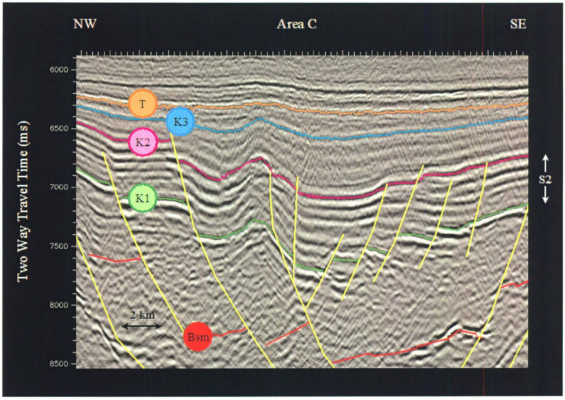

Figure 3.16: NW-SE dip profile through Area C showing seismic character of S2 sequence. Yellow lines are faults. Overlying and underlying sequence boundaries are also shown. Location shown in Figure 3.1.

Figure 3.17 is a compilation of Figures 3.15 (through Area B) and 3.16 (Area C) for side-by-side comparison of the S2 sequence boundary.

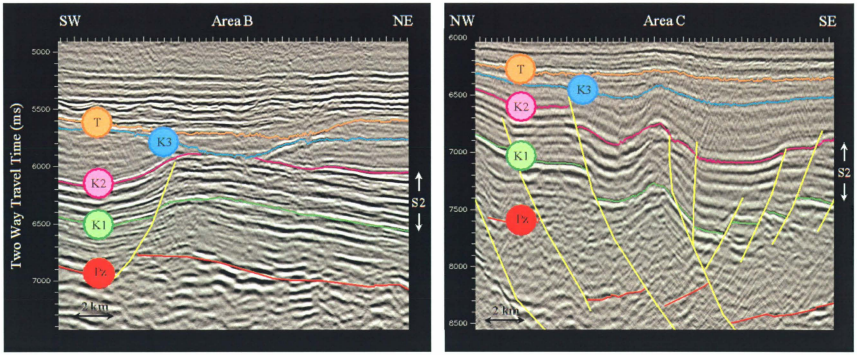

Figure 3.17: Figure 3.15 through Area B and Figure 3.16 through Area C displayed side-by-side for comparison of S2 seismic sequence. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.6 K2 Sequence Boundary: Mid Cretaceous Unconformity

The K2 sequence boundary marks the division between the Early Cretaceous (mainly synrift) and Late Cretaceous (mostly thermal subsidence) sedimentary sequences and is likely coeval to the Avalon Unconformity in the Jeanne d'Arc Basin. The K2 sequence boundary was mapped over Areas B and C and is marked by a coherent, high amplitude reflector formed by a positive impedance contrast. It was not mapped in Area A and was not intersected by any of the Orphan Basin wells as at the drillsites it was obscured by younger Tertiary coalescing unconformities. The seismic correlation confidence in this marker is good. On interpreted seismic sequences the K2 sequence boundary is displayed in pink.

In Area B the K2 sequence boundary is a strong amplitude event and marks a major change in seismic character from the overlying, predominantly transparent sequence (S3), to the underlying, highly reflective seismic sequence (S2) (Figure 3.18). K2 is dissected by thin-skinned faults. It is a fairly continuous marker throughout Area B and its correlation confidence is good. The K2 sequence boundary marks the upper termination of fault movements. Overlying sediments are relatively undisturbed.

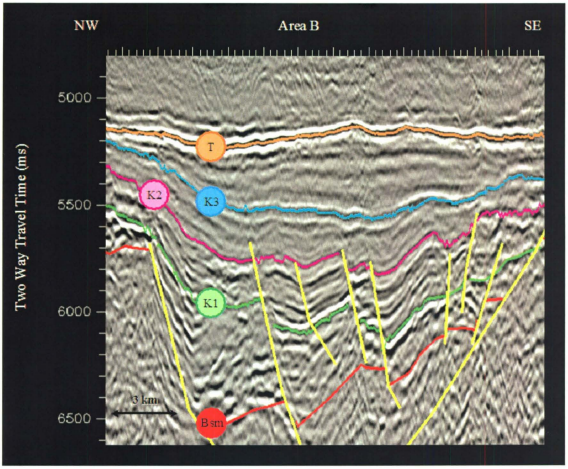

Figure 3.18: NW-SE dip seismic profile through Area B showing K2 sequence boundary. Yellow lines are faults. Also shown are overlying and underlying sequence boundaries. Location shown in Figure 3.1.

The K2 boundary becomes relatively conformable in the central part of Area C where the underlying reflections of the S2 seismic sequences and the overlying reflectors of the S3 seismic sequence are parallel to sub-parallel. The K2 sequence boundary in this area also marks a change in seismic character from low amplitude to transparent events above to higher amplitude events below. There is local evidence of onlap of the overlying S3 sequence reflectors at the sub-basin margin. This marker is continuous throughout Area C and the correlation confidence is good.

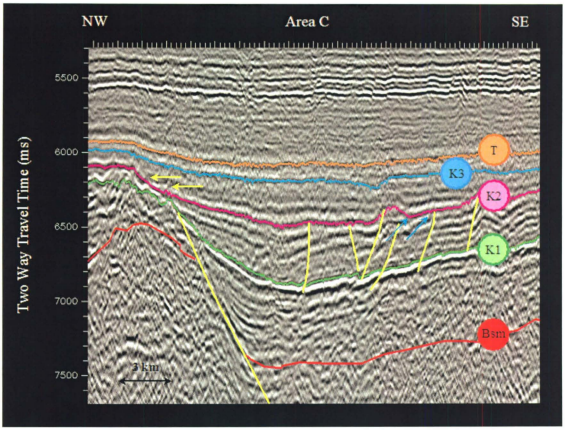

Figure 3.19: NW-SE dip seismic section through Area C showing K2 sequence boundary. Yellow lines are faults. Yellow arrows show onlap of the upper (S3) reflectors. Blue arrows show apparent truncation of the lower (S2) reflectors. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

Figure 3.20 displays Figures 3.18 (Area B) and 3.19 (Area C) side-by-side for comparison of K2 sequence boundary.

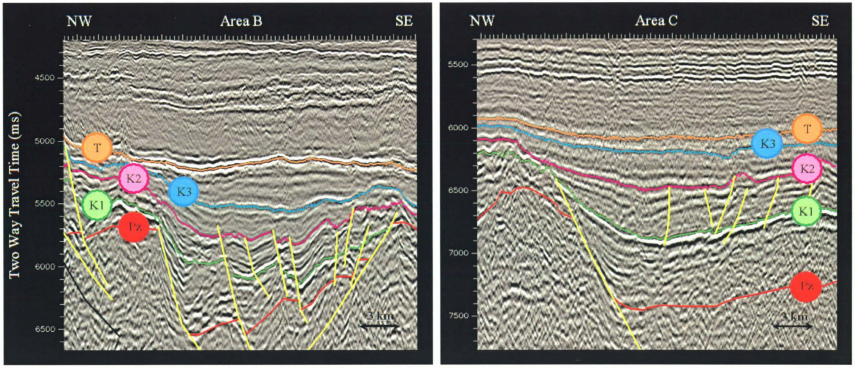

Figure 3.20: Figure 3.18 through Area B and Figure 3.19 through Area C displayed side-by-side for comparison of K2 sequence boundary. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.7 Seismic Sequence S3

Seismic sequence S3 is bounded at the top by the K3 sequence boundary and at the base by the K2 sequence boundary in Areas B and C, and the seismic basement (Bsm) in Area A. The sequence has been interpreted over the entire Orphan Basin (Areas A, B and C) and is likely equivalent to the Dawson Canyon Formation open marine shales of the Jeanne d'Arc Basin. It was deposited during the early Late Cretaceous at a time when sea level was high and the area was likely an open marine environment.

The seismic character of S3 is mostly transparent in Area A; however, there are some internal reflectors which indicate a change in stratigraphy (Figure 3.21). Due to the proximity of the Bonavista Platform, Area A received clastic sediments which were shed from the local highs during the Late Cretaceous. These likely correspond with the Otter Bay member sandstones of the Jeanne d'Arc Basin. The Dawson Canyon Formation was encountered by all seven of the earlier Orphan Basin wells and Blue H-28, Baie Verte J-57, Bonavista C-99, Cumberland B-55, Hare Bay E-21 and Linnet E-63 encountered Otter Bay member sandstones. The S3 sequence is thickest in Area A (upwards of 1700ms) and has few thin-skinned faults. The sequence has been affected mainly by major, thick-skinned, basement involved faults. The sequence is extremely thin and commonly non-existent on basement highs due to non-deposition or erosion at the Base Tertiary unconformity (T).

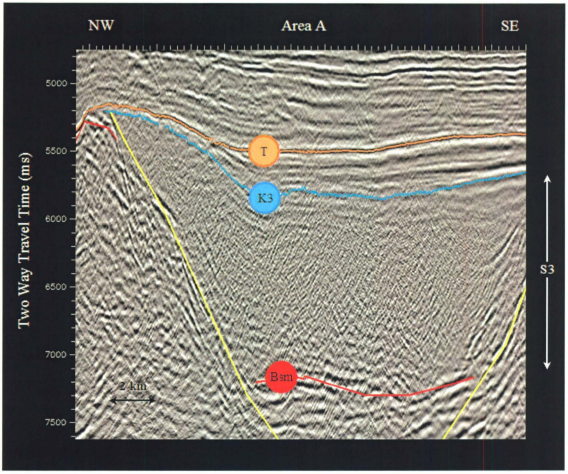

Figure 3.21: NW-SE dip seismic section through Area A showing the seismic character of S3. Yellow lines are thick-skinned, basement involved, faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

In Area B the seismic character of S3 is dominated by low amplitude, parallel to sub-parallel events which locally onlap the underlying K2 sequence boundary (Figure 3.22). Late movement along thin-skinned faults has affected the sequence; however, the sequence appears to be composed mainly of thermal subsidence stage sediments. This sequence is comprised of a wedge of flat lying, late Cretaceous and mostly Tertiary sediments. The S3 sequence has variable thickness throughout Area B and is thickest in

the deeper depocentres (approximately 500ms) and thinnest or non-existent on basement highs. The S3 sequence has been locally eroded in places by the Base Tertiary unconformity.

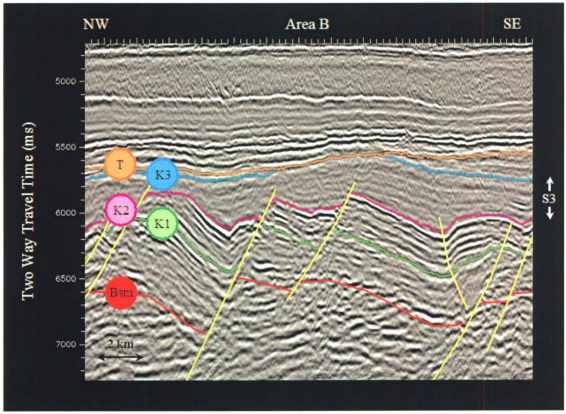

Figure 3.22: NW-SE dip seismic section through Area B showing the seismic character of the S3 sequence. Line shows erosion of S3 by the Base Tertiary unconformity. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

In Area C the seismic character of S3 is variable. In areas it is dominated by low amplitude parallel to sub-parallel events (Figure 3.23) and in others it is chaotic with few visible internal reflectors. In general the sequence is extremely thin (<100ms) but

locally, in areas where the underlying synrift sequence has been heavily faulted, the thickness of the S3 thermal subsidence sequence is upwards of 300ms. This sequence has not been strongly affected by faulting except by thick-skinned (basement involved) faults seen along basement highs.

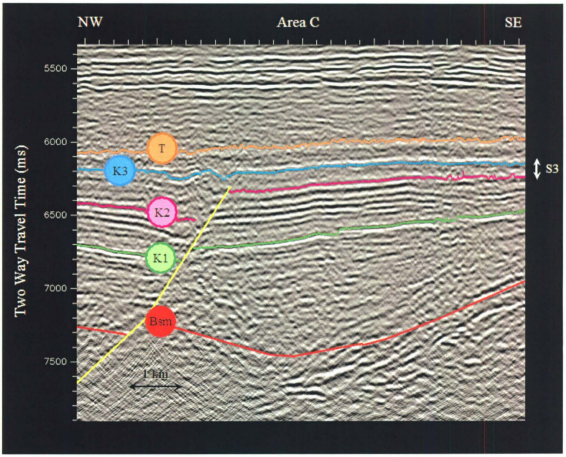

Figure 3.23: NW-SE dip seismic section through Area C showing seismic character of S3 sequence. Profile shows thickness variation of sequence across fault (yellow). Also shown are underlying and overlying sequence boundaries.

Figure 3.24 displays Figures 3.21 (Area A), 3.22 (Area B) and 3.23 (Area C) side-by-side for comparison of S3 seismic sequence.

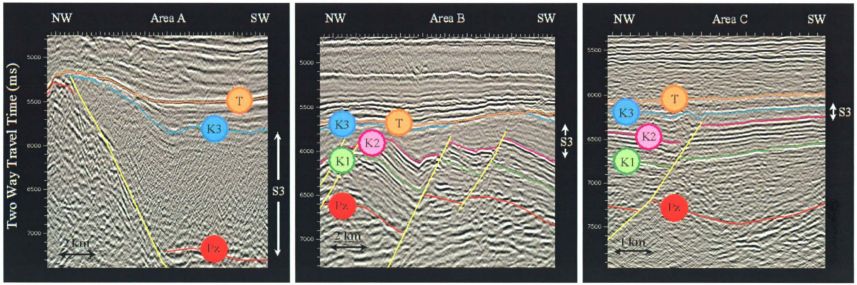

Figure 3.24: Composite of Figure 3.21 through Area A, Figure 3.22 through Area B and Figure 3.23 through Area C displayed side-by-side for comparison of S3 seismic sequence. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.8 K3 Sequence Boundary: Santonian Unconformity

The K3 sequence boundary was mapped over the entire Orphan Basin (Areas A, B and C) and is a localized erosional unconformity equivalent to the late Cretaceous Santonian unconformity in the Jeanne d'Arc Basin. The quality of the K3 sequence boundary is fair to good and confidence of picking varies between the three areas. A positive peak due to a fairly large impedance contrast marks the unconformity. On the interpreted seismic sections this horizon is coloured blue.

In Area A the K3 sequence boundary was not penetrated by the Orphan Basin wells. This is likely due to erosion at the Base Tertiary unconformity of the basement highs which obscured the older unconformities (i.e. K3 and K2). The K3 sequence boundary is marked by a strong peak onto which the overlying events of the S4 sequence onlap (Figure 3.25). This boundary also marks a change in seismic character from the reflective S4 sequence above to the low amplitude, mainly chaotic nature of the S3 sequence below. It is most easily seen in the deepest parts of the sub-basin. The confidence in the seismic correlation of this sequence boundary in this area is fair.

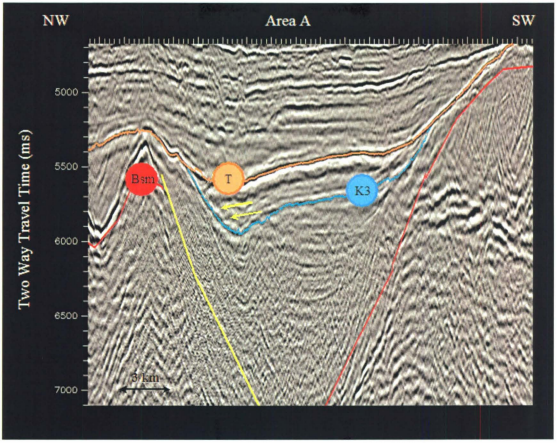

Figure 3.25: NW-SE dip seismic section through Area A showing the K3 sequence boundary (blue marker). Yellow arrows depict onlap of overlying sediments onto the K3 sequence boundary. Yellow lines are basement involved faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

In Area B the K3 sequence boundary is an erosional unconformity as seen by the erosional truncation of the underlying S3 reflectors and the onlap of the overlying S4 reflectors (Figure 3.26). This sequence boundary is a channel which locally erodes the underlying S3 sequence and in the southwest erodes the S2 sequence. The head of the channel is toward the Grand Banks and is oriented northeast toward the Charlie Gibbs

Fracture Zone. Lack of drilling preclude us from knowing if it is totally submarine or subaerial. The confidence in the seismic correlation of the K3 sequence boundary is greatest in Area B.

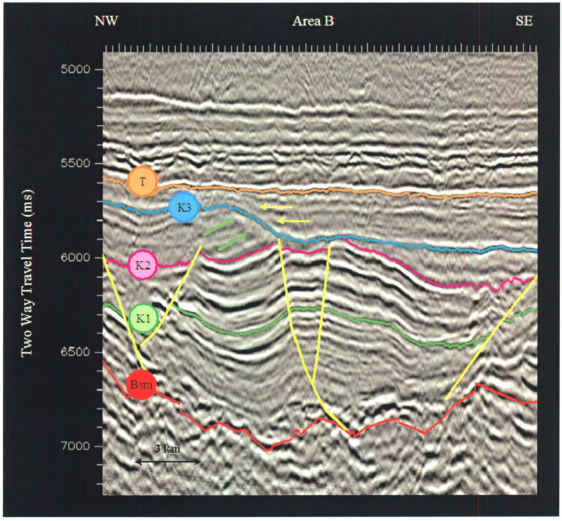

Figure 3.26: NW-SE dip seismic section through Area B showing the K3 sequence boundary (blue marker) interpreted as a channel. Yellow lines are faults. Green arrows show erosional truncation of S3 events by K3 and yellow arrows show onlap of S4 reflectors. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

In Area C the K3 sequence boundary has been interpreted as a correlable conformity in the central part of the subbasin where seismic events above and below the sequence boundary are parallel. At the basin's eastern margin the underlying K2 sequence boundary and the K3 sequence boundary converge (Figure 3.27). K3 is marked by a positive peak. The confidence in seismic correlation of this event in Area C is fair.

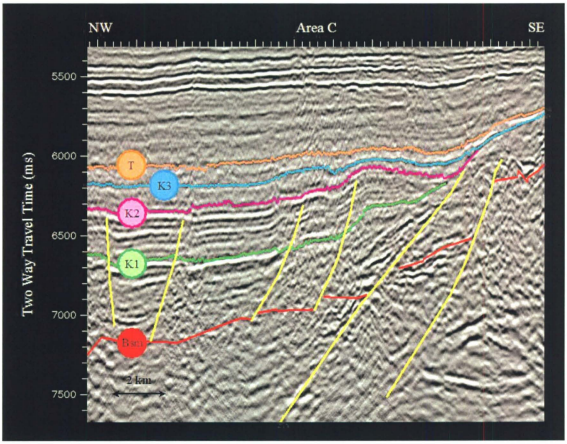

Figure 3.27: NW-SE dip seismic section showing K3 sequence boundary (blue marker) through Area C. Profile shows the convergence of the K2 and K3 sequence boundaries at the eastern margin of the basin. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

Figure 3.28 displays Figures 3.25 (Area A), 3.26 (Area B) and 3.27 (Area C) side-by-side for comparison of the K3 sequence boundary.

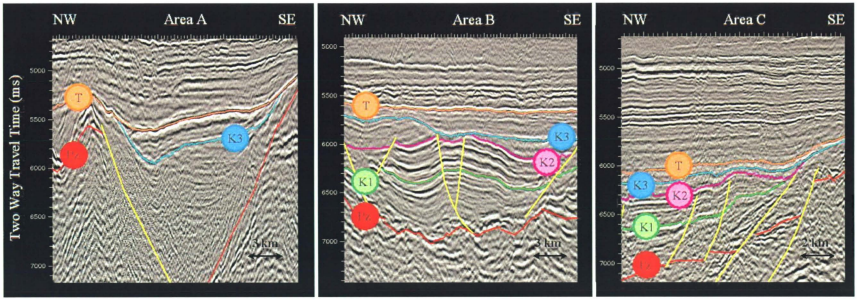

Figure 3.28: Figure 3.25 through Area A, Figure 3.26 through Area B and Figure 3.27 through Area C displayed side-by-side for comparison of K3 sequence boundary. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.9 Seismic Sequence S4

Seismic sequence S4 is bounded by the K3 sequence below and the Base Tertiary unconformity (T) above. This sequence was mapped over Areas A, B and C and corresponds to the Upper Cretaceous Fox Harbour member of the Dawson Canyon Formation in the Jeanne d'Arc Basin.

In Area A the seismic character of S4 is moderately reflective with parallel to sub-parallel reflectors which onlap onto the underlying K3 sequence boundary (Figure 3.29). Blue H-28, Baie Verte J-57, Bonavista C-99, Cumberland B-55, Hare Bay E-21 and Linnet E-63 wells encountered Fox Harbour sediments. The S4 sequence is thickest in

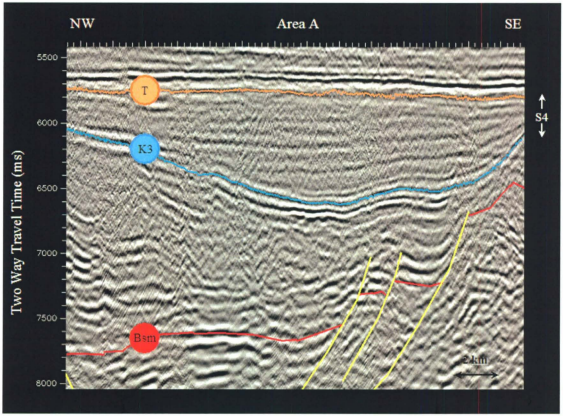

Figure 3.29: NW-SE dip seismic section showing seismic characteristics of the S4 sequence. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

the deepest regions (upwards of 800ms), thins and is mostly non-existent on the basement highs where it has been eroded by the Base Tertiary unconformity. The sequence has not experience faulting except along the basin bounding and basement involved faults.

In Area B the S4 seismic sequence is channel fill and is made up of low amplitude parallel to sub-parallel reflectors which onlap the K3 sequence boundary (Figure 3.26 and 3.30). The thickness of this sequence varies throughout the area, but is thickest (500ms) in areas where the underlying channel unconformity is deepest. This sequence thins significantly and pinches out in areas where the K3 and T sequence boundaries converge (i.e. on tops of basement highs). The sequence has not experienced any significant faulting except along major basement involved and basin bounding faults.

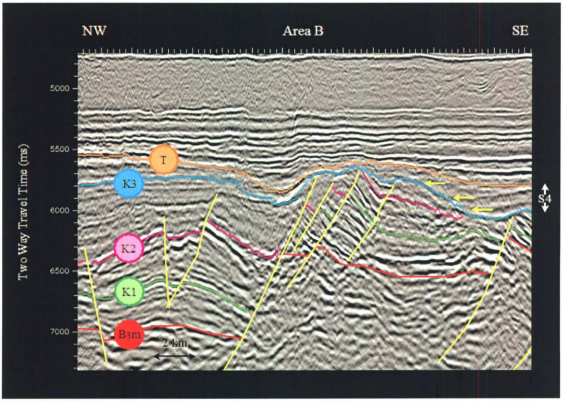

Figure 3.30: NW-SE dip seismic section through Area B showing seismic character of S4 sequence. Yellow arrows show onlap of S4 events onto K3 sequence boundary. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

In Area C the S4 sequence is extremely thin, with a relatively uniform thickness throughout the area (average thickness: 100-200ms). It is a chaotic sequence with very few internal reflectors. This sequence onlaps the K3 sequence boundary only at the western and eastern margins of the basin. The sequence is flat lying in this area, has little topography and has not experienced any major faulting, except at its margin where movement occurred along major basement involved faults.

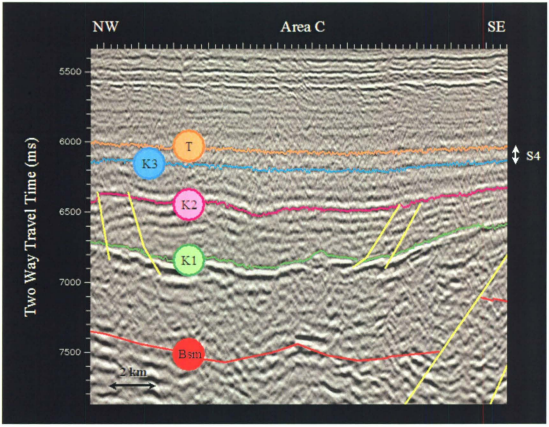

Figure 3.31: NW-SE dip seismic section through Area C showing seismic character of S4 seismic sequence. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Location shown in Figure 3.1.

Figure 3.32 is a composition of Figures 3.29 (Area A), 3.30 (Area B) and 3.31 (Area C) for side-by-side comparison of the S4 seismic sequence.

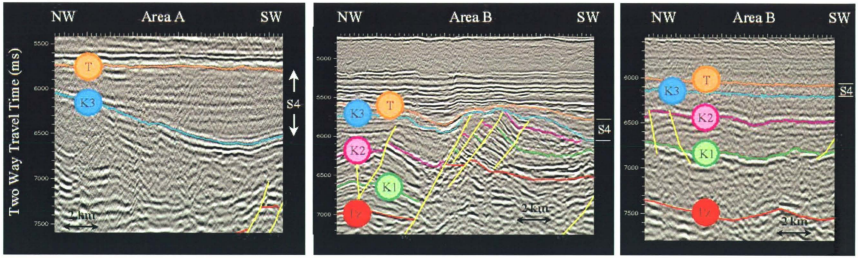

Figure 3.32: Figure 3.29 through Area A, Figure 3.30 through Area B and Figure 3.31 through Area C displayed side-by-side for comparison of S4 seismic sequence. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.10 T Sequence Boundary: Base Tertiary Unconformity

The T sequence boundary is a highly erosional event mapped across the entire Orphan Basin (Areas A, B and C). This boundary is an excellent regional marker as it has been mapped throughout the offshore Newfoundland and Labrador basins. The confidence in correlating this event is excellent; however, confidence deteriorates on local highs as strong events in the Eocene and Paleocene obscure the older events. On interpreted seismic sections this boundary is displayed in orange.

In Area A the T sequence boundary is a highly erosive unconformity which peneplained basement blocks. This surface can be reconstructed by connecting the Bonavista Platform and eroded tops of the ridges, showing that strong uplift and sub-aerial erosion took place in this part of the basin during the Late Cretaceous – early Tertiary Labrador rift (Enachescu *et al.*, 2005 and Burton-Ferguson *et al.*, 2006). The sequence boundary divides the overlying Paleocene and Eocene sediments from the underlying Late Cretaceous sequences. It is marked by a strong amplitude event which is overlain in areas by channelized sedimentary fans (Figure 3.33). The underlying events are locally truncated by the T sequence boundary. On the tops of basement highs this sequence boundary has eroded most of the underlying Mesozoic sequences and directly overlies the Paleozoic metasedimentary or Precambrian metamorphic basement. The correlation confidence of the T sequence boundary in Area A is excellent.

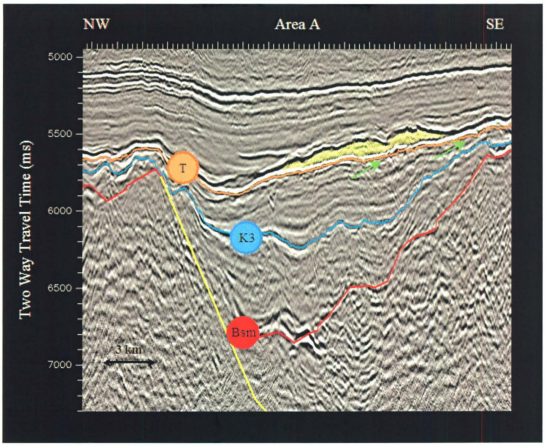

Figure 3.33: NW-SE dip seismic profile through Area A showing T sequence boundary. Profile shows a sedimentary fan (yellow shaded region) overlying the T marker. Green arrows show truncation of underlying S4 reflectors. Yellow lines are faults. Also shown are underlying sequence boundaries. Location shown in Figure 3.1.

In Area B the T sequence boundary is marked by a very strong amplitude event caused by a positive impedance contrast (Figure 3.34). It is a highly erosive unconformity as seen by the truncation of the underlying events of the S4 seismic sequence. In this area the basement ridges have subsided to greater depths than in Area A, and the T sequence boundary does not erode the rotated blocks as pervasively. The depth of the basin drops dramatically in Area B and the T sequence boundary follows this trend. Locally the unconformity erodes the earlier K3 sequence boundary and underlying

sequences. The T sequence boundary registers a regional event which may be a combination of significant uplift due to inversion and a dramatic eustatic sea level fall. The correlation confidence in this area is excellent in the western regions to good in the east as the resolution decreases with depth and the event is slightly obscured by Paleocene and Eocene events.

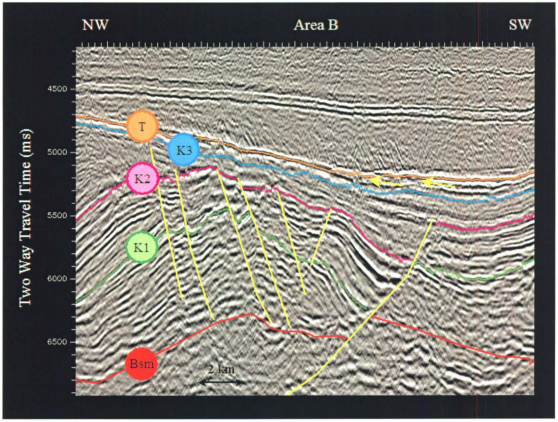

Figure 3.34: NW-SE dip seismic profile showing the T sequence boundary. Yellow arrows show local truncation of S4 events. The boundary is marked by a very strong, positive amplitude event. Yellow lines are faults. Also shown are underlying sequence boundaries. Location shown in Figure 3.1.

In Area C the T sequence boundary is not marked by a strong impedance contrast due to the depth of the marker, the resolution of the seismic data and the interference of strong Paleocene and Eocene events. In the northeast region the T marker is interpreted at

the base of a series of strong amplitude Paleocene events interpreted as sedimentary fans and the correlation confidence is excellent (Figure 3.35). This package of strong reflectors is not ubiquitous throughout the area and correlation confidence decreases (fair-good) toward the south. This unconformity overprints the earlier K3 sequence boundary at the western margin of the basin where it rises up over the terrace into the Flemish Pass Basin and is marked by the onlap of Paleocene and Eocene events.

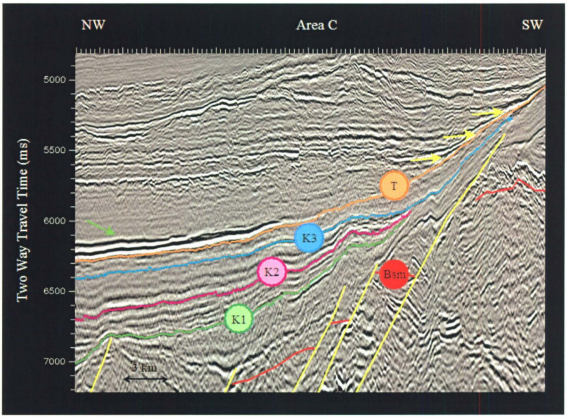

Figure 3.35: NW-SE dip seismic section through northeast region of Area C showing T sequence boundary. Profile shows highly reflective package overlying T marker (green arrow). Yellow arrows depict onlap of Paleocene/Eocene reflectors. Yellow lines are faults. Also shown are underlying sequence boundaries. Location shown in Figure 3.1.

Figure 3.36 is a composite of Figures 3.33 (Area A), 3.34 (Area B) and 3.35 (Area C) displayed side by side for comparison of T sequence boundary.

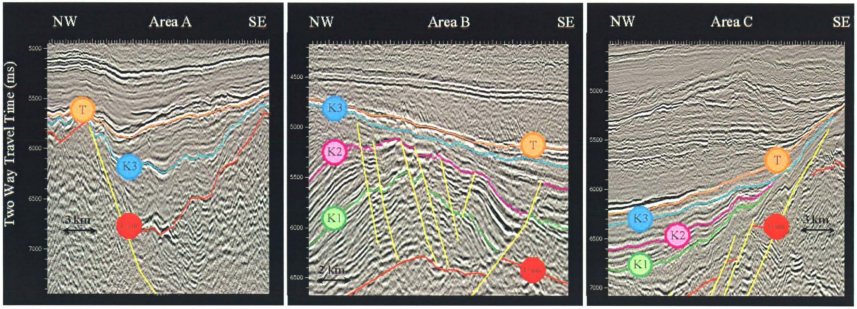

Figure 3.36: Figure 3.33 through Area A, Figure 3.34 through Area B and Figure 3.35 through Area C displayed side-by-side for comparison of T sequence boundary. Yellow lines are faults. Also shown are underlying and overlying sequence boundaries. Locations shown in Figure 3.1.

3.3.11 Seismic Sequence S5

Seismic Sequence S5 is bounded at the top by the waterbottom (WB) and at the base by sequence boundary T (Figure 3.37). This sequence corresponds with Paleocene, Eocene, Oligocene and Miocene-aged sediments which were deposited during the thermal subsidence phase of the last rift event. There are numerous sub-sequences which can be identified within the Tertiary succession; however, as the scope of this thesis is concerned with identifying Cretaceous sequences, no attempt was made to map these sub-sequences. A brief regional description has been made in order to highlight the general thickness variations of the sequence across the Orphan Basin. This is important for identifying potential Cretaceous and Tertiary source rocks.

The S5 sequence is thickest in Area A (>3000ms) and decreases across Areas B (average 2000ms) and C (~2500ms). The sequence is thinnest in the north central part of Area B at the eastern shoulder of the Orphan Basin where basement blocks were severely uplifted. The S5 sequence was sediment starved in Area B during the time of deposition as the provenance source for sediments was likely from the distal Bonavista Platform to the west and from the eastern terrace (Flemish Pass) in the east.

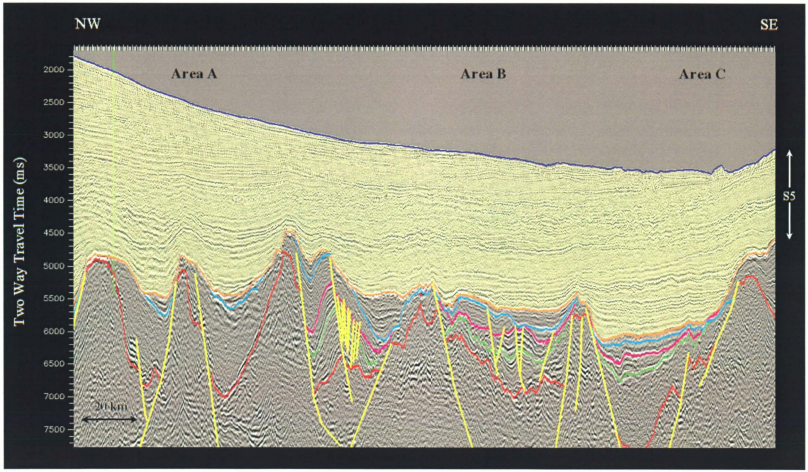

Figure 3.37: NW-SE dip seismic section showing S5 seismic sequence (yellow fill) through Areas A, B and C. Also shown are underlying and overlying sequence boundaries. Red = seismic basement, green = K1 sequence boundary, pink = K2 sequence boundary, blue = K3 sequence boundary, orange = T sequence boundary and dark blue = water bottom. Yellow lines are faults. Location shown in Figure 3.1.

3.3.12 Sequence Boundary WB: Water Bottom

The uppermost reflector imaged on all seismic sections is interpreted as the water bottom. The water bottom extends from approximately 1800ms (1300m) in Area A to >3500ms in Areas B and C (Figure 3.37). This horizon is continuous and a positive acoustic impedance, high amplitude event which allows for excellent seismic correlation confidence over the entire study area (Figure 3.38). The gradient of this marker is approximately 2-3° on the slope. The water bottom rises sharply over the Orphan Knoll on which seamounts can be seen (Enachescu *et al.*, 2004). Tilting and rapid subsidence, differential compaction, inversion and late movements of basement blocks, direction of mass transport deposits, bottom currents and glaciation of the margins caused the significant bathometric relief.

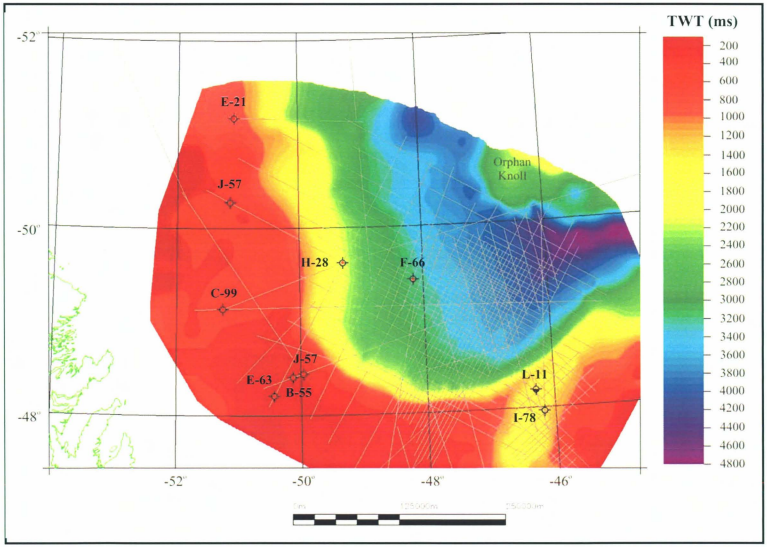

Figure 3.38: Time structure map of water bottom sequence boundary. Map is in two way travel time (ms).

3.3.13 Volcanics

Very minor volcanic activity can be interpreted on the Orphan Basin data set. Strong amplitude events are seen in the northern area at the mid to Late Cretaceous level and can be interpreted as sills or lava flows (Figure 3.38). These events are high amplitude, high velocity events not dissimilar to those recorded in the Labrador basins to the north. These amplitude anomalies do not appear to be widespread and cannot be mapped due to the coarse grid spacing.

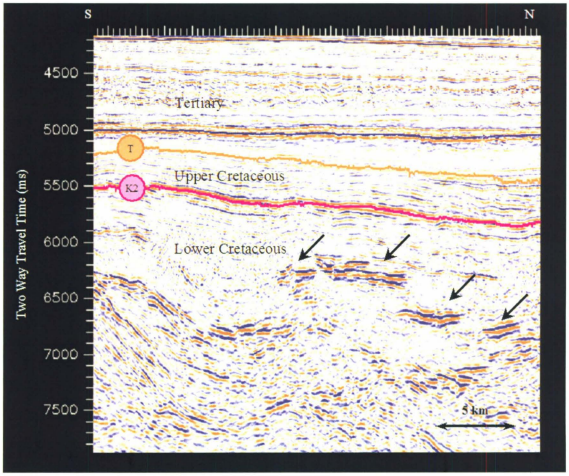

Figure 3.39: N-S strike seismic section through northern part of Area B. Black arrows show strong amplitude anomalies which have been interpreted as being volcanic in origin. Also shown are overlying K2 and T sequence boundaries. Location shown in Figure 3.1.

Chapter 4

Tectonostratigraphic Evolution of Cretaceous Sub-Basins

4.1 Introduction to West and East Orphan Sub-Basins

From both tectonostratigraphic and petroleum potential points of views, the Orphan Basin can be subdivided into an older East Orphan Basin situated in deep water (1,500-3,000m) and a younger West Orphan Basin situated in shallower water (1000-1,500m) (Figure 4.1). These two sub-basins have distinct sedimentological and structural histories (Enachescu *et al.*, 2004a; Enachescu *et al.*, 2004b; Enachescu *et al.*, 2004c and Enachescu *et al.*, 2005). The Cretaceous basin subdivisions A, B, and C described in Chapter 3 were based on seismic stratigraphic and structural features identified during this study within the Cretaceous seismic sequences. These areas will be referred to when describing the regional Cretaceous tectonic and stratigraphic histories of the two main sub-basins.

Due to the large spacing of the available 2D grid, the fault patterns presented here are non-unique, nor definitive solutions. 3D seismic grids would be needed in order to properly map these faults. The 2D interpretation presented here is acceptable from a regional point of view as it is based on structural style considerations and along strike continuity of major faults and their associated half-graben fills.

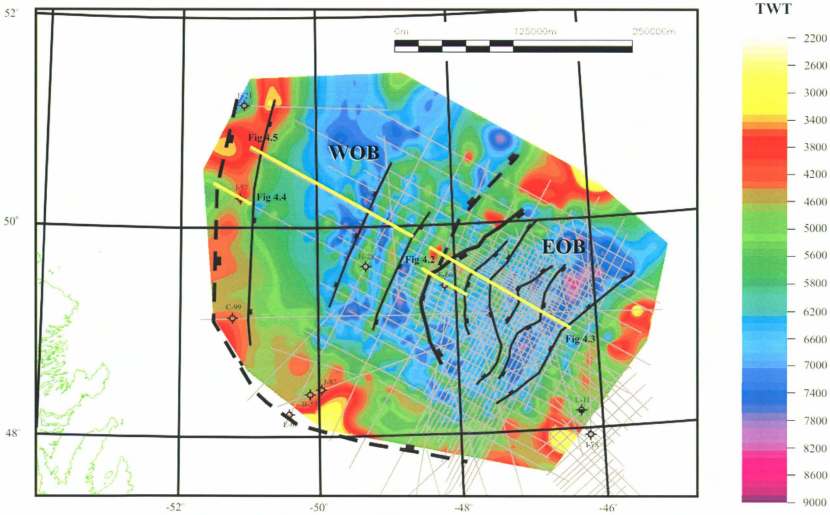

Figure 4.1: Basement Time Structure map showing the West (WOB) and East (EOB) Orphan basins. Black lines are major basement involved faults, thick black lines are basin-bounding faults and dashed lines are faults that were interpreted in areas where seismic coverage or resolution is low. Map is displayed in two way travel time (ms).

4.2 East Orphan Basin Fault Families

The East Orphan Basin comprises the area east of the White Sail Fault (approximately 80,000 square kilometers) and extends to the Flemish Pass Basin and the continent-ocean boundary to the east. The grid spacing is densest in the northeast where distance between lines is approximately10 kilometers. This grid spacing allows for fairly confident correlations of seismic events and major faults. To the north and to the south the grid spacing is coarser and correlations are less certain. The East Orphan Basin is the older of the two rifting areas (Enachescu *et al*., 2004a and 2005). This area was affected by the initial Late Triassic-Early Jurassic (Tethys) rift event, the Late Jurassic – Early Cretaceous (Atlantic) rift event and has experienced some minor readjustment during the Late Cretaceous (Labrador) rift event in its western parts.

4.2.1 Basin Bounding Fault Family

The basin bounding fault for the East Orphan Basin is the White Sail Fault that has a large, normal sense separation with eastward downthrow into the basinal area (Figure 4.2). This fault began to form in the late Triassic-Early Jurassic likely as a series of en echelon faults that propagated from south to north during the Tethys rift phase (Figure 4.2). This fault developed into a basement involved, thick-skinned fault system and accounts for the majority of extension in the East Orphan during the initial rift phase.

The White Sail Fault is listric in shape and soles deep into the pre-Mesozoic basement. This fault shallows to the southeast and soles at depths >9000ms TWT. The

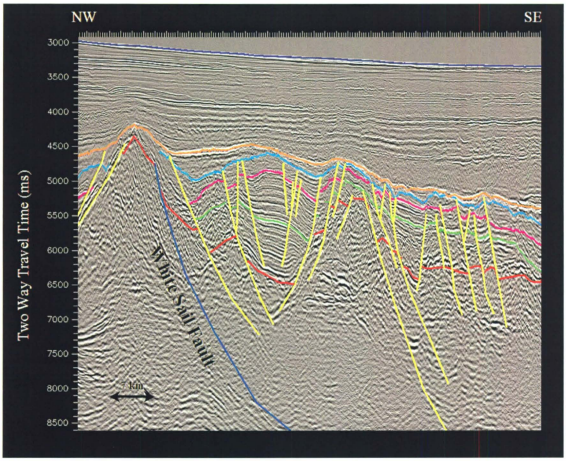

Figure 4.2: NW-SE dip profile through East Orphan Basin showing White Sail basin bounding fault (blue). Yellow lines are faults. Sequence boundaries are orange = Base Tertiary Unconformity; blue = K3 (Late Cretaceous) sequence boundary; pink = K2 (Early Cretaceous) sequence boundary; green = K1 (Base Cretaceous/Tithonian) sequence boundary and red = basement. Location shown in Figure 4.1.

resolution of the seismic data at depth is poor and its detachment plane is not clearly imaged. During the Late Jurassic-Early Triassic rift phase the White Sail Fault was likely oriented NE-SW in line with the Jeanne d'Arc and Porcupine basins. Reactivation of the major fault zone during the Late Jurassic – Early Cretaceous (Atlantic) rift phase and

possible minor reactivation during the Aptian – Albian (Labrador) rift phase caused a change in orientation of this basin bounding fault to N-S. This fault was subsequently active until Late Cretaceous-Early Tertiary. The White Sail Fault marks the limit of Late Triassic and Jurassic sedimentation in the Orphan Basin (Enachescu *et al.*, 2005).

4.2.2 Basement Involved Fault Family

Within Area C the faults that make up the Basement Involved Fault Family have normal dip orientation and sole into the basin bounding fault system. They are synthetic and antithetic to the White Sail Fault and delineate the major structural units of the East Orphan Basin. In its hanging wall are 1) asymmetric half grabens; 2) horsts; and 3) symmetric grabens. These faults were identified in Area C based on the mapping of significant discontinuities in the K1 and K2 sequence boundaries and offsets of the intervening reflections. The faults that are synthetic to the Basin Bounding White Sail Fault trend west southwest – east northeast and generally dip steeply to the southeast. They define rotated fault blocks or form the seaward dipping faulted side of basement involved horst blocks. The faults which are antithetic to the White Sail Fault trend west southwest-east northeast and dip steeply to the northwest. They define the landward dipping flank of basement involved horst blocks.

The Basement Involved Fault Family segments the pre-Mesozoic basement and synrift successions. The K2 sequence boundary marks the uppermost stratigraphic level disturbed by these faults. These faults were likely formed during the initial Late Triassic – Early Jurassic (Tethys) rift phase and were reactivated during subsequent rift phases

(Late Jurassic – Early Cretaceous Atlantic rift and Aptian – Albian Labrador rift). In the East Orphan Basin the Basement Involved Fault Family defines rotated basement blocks and horst features. Those faults that define the seaward dipping or landward side of basement involved horsts, seen in the westernmost parts of the East Orphan Basin, were commonly active until the end of Cretaceous-start of Tertiary.

Within the East Orphan Basin five major basement involved faults were mapped (Figure 4.1). These faults show a general NE-SW trend, are sinuous in shape and define major basement highs and associated depocenters. To the north the faults diverge, creating multiple rotated basement blocks and horsts. This is pervasive in the region north of the Great Barasway F-66 well. The basement is deepest in the northeast region of the East Orphan Basin. Numerous large-scale structural features (i.e. extensional anticlines) exist in the western part of the sub-basin, around the Great Barasway F-66 well. Due to poor resolution of the seismic data and the coarse grid spacing in the northern and southern parts of the basin, basement involved faults cannot be linked with a great degree of confidence.

4.2.3 Cretaceous Faults

Within the Cretaceous sequences in the East Orphan Basin there are major faults within the basin fill, which are slightly curved and are normal faults. These faults dip both landward and seaward depending on the underlying basement structure. The major faults typically link with the basement involved faults and were active until the Tertiary

(Figure 4.3). Due to the low resolution of the data and the large grid spacing, it is not possible to map these faults with a high degree of confidence. Seismic resolution below the base Cretaceous unconformity decreases and the internal character of the older sediments is transparent. This does not allow for confidence in extending major fault planes to the basement level, but some may detach at the basement.

The minor faults are seen in the lower Cretaceous sedimentary successions and were active from Late Jurassic to the mid Cretaceous. These faults are predominantly associated with the Late Jurassic to Early Cretaceous (Atlantic) rift event. They vary from slightly curved to planar and typically have less than 100ms (TWT) of throw associated with them. Due to the large grid spacing it is not possible to either link these faults nor map them with a great degree of confidence.

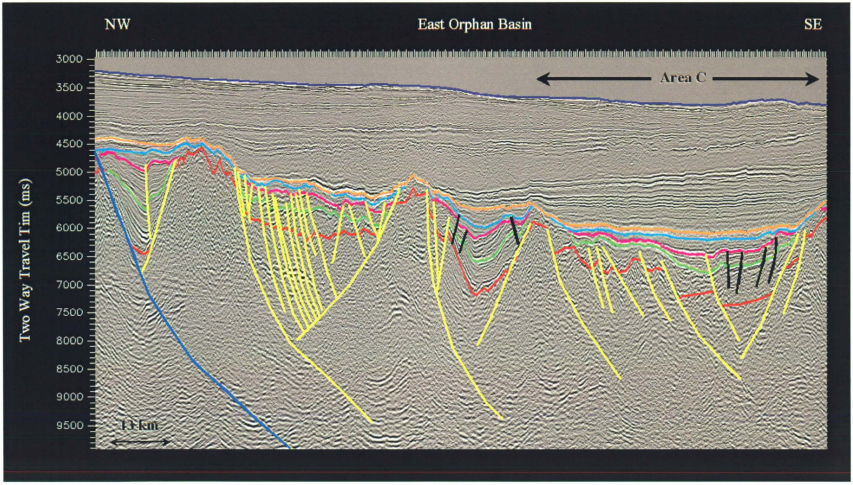

Figure 4.3: NW-SE dip seismic section through the East Orphan Basin showing basin bounding fault (blue line), basement involved faults (yellow lines) and intra basinal faults (black lines). Sequence boundaries are: orange= Base Tertiary Unconformity, blue = K3 sequence boundary, pink = K2 sequence boundary, green = K1 sequence boundary and red = basement. Location shown in Figure 4.1.

4.3 West Orphan Basin Fault Families

The West Orphan Basin comprises the areas west of the White Sail Fault (Figure 4.1) and encompasses and area of approximately 80,000 square kilometers. This region contains all seven of the earlier wells drilled in the basin. The West Orphan Basin, the younger of the two main sub-basins, began opening in its eastern part during the Late Jurassic-Early Cretaceous Atlantic rift event and was affected mainly by the mid – Late Cretaceous Labrador rift event. The seismic grid in the West Orphan Basin is coarse with distances between seismic lines averaging 25 km. At the western limit of the data coverage the distances between lines greater than 50 km. This does not allow for confident correlation of faulting events; however, the larger faults, delineating basement highs and associated lows, are well tracked during the mapping of the seismic horizons (Figure 4.1).

4.3.1 Basin Bounding Fault Family

The West Orphan basinal area is bounded by the Bonavista Fault and its imbricates (Figure 4.4). In many places a hinge-like zone defines the basin margin as the upper fault plane is located further west of the seismic line end. Due to the short extent of the seismic data this fault can only be seen on one or two lines so the Bonavista Fault has been inferred from previously published maps (i.e. Enachescu *et al.*, 2005) or based on adjacent basement trends. The fault was continuously mapped in the past using proprietary data not available for use in this study. The dip of this fault is fairly steep in

its upper part (~80º), shallows at medium depths (40º) and soles at depths >9000ms. This fault is a major crustal detachment which strikes to the N-S, dips to the east and was likely initiated in the Early Cretaceous and developed mainly in the mid to Late Cretaceous during the Labrador rift phase.

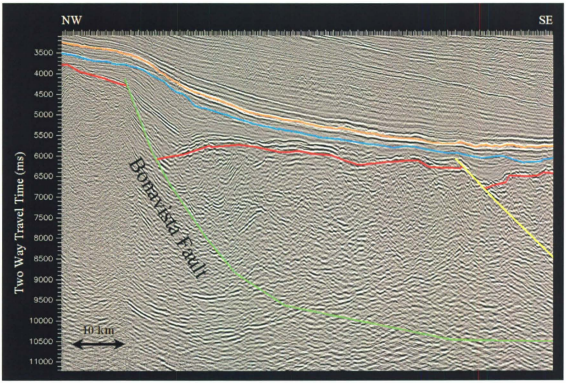

Figure 4.4: NW-SE dip profile through the West Orphan Basin showing basin bounding Bonavista Fault (green). Location shown in Figure 4.1.

4.3.2 Basement Involved Fault Family

Within the West Orphan Basin there are a series of basement involved faults which link at depth with the basin bounding Bonavista Fault, are normal faults, and are synthetic (seaward dipping) or antithetic (landward dipping) to the Bonavista Fault (Figure 4.5). These faults dissect the Bonavista Fault's hanging wall into a series of

horsts with associated full grabens and rotated basement blocks with associated half grabens. Basement involved faults were mapped based on offsets of the K3 sequence boundary and the character of the overlying Base Tertiary Unconformity (T). They are linear in the central part of the basin and curve sharply to the east as they merge with the basin bounding fault. Although the resolution of the data and the scarcity of coverage do not allow the termination of these faults to be imaged, basement trends show the curved nature of the faults.

The synthetic basement involved faults nearest the Bonavista Fault have a strike orientation roughly N-S and dip to the east (basinward). Those that are antithetic have a strike orientation of N-S and dip to the east (seaward). Farther east towards the Blue H-28 well the orientation of the basement involved faults changes to NNW-SSE with dips to the SE (synthetic) and NNW-SSE with NW dips (antithetic). This change in direction of the faults is a result of a change in the direction of the extensional vector as the rift propagated landward. The orientation of the faults rotates in a counterclockwise direction as the locus of extension changes from the NE-SW in the Late Jurassic-Early Cretaceous to N-S in the Late Cretaceous. The faults nearest the Blue H-28 well (Area B) show this change in rift orientation.

This fault family affected the pre-Mesozoic basement and the synrift successions. The resolution of the seismic data and the coarse nature of the seismic grid does not allow for detailed mapping of these faults. Mapping of the upper Cretaceous (K3) unconformity and the Base Tertiary Unconformity (T) does show that these faults were active until the Tertiary.

4.3.3 Cretaceous Faults

Major and minor faults likely exist in the West Orphan Basin; however, due to the coarse grid spacing, the resolution of the seismic data and the chaotic and opaque nature of the upper Cretaceous sequence, they cannot be easily identified nor correlated over large distances with any degree of confidence. Also, their detailed mapping was beyond the scope of this regional work.

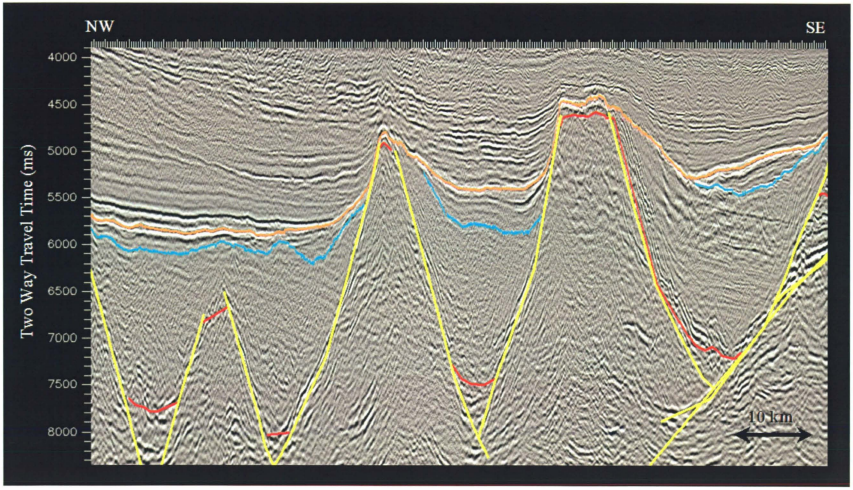

Figure 4.5: NW-SE dip seismic profile through the West Orphan Basin. Yellow lines are major basement involved faults. Sequence boundaries are: orange = Base Tertiary Unconformity, blue = K3 sequence boundary and red = basement. Location shown in Figure 4.1.

4.4 Transfer Fault Family

Transfer faults are the cratonic equivalent of transform faults, which are associated with mid-oceanic ridges and oceanic crust. Transfer faults are associated with regional extensional and compressional regimes (Gibbs, 1984) and can only be imaged seismically when the lithology and deformation style varies across the fault plane.

The Orphan Basin is separated from the Jeanne d'Arc Basin by a transfer zone known as the Cumberland Belt Transfer Zone (CBTZ). This zone is marked by a series of high relief basement blocks and is discernible by a linear, magnetic signature, which corresponds to a high gravity anomaly (Enachescu, 1987 and 1988, Enachescu *et al.*, 2005).

A transfer zone, the Charlie Gibbs Fracture Zone (CGFZ), which continues oceanward and joins a known transform fault with the same name, bounds the Orphan Basin to the north (Figure 2.1). Within the continental crust, this prerift feature separates rocks of the Precambrian, Avalon platform from the Central Appalachian mobile belt. The Charlie-Gibbs fracture zone is aligned with the offshore projection of the Dover fault, implying that a major offset in the modern Atlantic Ocean crust coincides with the Gander-Avalon collisional zone boundary (Williams *et al.*, 1999).

Within the study area no transfer faults were clearly identified; however, the existence of the Cumberland Belt Transfer Zone may provide a possible explanation for the easterly curve of the basin bounding and basement involved faults at the southern region of the Orphan Basin (Figure 4.1) and the geological complexity in the western region of the East Orphan Basin.

Several basement highs and lows and regional fault zones show offset along strike. This implies that transfer faults and accommodation zones have played a role in shaping the general structure of the Orphan Basin.

4.5 Tectonostratigraphic Evolution

Located the Atlantic passive margin, the Orphan Basin has undergone multiple stages of extension lasting approximately 160 Ma. Each period of extension was followed by subsidence and ended with a final, long lasting postrift stage in the Eocene, which resulted in the rapid subsidence of the basin. Initial rifting began in the East Orphan Basin and gradually moved westward with the later rift events causing remobilization of older tectonic and structural features in the basin. These multiple rift stages created two asymmetrical subdivisions known as the East Orphan and West Orphan basins. Within this section the areas previously described in 3.1 as Areas A, B and C, will be referred to in order to highlight important elements and features related to the Cretaceous tectonostratigraphic evolution of the Orphan Basin (Figure 4.6).

This long-lived extensional history with multiple rifting stages may explain the large area affected, the striking succession of ridges and troughs, the lack of major volcanic features and the great amount and rapid rate of thermal subsidence during the final postrift stage (Enachescu *et al.*, 2005). The structural complexity seen within the western parts of the East Orphan Basin (Area B) were likely caused by successive rifting and strike slip in a transtensional regime along the major transfer zones.

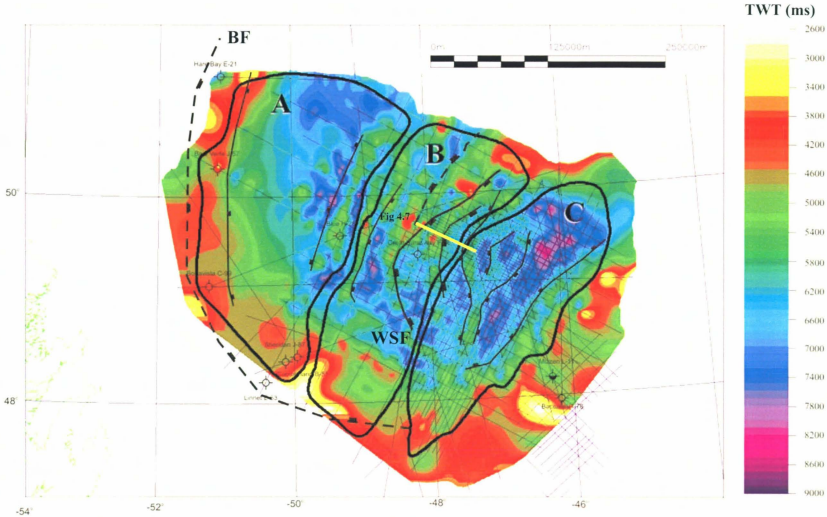

Figure 4.6: Time structure map of the seismic basement. The black polygons outline Areas A, B and C. Also shown are basin bounding faults (thick solid and dashed black lines) and major basement involved faults (thin black lines). BF = Bonavista Fault; WSF = White Sail Fault. Map is shown in two way travel time (ms).

4.5.1 Late Triassic – Early Jurassic

Based on the seismic mapping of the Orphan Basin and correlating seismic events to available wells in neighbouring basins, it was suggested that the East Orphan Basin contains complete Late Triassic and Jurassic sequences. This observation along with the mapping of major basin bounding and basement involved faults in the area shows that the East Orphan Basin was part of the initial Late Triassic – Early Jurassic Tethys rift that affected the Pangean continent. During this rift period an early synrift Mesozoic sedimentary basin chain extended from the future Gulf of Mexico to northern Europe (Enachescu *et al*., 2005).

The White Sail basin bounding fault (Figure 4.6) was initiated during the Tethys rift stage as a continuation of a major fault mapped in the Grand Banks area and bounds now the main Late Triassic-Early Jurassic East Orphan depocentre that has a NE-SW orientation. The Tethys rift phase affected Area C and the eastern parts of Area B of the basin. To the north the East Orphan Basin was likely connected to the Porcupine Basin while to the south, the East Orphan Basin was connected to the Grand Banks basins (Jeanne d'Arc and Flemish Pass basins). During this time basement involved faults formed which are synthetic and antithetic to the basin bounding fault and created large rotated basement blocks and horsts. The major basement involved faults in the East Orphan Basin (Area C and the eastern parts of Area B) have a predominantly NE-SW orientation approximately aligned with the orientation of the Late Triassic – Early Jurassic Tethys rift (Figure 4.6).

The White Sail Fault marks the limit of Triassic – Early Jurassic rifting deposition in the East Orphan Basin (Enachescu *et al.*, 2005). At the time of this initial rift the future West Orphan Basin was still an elevated part of the continent. It formed the western rift shoulder and during this rift stage was the likely provenance area for the Early Mesozoic alluvial and lacustrine sediments, which were deposited in the subsiding grabens and half grabens between basement highs. The thickest areas of Triassic-Jurassic sediments are seen along the basinward side of the White Sail fault and within the NE-SW trending depocentre in the central part of the East Orphan Basin (Figure 4.7). The early Mesozoic sediments thicken towards the large basement involved faults. Based on previous work by Enachescu *et al.* (2005), the sequences deposited east of the White Sail Fault during this early rift phase within the Orphan Basin are likely analogous to those encountered in the Jeanne d'Arc and Flemish Pass basins. Rifting was followed by thermal subsidence, marine invasion and deposition of a mixed evaporite interval. The presence of salt has been interpreted in this area based on correlations from adjacent basins (Enachescu et al., 2005); however, no obvious diapiric features are interpreted in the seismic data set like those seen in the Jeanne d'Arc Basin (Enachescu, 1987). In the East Orphan Basin the evaporite interval would be local and form stratified "salifere" sequences similar to the one drilled in the Porcupine Basin (Enachescu *et al.*, 2005).

The Triassic to Jurassic sedimentary successions were not mapped in any detail in this study and the above statements are observations noted during the interpretation and mapping of the Cretaceous sequences within the basin and during the Pan-Atlantic Petroleum Systems Consortium (PPSC) Basin Study Group work in the Orphan Basin (since 2004).

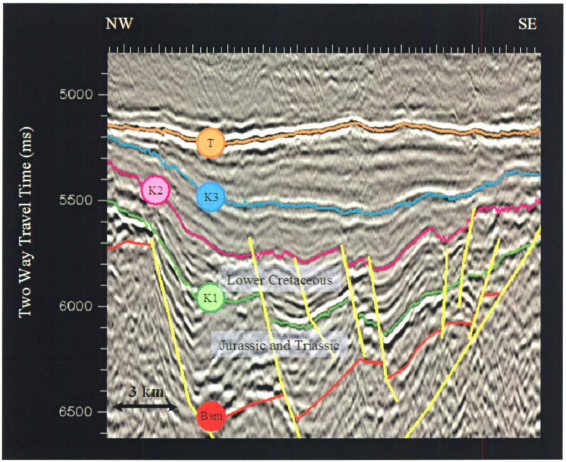

Figure 4.7: NW-SE seismic dip profile through Area B (East of the White Sail Fault) showing Jurassic and older sediments that thicken into large basement involved faults. Yellow lines are faults. Location shown in Figure 4.6.

In the mid Jurassic, Nova Scotia s~~eparated from~~ Morocco, the embryonic North Atlantic Ocean was formed, and the newly separated continental masses of Africa and North America began to move apart. Transfer movements took place on the Newfoundland Transform Zone, placing the continental crust of the Grand Banks in contact with transitional crust and newly formed oceanic crust, while the mid-Atlantic Ridge steadily produced basaltic oceanic floor marked by magnetic lineations (Enachescu *et al*., 2005).

4.5.2 Late Jurassic – Early Cretaceous

After a long period of thermal subsidence, the Atlantic rift was initiated in the Late Jurassic and had an approximate N-S orientation. During this rifting phase the basin bounding and basement involved faults, which were formed during the previous Tethys rift, were reactivated. Rifting propagated landward, beyond the White Sail Fault, new faults were formed and the East Orphan Basin (Areas B and C) continued to deepen and expand (Figure 4.6). The majority of the sediments deposited during this rift phase were likely derived from the western platform, which at that time was part of the present West Orphan Basin (Area A). The majority of this area was not involved in the Atlantic rift event. Some local basement highs were emergent within the basinal area and developed into proximal sediment sources. This is evidenced by the existence of Bajocian alluvial sands that were sampled at DSDP Site 111 on the Orphan Knoll (van Hinte *et al.*, 1995).

The Late Jurassic sediments were likely deposited in a similar paleoenvironment to that of the Jeanne d'Arc Basin, where a shallow epicontinental sea extended from Nova Scotia to the North Sea in the Kimmeridgian. Marine invasion occurred in the East Orphan Basin as the Atlantic rift caused the deepening of the basin. This is supported by the correlation of the Base Cretaceous (Tithonian Unconformity) marker (K1) from the Flemish Pass Basin into the East Orphan Basin. The time structure map of the Base Cretaceous unconformity shows a general deepening to the northeast and local deepening in the intervening troughs between basement highs (Figure 4.8).

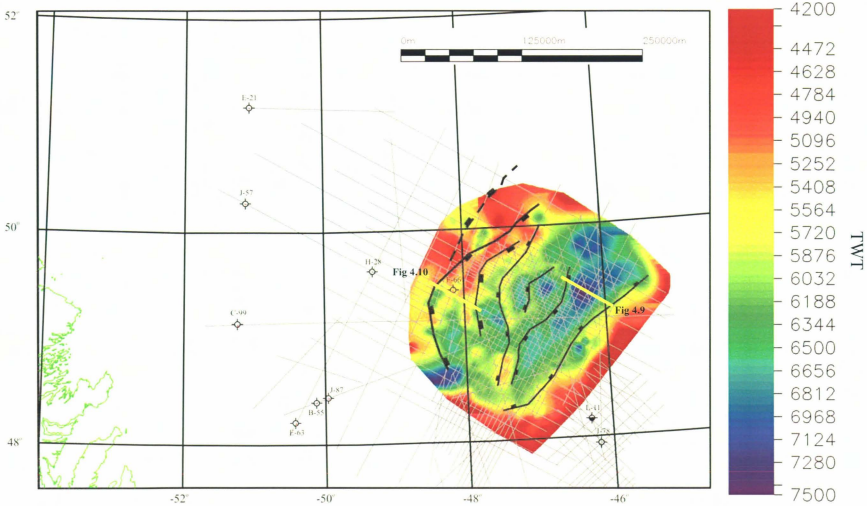

Figure 4.8: Time Structure map of the K1 Sequence Boundary (Base Cretaceous/Tithonian Unconformity) including the major basement involved and basin bounding faults which were active at this time (black lines). Mapping is done in two way travel time (ms).

Deposition of siliciclastic sediments occurred in the basin during the Early Cretaceous. These sediments show a highly reflective character on the seismic sections suggesting an alternating sandstone and shale succession, similar to the characteristics of the sequence in the Jeanne d'Arc Basin and at Blue H-28 (Figure 4.9). They are classified as the S2 depositional sequence in Chapter 3. This sequence is defined as the synrift sequence of the Atlantic rift. The sediments were likely derived from local basement highs and the western rift shoulder from erosion of Precambrian and Paleozoic rocks or older Mesozoic deposits.

In the basins adjacent to the Orphan Basin (Jeanne d'Arc and Porcupine basins), two major pulses of coarse clastic deposition occurred. The coarse clastics deposited in the East Orphan Basin are likely equivalent to the Late Jurassic Jeanne d'Arc Formation and the Early Cretaceous Hibernia Formation sandstones (Enachescu *et al.*, 2005; Driscoll *et al.*, 1995 and Sinclair *et al.*, 1994; McAlpine, 1990; Enachescu, 1987).

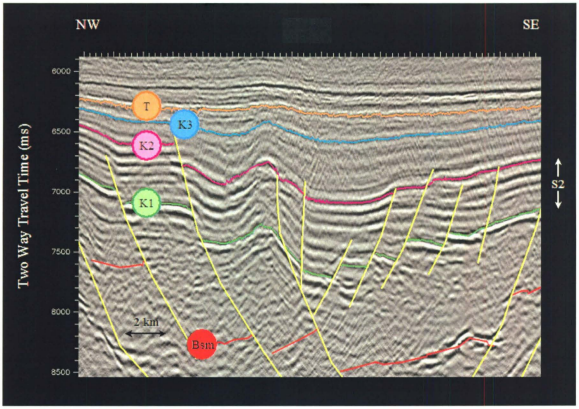

Figure 4.9: NW-SE seismic dip profile through Area C of the East Orphan Basin showing highly reflective Early Cretaceous S2 synrift sequence. Faults are mainly contained within the synrift (S2) sediments. Location shown in Figure 4.8.

During the Atlantic rift the extensional vector changed direction, and this change is seen in the orientation of the major basement involved faults (Figure 4.6). As the western parts of Area B were involved in this rift, the trend in the orientation of the faults changed to NNE-SSW indicating a more west-east extension. Transtension due to the rotation of the extensional vector caused inversion and complex structures. Large extensional anticlines are pervasive through the Early Cretaceous sequences in Area B (Figure 4.10), while in Area C, which was less affected by the change in rift orientation,

the effects are much more subdued (Figure 4.9). As rifting propagated landward, so did the deposition of the S2 (Early Cretaceous) depositional sequence. The upper part of this sequence (K2) extends to the most eastern regions of Area A (Figure 4.11).

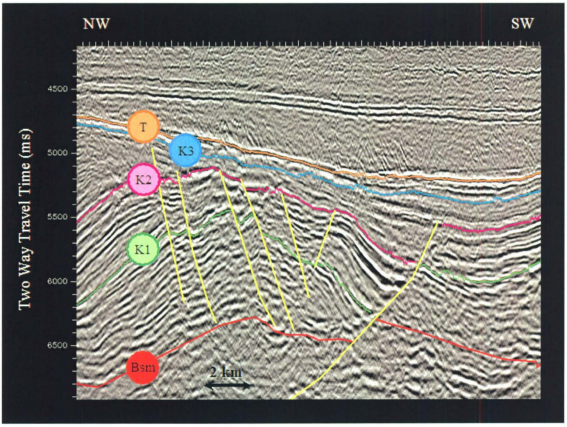

Figure 4.10: NW-SE seismic dip profile through Area B showing large-scale antiform of Early Cretaceous age affecting Early Cretaceous and earlier sediments. This feature was later reactivated and inverted during the Aptian-Albian Labrador rift. Location shown in Figure 4.8.

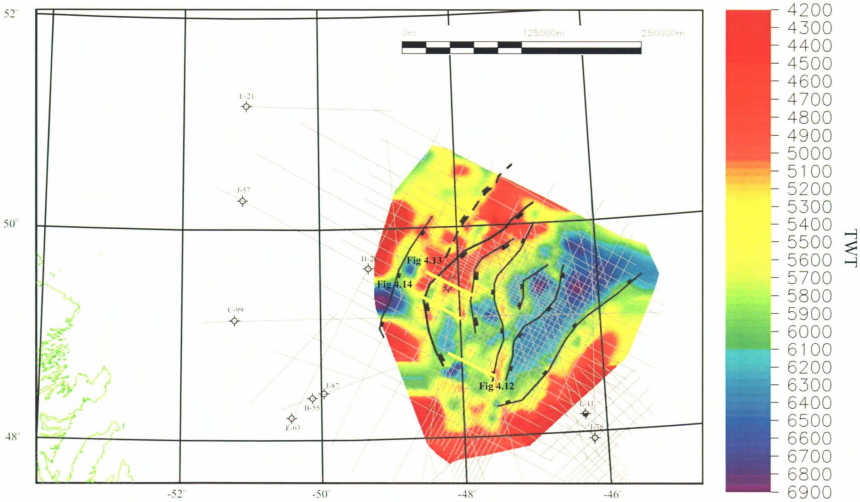

Figure 4.11: Time Structure map of K2 sequence boundary (top of Atlantic synrift sequence) including major basement involved and basin bounding faults active during this period. Mapping was done in two way travel time (ms).

In Area C, the K2 sequence boundary marks the end of rifting. This was concluded as the faults that affected the synrift sequence commonly do not displace the upper K2 sequence boundary (Figure 4.9). The overlying S3 depositional sequence is seismically transparent. This has been interpreted as being composed primarily of shales equivalent to the Nautilus shales in the Jeanne d'Arc Basin, which were likely deposited as the basin underwent thermal subsidence and as sea level rise occurred. In Area B the K2 sequence boundary marks the end of the rifting associated with the Atlantic rift; however, the synrift faults show late movement due to the reactivation of these faults during the Aptian-Albian Labrador rift event (Figure 4.12).

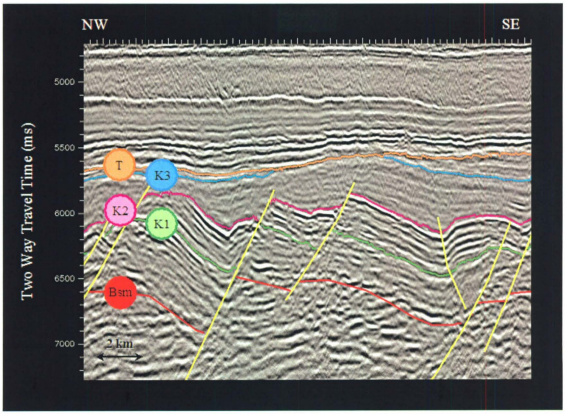

Figure 4.12: NW-SE dip seismic profile through Area B showing faults, which affect the K2 (Early Cretaceous) sequence boundary. This implies late movement along these faults attributed to the Aptian-Albian Labrador rift. Location shown in Figure 4.11.

4.5.3 Aptian - Albian

The third phase of rifting to affect the Orphan Basin took place during the Aptian-Albian. This event marks the final stage of the separation of the Grand Banks from Iberia and culminated with the disconnection of the Flemish Cap from Galicia Bank in the Aptian. Also at this time the Orphan Basin began to separate from its Irish conjugate basins (Enachescu *et al.*, 2005). This rift event also caused the early separation of Greenland from Labrador and the initial development of the Cretaceous Saglek and Hopedale basins of the Labrador margin.

As this rifting started, the western rift shoulder migrated landward and the Bonavista basin bounding fault developed. This progressive migration of the basin bounding fault in a landward (westward) direction dissected the Paleozoic platform area of the West Orphan Basin (Area A) into progressively younger sedimentary troughs. The oldest parts of the West Orphan Basin are around the Blue H-28 well and the youngest areas are adjacent to the western Bonavista Platform. The change in rift direction is again marked by the counterclockwise rotation of the major basement involved faults in Area A. They show an orientation of N-S to NNW-SSE (Figure 4.6) roughly perpendicular to the direction of extension. The timing of opening of the West Orphan Basin is age-equivalent to the opening and development of the Labrador basins.

Deposition of Aptian-Albian sediments in the West Orphan Basin were likely derived from the western platform and local basement highs that emerged and became sub-aerial at this time. The sediments are likely composed of siliciclastics analogous to

those seen in the adjacent basins such as the Bjarni Formation sandstones in the Labrador basins to the north and the Ben Nevis sandstones in the Jeanne d'Arc Basin to the south.

During the Albian the main intra-basinal ridges, the Orphan Knoll and the Central Orphan High began to emerge and became likely sources for locally derived sediments. The extensional anticlines that were formed during the previous Atlantic rift phase in Area B were modified and uplifted as a result of transtension due to a change in the extensional vector and associated uplift of local basement highs (Figures 4.10 and 4.13). Differential, multi-directional, ridge push was also invoked as a possible factor in the inversion of these structures (Enachescu and Hogg, 2005; Enachescu *et al.*, 2005).

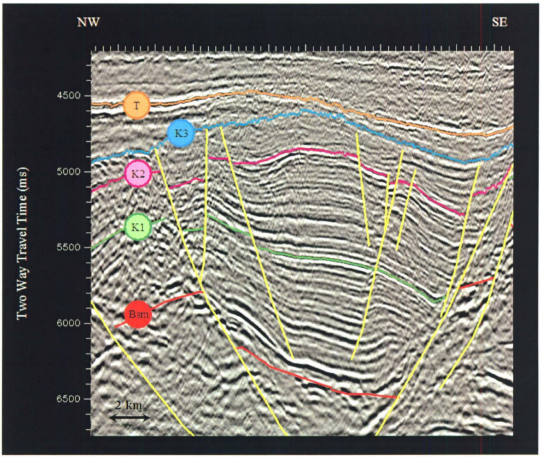

Figure 4.13: Extensional anticline in Area B which has been modified and inverted due to transtension and "ridge push". Location shown in Figure 4.11.

These compressional events modified the extensional structures within the East Orphan Basin. The resulting structures are very complex features reflecting multistage synrift deformation in multiple directions causing complicated relationships between the basement and sedimentary cover.

At the end of the Albian, the Orphan Basin separated from the southwestern Irish offshore basins while extension within the basin continued through the early Late Cretaceous. The West Orphan Basin was connected to the south Labrador shelf and slope basins. Numerous parallel ridges and troughs, with a roughly north south orientation, were formed throughout the sub basin. The local depressions later deepened as a result of tectonic subsidence during the Late Cretaceous and rapid thermal subsidence in the Eocene. These troughs were filled with mainly siliciclastic sediments derived from the western platform and local highs (i.e. basement highs, Central Orphan High and the Orphan Knoll).

4.5.4 Late Cretaceous to Paleocene

A fourth rift phase that affected the West Orphan Basin has been proposed by Enachescu *et al.* (2005). The locus of extensional movements during the Late Cretaceous-Early Tertiary was between Labrador and Greenland and Greenland and northern Europe. The area was also affected by the West Greenland volcanic event and the formation of the Iceland hot spot. It is proposed that this rift event caused reactivation of the faults seen in the West Orphan Basin. Movements along the Charlie Gibbs

Transform Zone were oblique-slip and caused block movements and reactivation of the basement highs. These basement highs are commonly devoid of Mesozoic cover or have a thin condensed Late Cretaceous section as seen at the Blue H-28 well.

During the Late Cretaceous, uplift and/or sea level fall have caused the development of a regional unconformity of Santonian age (K3 sequence boundary). This erosional unconformity primarily affected Areas A and B eroding Early and Late Cretaceous sequences (Figure 4.13). In Area C this sequence boundary is a correlable conformity as it does not appear to erode the underlying sequences.

This unconformity is channelized in Area B and the overlying S4 depositional sequence (Late Cretaceous) shows much more seismic reflectivity than the underlying S3 depositional sequence (Figure 4.14). This indicates the deposition of channel fill sands likely equivalent to the Fox Harbour Member sandstones seen in the Jeanne d'Arc Basin. The channel is oriented NE-SW (Figure 4.15) which is confidently resolved in Area B. In Area A this sequence boundary is unmistakably an unconformity, but it does not appear to be channelized. The extent of this channel to the northwest is inferred by mapping the deep regions in Area A. These inferred regions are annotated on the K3 time structure map by dashed lines (Figure 4.15).

While the strike of major basement involved faults in the Orphan Basin show a counterclockwise rotation in the landward direction due to long lasting wide rifting, mid to Late Cretaceous movement of the Flemish Cap had an apparent clockwise rotation (Enachescu et al., 2005; Sibuet *et al.*, 2007).

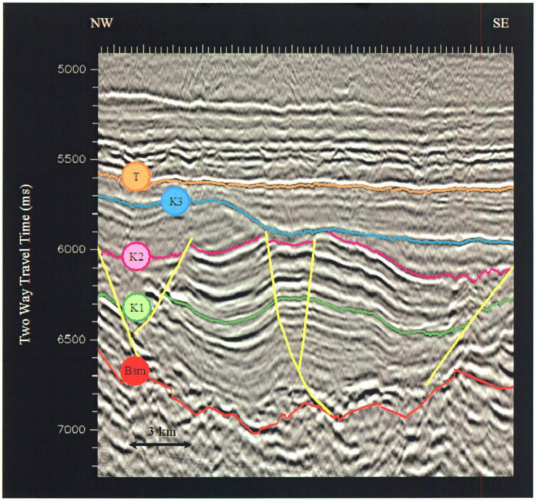

Figure 4.14: NW-SE dip seismic profile through Area B of the Orphan Basin showing the K3 (Santonian) erosional/channelized unconformity. Location shown in Figure 4.11.

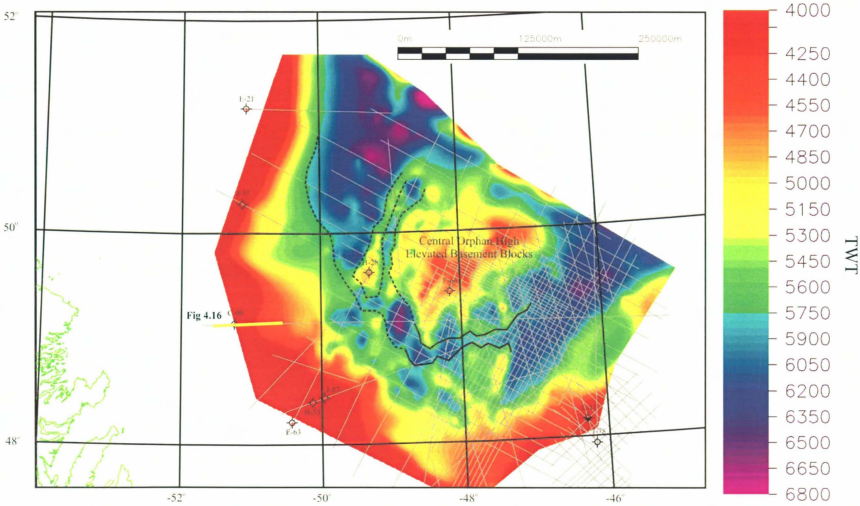

Figure 4.15: Time structure map of the K2 (Santonian) sequence boundary. In some areas the erosional unconformity appears channelized. Black lines outline area where seismic sections show an erosional channel. Dashed black lines represent areas where seismic resolution is too low to continuously map the channel.

Extensive erosion took place in the Orphan Basin during the Late Cretaceous – Early Tertiary. This erosional event is commonly referred to throughout the Grand Banks and Labrador basins as the Base Tertiary Unconformity. This unconformity eroded the tops of many of the uplifted basement blocks in Areas A and B (Figure 4.16) removing most, if not all, of the Mesozoic sediments. This unconformity is widespread and mappable over the entire Orphan Basin (Figure 4.17). Area A (West Orphan Basin) was affected the most by erosion at the Base Tertiary Unconformity showing that significant structural inversion took place in the western part of the basin.

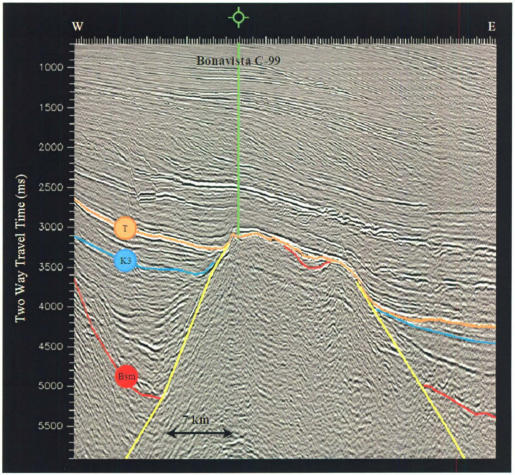

Figure 4.16: W-E seismic profile through Area A of the Orphan Basin showing eroded top of a basement block at the Base Tertiary Unconformity. Location shown in Figure 4.15

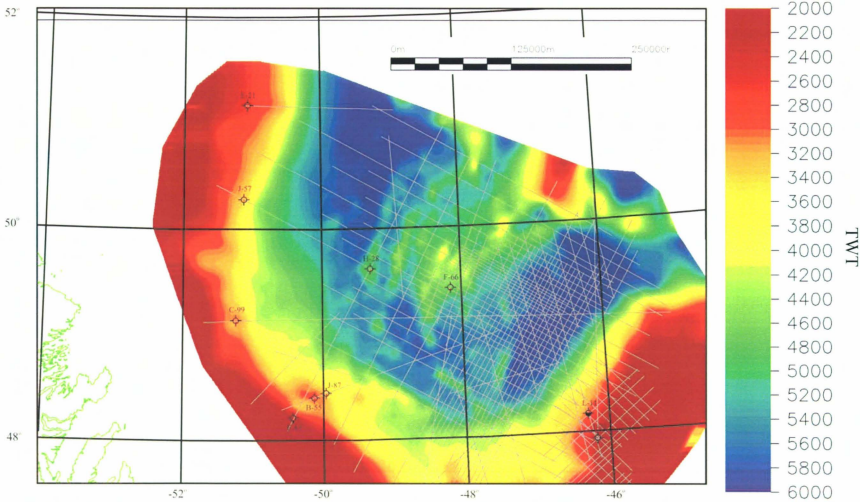

Figure 4.17: Time structure map of T sequence boundary (Base Tertiary Unconformity). Mapping was done in two way time (ms).

The Orphan Basin underwent thermal subsidence since the Late Cretaceous – Early Tertiary. The Paleocene to present sequences are dominated by thick shales and sands derived mainly from the Bonavista Platform. A study of the Tertiary sequences was outside the scope of this study; however, isochron mapping of the Tertiary to Water Bottom was done in order to highlight thickness variations and potential areas of maturation of Late Cretaceous – Early Tertiary source rocks. This will be discussed in the subsequent chapter. The following two figures (Figures 4.18 and 4.19) summarize the tectonostratigraphic evolution of the Orphan Basin.

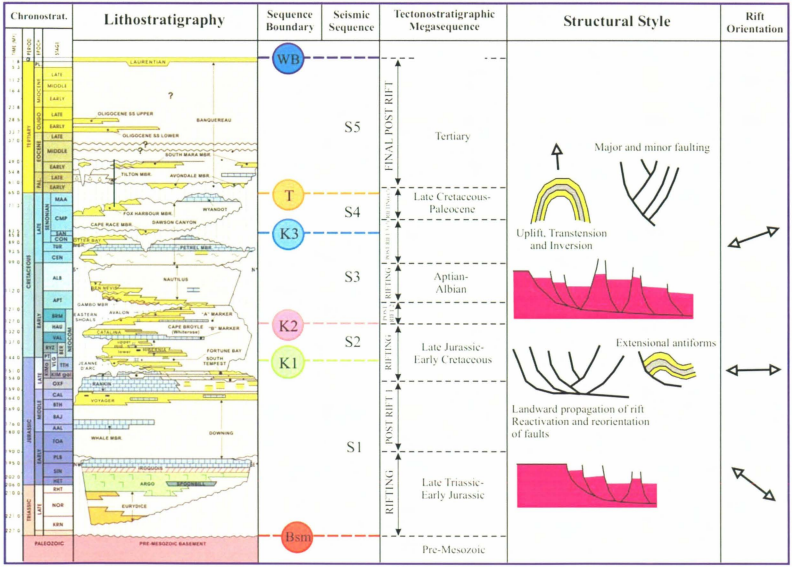

Figure 4.18: Lithostratigraphy of Jeanne d'Arc Basin after C-NLOPB (2003) and Sinclair (1988), seismic sequence boundaries and seismic sequences mapped in the Orphan Basin in this thesis and structural evolution.

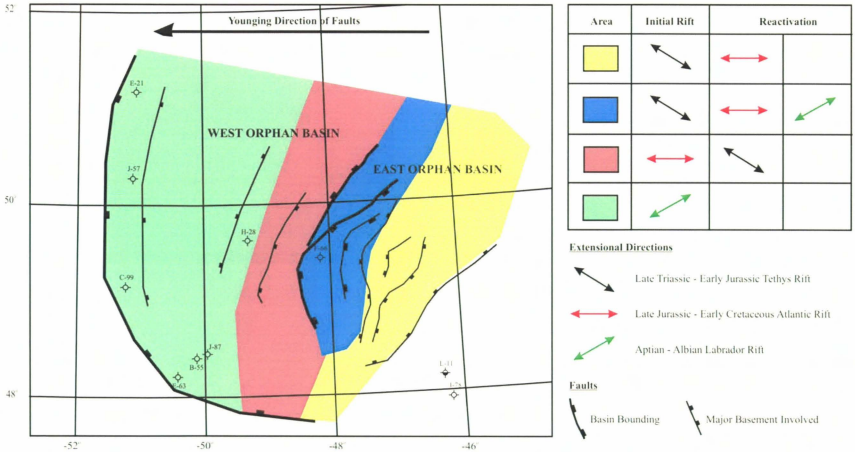

Figure 4.19: Schematic structural map of the Orphan Basin showing subdivisions and ages of areas affected by rifting events. Black lines are basin bounding and major basement involved faults showing counterclockwise rotation from east to west. Age of rifting and age of fault development younging in the landward direction.

Chapter 5

Implications for Petroleum Systems

5.1 Introduction

There were 133 exploration wells drilled in the past four decades in the Newfoundland and Labrador offshore area that have yielded 23 confirmed oil and gas discoveries. These discoveries have been estimated at 2.1 billion barrels of oil, 10 trillion cubic feet of natural gas and 450 million barrels of Natural Gas Liquids (C-NLOPB statistics). The majority of the discoveries have been made in and around the Jeanne d'Arc Basin while five gas discoveries were made in the Labrador basins. Since the first large discovery in 1979 (the Hibernia field), exploration has been focused mostly around the Jeanne d'Arc Basin and adjacent Central Ridge with only a few wells drilled in the other Mesozoic rift basins.

The Orphan Basin is truly a frontier area. Although exploration permits and licenses were held in the area throughout the 1970s and early 1980s and various operators drilled seven wells (six in the shallow water margin of the basin), unsuccessful drilling results led to the abandonment of future programs and the basin remained unexplored for more than 20 years.

Renewed interest in the basin came on the heels of a major non-exclusive seismic acquisition effort by GSI during 2000 to 2003. They collected approximately 20,000 km of new data covering most of the basin. This data revealed two large Mesozoic aged sub-

basins (East and West Orphan Basin) and showed the existence of large-scale closures (Smee *et al.*, 2003; Smee, 2003). This new information brought about a record land sale for the Newfoundland and Labrador offshore area in December 2003 with $672 Million in exploration work commitments for eight large blocks situated in deep and ultra-deep water. Several recent presentations and articles discussed the regional geology and possible petroleum systems for the East and West Orphan basins and its relationship to the Jeanne d'Arc, Flemish Pass and Labrador basins (Enachescu *et al.*, 2004a; Enachescu *et al.*, 2004b; Enachescu *et al.*, 2004c; Enachescu *et al.*, 2005; Hardy and Enachescu, 2005 and 2007; Kearsey and Enachescu, 2005).

"A petroleum system is a natural system that encompasses a pod of active source rock and all the related oil and gas and which includes all the geological elements and processes that are essential if a hydrocarbon accumulation is to exist" (Magoon and Dow, 1994). A working petroleum system is one that includes all elements of a petroleum system (source rock, migration route, reservoir rock, seal and trap) and has undergone the processes necessary (generation, migration and accumulation) to produce economic accumulations of oil and gas.

5.2 Potential for Source Rocks

Late Jurassic paleogeographic reconstructions and regional mapping (Masson and Miles, 1986; Coffin *et al.*, 1992; Verhoef and Srivastava, 1992; Srivastava *et al.*, 2000; Sibuet *et al.*, 2005; Enachescu *et al.*, 2005; and Kearsey and Enachescu, 2005) show that the East Orphan Basin was connected until the Early Cretaceous to the Grand Banks and

the west Irish margin rift basins (Porcupine and Rockall). During the Late Jurassic-Early Cretaceous Atlantic rifting stage, the Orphan Basin was connected to areas with proven petroleum systems: the petroleum prolific Jeanne d'Arc Basin to the south, the source proven Flemish Pass Basin to the southeast and the oil prone Porcupine Basin to the northeast. The euxinic conditions that likely existed in many of the North Atlantic (Enachescu *et al.*, 2005) inter-connected marginal basins during the Late Jurassic lend credence to the potential presence of oil generating source rock in the East Orphan Basin.

The prolific Kimmeridgian Egret Member has been a proven source for oil and gas in the Jeanne d'Arc Basin and has charged some world-class fields in that area, namely Hibernia (1244 mmbls), Terra Nova (354 mmbls) and White Rose (283 mmbls) (CNLOPB, 2003). In this basin the organic rich Egret Member is a basin-wide occurring source rock, has an average total organic content (TOC) of approximately 3-4% and hydrogen index (HI) values ranging from 500-800mg/g TOC (von der Dick *et al.*, 1989; Mackay *et al.*, 1990; McAlpine, 1990). There are also Kimmeridgian source rocks in the North Sea (Viking and Central Graben) and the Porcupine Basin. The oil accumulations seen at the Connemara field in the northern Porcupine basin show a mixed marine and lacustrine Middle Jurassic source with a variable marine Upper Jurassic (Kimmeridgian) component (Scotchman, 2001). It is likely that this proto-Atlantic epeiric sea that deposited the Egret Member extended from the southern Grand Banks, through the East Orphan Basin and northwards into the Irish Margin basins (Figure 5.1)

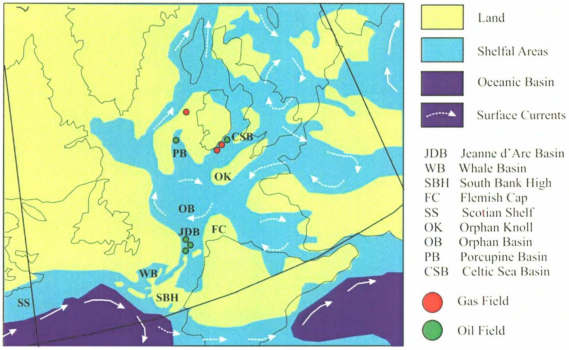

Figure 5.1: North Atlantic Oxfordian-Kimmeridgian paleo-oceanography (154 ma) created by Jonathan Bujak, Bujak-Mudge. Modified from C-NLOPB Call For Bids NF 03-1 (Smee, 2003).

Several key wells in adjacent basins, i.e. Panther P-52 in the Jeanne d'Arc Basin; and Baccalieu I-78, and Mizzen L-11 in the Flemish Pass Basin, encountered thick Kimmeridgian-age source rocks and are located up-dip in areas presently connecting with the East Orphan Basin. The Egret Member sequence penetrated in these wells can be easily correlated along seismic lines running into the licensed area of the Orphan Basin (Enachescu *et al*., 2005). Geochemical analysis of wells of the West Orphan Basin have determined that "the hydrocarbon shows present in the sediments penetrated by the Sheridan J-87 well and the Baie Verte J-57 well show a close similarity to the oils reservoired in the Jeanne d'Arc Basin" (Smee, 2003; Bayliss, 1982).

It was beyond the scope of this study to map sequences below the Base Cretaceous Unconformity; however, an inferred Kimmeridgian horizon was created using information from the Baccalieu I-78 and Mizzen L-11 Flemish Pass Basin wells. The distance between the Tithonian Unconformity (Top Jurassic/Base Cretaceous) and the Upper Kimmeridgian source rock was calculated at the Baccalieu well site. This distance was then converted to time using a velocity function derived from the time-depth information for the well (2100 m/s average velocity, see Appendix A). Adding this distance in time to the Base Cretaceous Unconformity in the Orphan Basin gives a rough approximation of the depth where the Kimmeridgian sequence is likely to be present.

Koning *et al.* (1988) reported the oil window for the basin to range between 3100 m and 5100 m. Condensate wet gas was present in the Blue H-28 well between 5060 m – 5281 m (top of Paleozoic). Using the velocity function obtained above and converting to time, the oil window in the East Orphan Basin ranges in time from approximately 2952 ms to 4857 ms. An isochron map (Figure 5.2) was generated for the Kimmeridgian to water bottom horizon and a colourbar was created to highlight the oil window. In the present configuration of the Orphan Basin, where the Kimmeridgian sequence lies higher than 2950 ms the source rock is immature, between 2950 ms and 4850 ms is mature and beyond 4850 ms is overmature. The assumption is made that the Kimmeridgian rocks are evenly distributed in the basin and that they have fair to good oil generating potential.

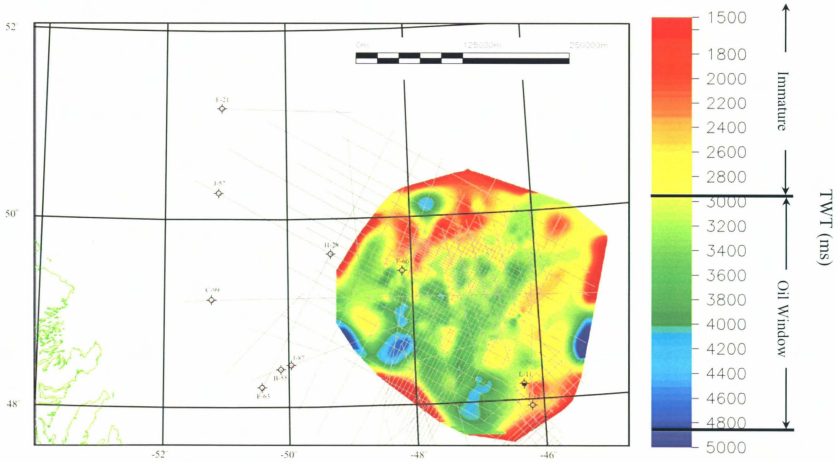

Figure 5.2: Isochron map of Kimmeridgian Horizon to Water Bottom. Thickness is in TWT (ms). The oil window was converted from depth to time using a tentative average velocity of 2100 m/s. This map indicates where hydrocarbons would be generated. The following ranges were recognized: < 2950 ms = immature; 2950 – 4850 ms = oil generating; >4850 ms = gas generating. Hydrocarbon generation depth after Koning *et al.*, 1988.

From this map we see that where the interpreted Kimmeridgian is today in the East Orphan Basin, a large area falls within the oil widow reported by Koning *et al.* (1988). The construction of the Kimmeridgian horizon map and the velocity function used to convert the oil window to depth are intended only as a first approximation to highlight the areas of potential mature source rock. This Kimmeridgian seismic horizon is located only in the East Orphan Basin (Areas B and C) and is not present west of the White Sail Fault except in deep half grabens. A large portion of the mature source rock is found in Area C, which is down dip of the large structural highs seen in the basin (Area B). Where the Kimmeridgian is deeper than 4857 ms and is overmature it may generate natural gas. Large accumulations of gas are therefore possible in the East Orphan Basin. Numerous bright spots and gas chimneys were detected on the seismic data (Enachescu *et al.*, 2005; Hardy and Enachescu, 2007).

Relatively high percentages of amorphous, oil-generating kerogens were present in the Eocene and Upper Cretaceous sections at Blue H-28. Severe insitu oxidation has reduced generation capacities, and the zones with significant organic richness within the oil window are too thin for effective hydrocarbon generation (Koning *et al.*, 1988). Blue H-28 was drilled on a basement high where Cretaceous sequences are extremely thin. These Eocene and Cretaceous source beds could contain organic rich sediments which have a good source potential if they were deposited in areas where the water was deep enough to provide anoxic conditions and where thicker accumulations of sediments occur.

In the Jeanne d'Arc Basin, von der Dick (1989) identified a potential source rock in a shale unit above the Jeanne d'Arc Formation sandstone (latest Jurassic or earliest Cretaceous). This interval was found to have a TOC as high as 4%, contains Type III

kerogen and matures below 4000m. This unit has apparently contributed a limited amount of liquid hydrocarbons to reservoired oils in the Jeanne d'Arc Basin (von der Dick, 1989).

At site 1276 during the Leg 210 IODP drilling expedition a thick interval of mudrocks was cored (Figure 5.3) These sediments were determined to be hemipelagic and turbiditic, with much of the preserved organic matter likely of terriginous origin. Within Subunits 5A and 5B there were recorded several thin intervals of laminated black shale with TOC 3-7% and HI values 231-452 mg HC/g TOC. These values are characteristic of marine algal organic mater. These black shales correlated with the latest Cenomanian – earliest Turonian Ocean Anoxic Event 2, which represents a time of enhanced organic productivity, perhaps triggered by tectonic activity or changes in ocean circulation (Tucholke *et al.*, Leg 210 Preliminary Report, 2004).

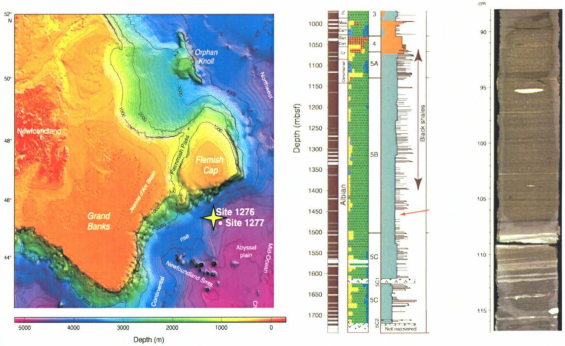

Figure 5.3: Results from drilling at IODP site 1276 (yellow star). Synthesis of lithostratigraphic units, age and lithology. Close up photograph of finely laminated black shales in lithologic Subunit 5B shown to the right. Modified from Tucholke *et al.* (2004).

In the Labrador basins to the north, the major source rock is the Early Cretaceous (Aptian-Albian) Bjarni Formation, which is a terrestrially derived gas prone source. The Bjarni shales are credited with being the primary source for the gas discoveries in the Saglek and Hopedale basins (Fowler *et al.*, 2005). They contain predominantly Type III kerogen and have a TOC 1-4%. The Late Cretaceous Markland Formation is another Type III source rock that has some marine influence (Geological Survey of Canada, 1989). A post Aptian seaway extended from the Grand Banks into the Orphan Basin and into northern Europe and the Labrador area. This provides possible gas prone mid to Late Cretaceous source rocks equivalent to the Bjarni Formation and the Markland shale of the Labrador basins in the West Orphan Basin. The Late Cretaceous section drilled at Blue H-28 contain relatively high percentages of amorphous oil generating kerogen which, if mature, could yield wet gas and some crude oil (Dow, 1979; Koning *et al.*, 1988).

In the Jeanne d'Arc Basin organic rich shales were encountered in the Paleocene section at Nautilus C-92 (Sinclair, 1992). Sampling showed that the kerogen was made up of mostly amorphous organic matter with some algal detritus of probably marine origin matter (von der Dick, 1989). The TOC values are high, 2-4% in the section; however, they have low source potential due to severe oxidation of the organics probably during or shortly after deposition in an open marine system (von der Dick. 1989, von der Dick *et al.*, 1989 and Sinclair *et al.* 1992). There is a good source potential in local anoxic pockets or in deeper parts of the basin where the shales may be in the oil window.

There is also a potential for source rocks in the Early Tertiary sequences in the Orphan Basin. Geochemical analysis of the Tertiary aged shales penetrated by the Blue Well in the West Orphan Basin indicates a high proportion of organic carbon (2-6%

TOC), described as "oil-prone amorphous-sapropelic kerogen" (Bayliss, 1990). Oligocene and younger rocks and the Paleozoic rocks in Blue H-28 contain primarily terrestrial, dry gas-generating kerogens. Organic-rich shales were also drilled in the lower Tertiary at Hare Bay E-21 (1.7-3.5% TOC), Baie Verte J-57 (1.5-6% TOC), Sheridan J-87 (1.3-3% TOC), Cumberland B-55 (1->3% TOC) and Linnet E-63 (1-7% TOC). These potential source rocks were deemed to be too thin and immature but could become an effective source rock where they are thicker in half grabens and with sufficient depth of burial. The thickness of the Tertiary sequences (Figure 5.4) in the Orphan Basin gives rise to the possibility that some of these organic shales are mature in places. Highly organic shales seen in the lower Tertiary may be mature due to greater depth of burial and cannot be discounted as a possibility for potential source (Sinclair *et al.*, 1992).

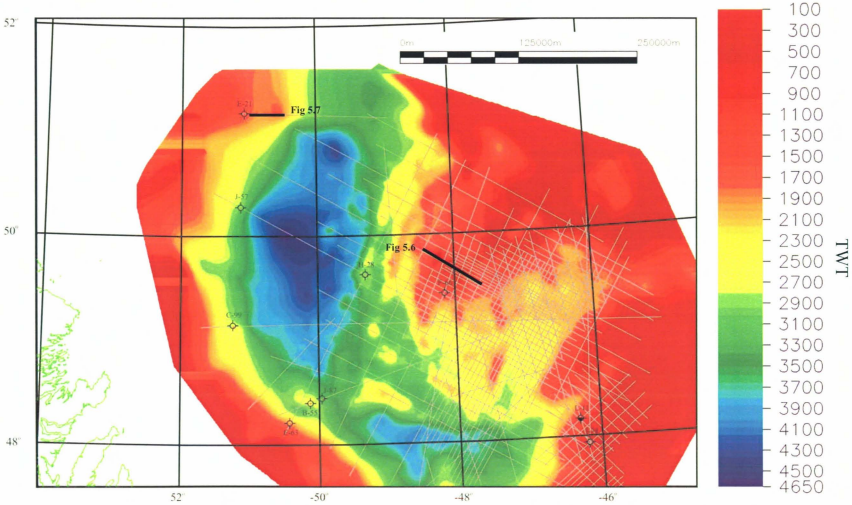

Figure 5.4: Isochron map of Tertiary sequence (Water Bottom to Base Tertiary Unconformity). Thickness is shown in two way travel time (ms). Areas of thickest accumulations of sediments (greens and blues) indicate areas where Lower Tertiary and Cretaceous source rocks may be mature. Gas is expected to be generated from deeper levels and accumulate in complex traps.

5.3 Potential for Reservoirs

Good to excellent Cretaceous sandstone reservoirs have been drilled in the Bonavista C-99, Linnet E-63, and Blue H-28 wells (Smee, 2003; Smee *et al.*, 2003; Hardy and Enachescu, 2005; Hardy and Enachescu, 2007), in the Flemish Pass (Enachescu and Hogg, 2007) and in the Jeanne d'Arc basins (McAlpine, 1990). Carbonate reservoirs of the Paleozoic "basement" have also shown reservoir properties in wells drilled in the Hopedale Basin, Labrador (Enachescu, 2006).

The major sandstone reservoirs in the adjacent Jeanne d'Arc Basin are Late Jurassic to Early Cretaceous in age and include the Jeanne d'Arc, Hibernia, Avalon and Ben Nevis sandstones. The Jeanne d'Arc Formation sandstone is the principal reservoir at the Terra Nova oilfield, the Hibernia Formation sandstone is the principal reservoir at the Hibernia oilfield and the Avalon and Ben Nevis formations are the drilling targets at the White Rose field. There are other excellent reservoirs in the Late Cretaceous Dawson Canyon Formation and in the Paleocene South Mara Formation; however, only a couple of oil/hydrocarbon pools have been encountered at these levels.

The Early Cretaceous sequences are the most likely reservoirs in the Orphan Basin. The DSDP 111 drilled on the Orphan Knoll suggests that the emergent blocks surrounding the Orphan Basin area are partly comprised of Paleozoic sandstones (Smee, 2003). These elevated blocks would have supplied the sediments deposited in the basin (Figure 5.5). Strong amplitude events and the seismic character of the interpreted Early Cretaceous sequences indicate a strong probability of coarse clastics in the basin (Figure 5.6).

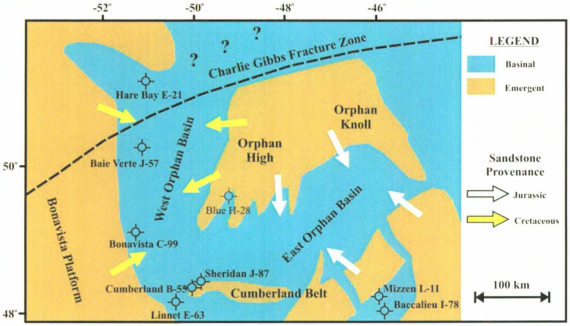

Figure 5.5: Schematic diagram showing provenance for predominantly Late Jurassic – Early Cretaceous (white arrows) and Aptian – Late Cretaceous (yellow arrows) reservoir sands. Modified from Smee (2003).

In the Orphan Basin the K2 sequence boundary marks the top of the Early Cretaceous synrift succession (Figure 5.6). This sequence exists in Areas B and C and in the most eastern regions of Area A. Large structural traps with thick sequences of the Early Cretaceous sediments are the most likely hydrocarbon plays for this part of the basin. Blue H-28 drilled 55 m of clean, medium to coarse-grained sandstones in the Lower Cretaceous section. The porosities were up to 19%; however, the reservoir interval was found to be water saturated (Koning *et al.*, 1988).

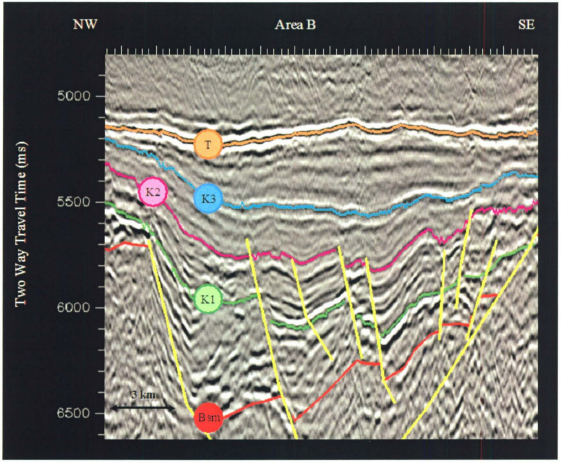

Figure 5.6: Seismic profile through Area B showing highly reflective Early Cretaceous sequence bounded by K1 (green) and K2 (pink) sequence boundaries. The highly reflective seismic character indicates potential for coarse clastics as seen at Blue H-28. Location shown in Figure 5.4.

The Late Cretaceous section of the Bonavista C-99 well and the Linnet E-63 well confirms that reservoir quality sands are present in the Orphan Basin. There were minor porous sands and gravels seen in the Tertiary section at Blue H-28 but they were not of significance since they are too shallow and do not occur in a structural closure position (Koning *et al*., 1988).

Evidence of basement floor siliciclastic fans of Late Cretaceous and Early Tertiary age are seen on seismic lines (Figure 5.7). These are postulated to have been

derived from the western platform and local basement highs and present an untested play type in the basin. These features are commonly seen in the Late Cretaceous and Tertiary sections of the West Orphan Basin.

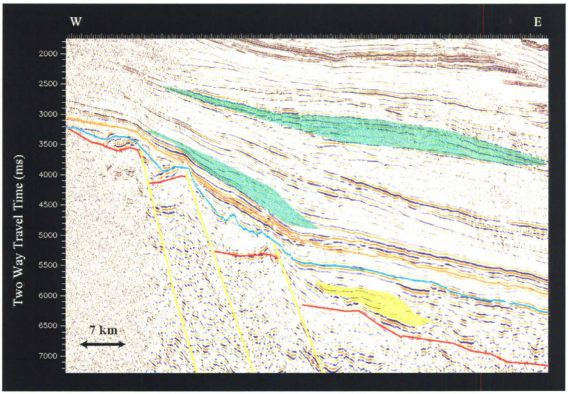

Figure 5.7: W-E seismic profile through West Orphan Basin showing interpreted Tertiary fans (green) and Late Cretaceous fan (yellow). Location shown in Figure 5.4.

5.4 Traps

Within the Orphan Basin there are numerous structures that can provide traps for migrated hydrocarbon. The largest and most attractive structures exist in Area B, where a thick Early Mesozoic (possible Triassic and Jurassic) sedimentary section exists. During the Atlantic rift stage the synrift sediments of Late Jurassic – Early Cretaceous age were eroded from surrounding rift shoulders and from intra-basinal highs, deposited in the basin and formed large extensional anticlines, horsts and rotated blocks. Some of the rollover anticlines show growth strata due to syn-depositional movement along listric faults. These large structures were later reactivated and modified during the Aptian-Albian Labrador rift. Structural inversion due to trans-tension amplified some of the structures during the mid-Cretaceous and Late Cretaceous-Paleocene time.

A time-structure map of the K2 sequence boundary (top of Atlantic synrift sequence) was created to show areas of prospectivity and closure of these large structures (Figure 5.8). This time-structure map is constructed at the top of the interpreted reservoir interval. Two examples of closure are shown in Figures 5.9-5.12. The K2 event is not always present over the basement highs. Using computer based mapping and contouring packages has limitations. The mapping package "fills in" and contours areas where the K2 sequence boundary was not interpreted, i.e. areas where K2 was eroded by overlying unconformities. The time structure map of this event shows areas of large structural closure; however, some areas are large basement highs with very thin (if any) Early Cretaceous cover (Figure 5.13).

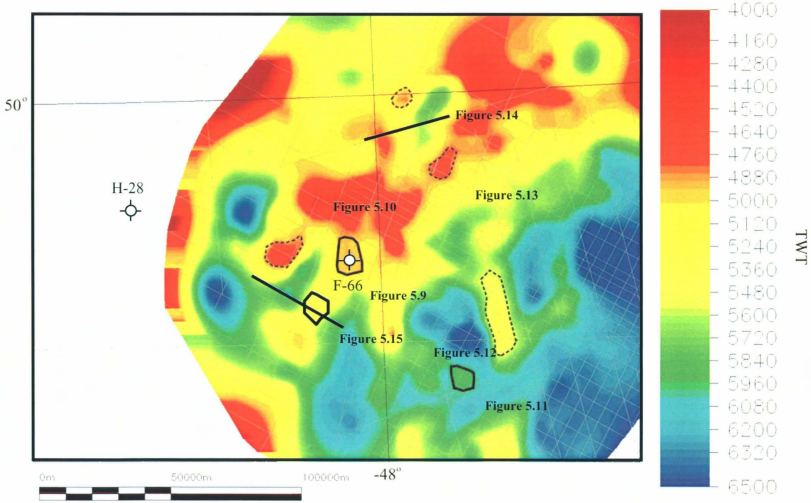

Figure 5.8: Time Structure map of K2 (Early Cretaceous/interpreted top of synrift) sequence boundary. Solid black polygons show areas of closure. Dashed polygons show areas where K2 unconformity overlies basement highs (thin Cretaceous cover). Black lines show locations of following figures. Map contours are in two way travel time (ms).

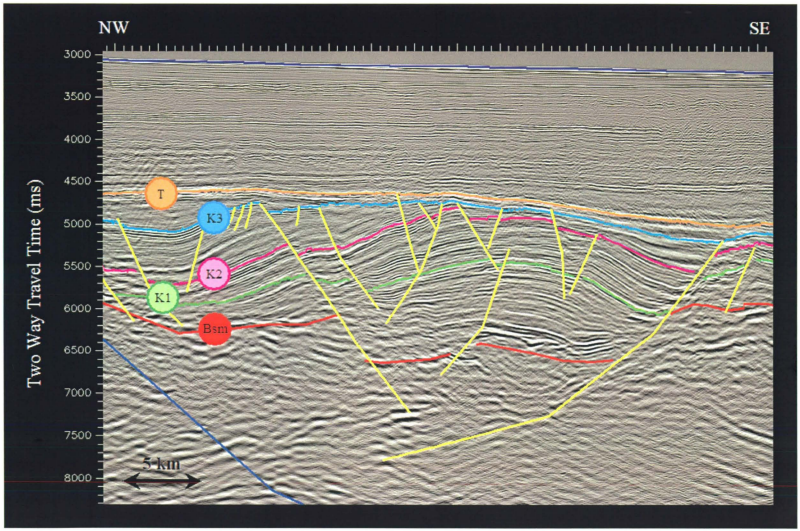

Figure 5.9: NW-SE profile through Area B of Orphan Basin showing large extensional anticline. Thick Triassic-Jurassic below Base Cretaceous Unconformity (K2 event) may be present. Thick and highly reflective synrift sequence (between K1 and K2 events) is the likely reservoir unit. Location shown in Figure 5.8.

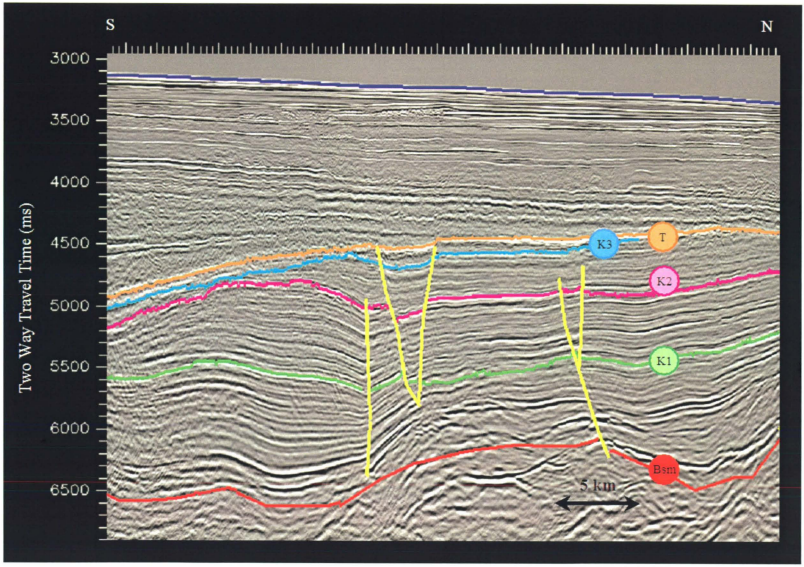

Figure 5.10: S-N profile through Area B of Orphan Basin. This is strike section through the large extensional anticline shown in Figure 5.9. Location shown in Figure 5.8.

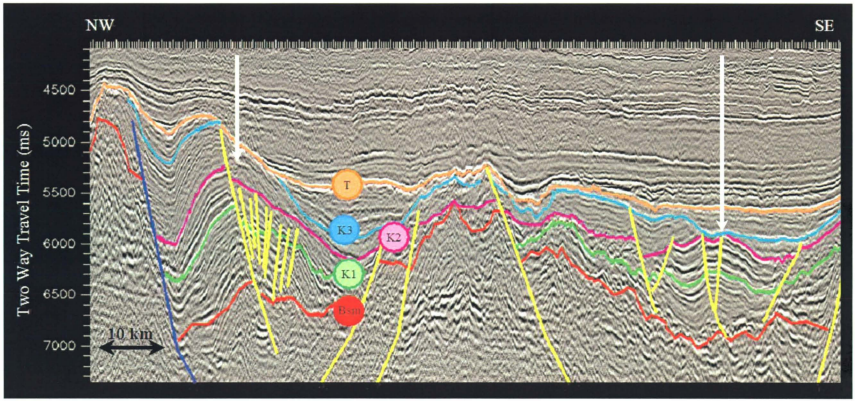

Figure 5.11: NW-SE seismic profile through Area B of Orphan Basin showing two potential structural traps (white arrows). The large structure to the NW is likely a continuation of the structure shown in Figures 5.9 and 5.10. A dip section through the SE anticline is shown in Figure 5.12. Location shown in Figure 5.8.

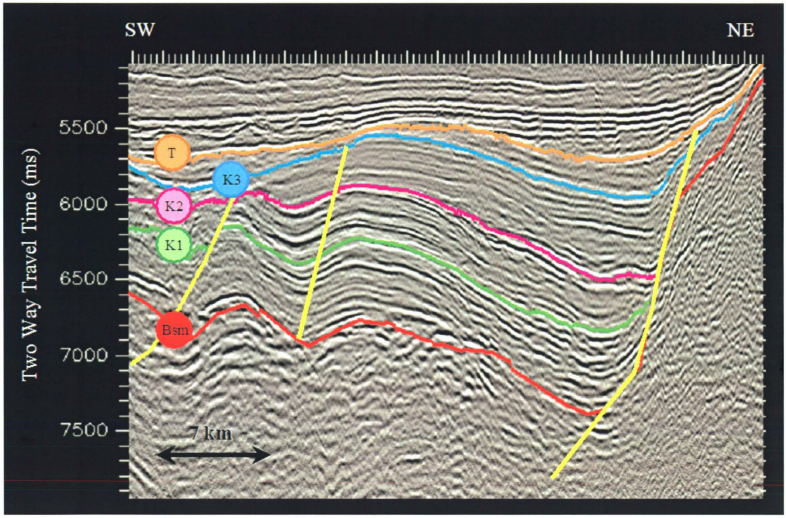

Figure 5.12: SW-NE strike section through the anticline also shown in Figure 5.11. Location shown in Figure 5.8.

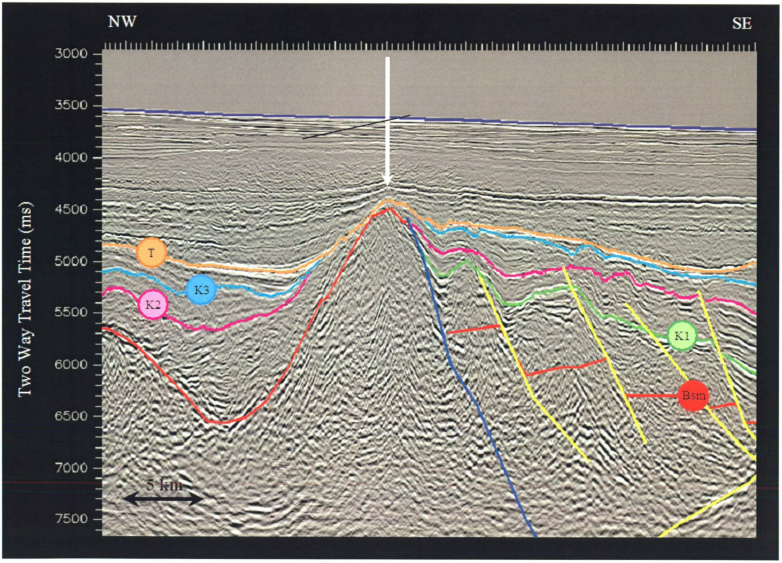

Figure 5.13: NW-SE seismic dip profile through the Orphan Basin showing basement high with thin Mesozoic cover (white arrow). Blue line is the East Orphan White Sail Fault. Location shown in Figure 5.8.

5.5 Hydrocarbon Indicators

Numerous gas chimneys (Figure 5.14) and bright spots (Figure 5.15) exist throughout the Cretaceous and Tertiary sections in the Orphan Basin. These types of hydrocarbon indicators are especially abundant through Area B.

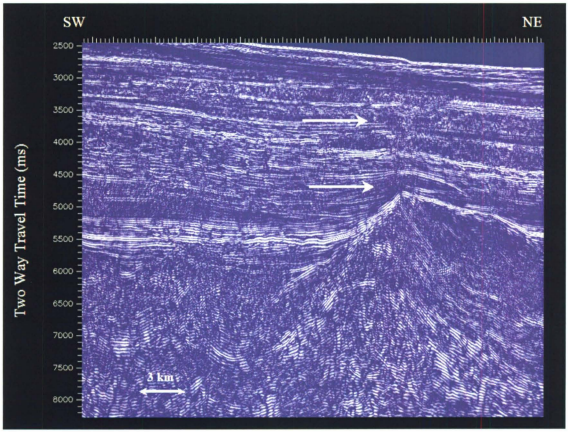

Figure 5.14: SW-NE seismic profile through the East Orphan Basin. White arrows show expression of gas chimneys in the Tertiary section. Display shown using Blue White Blue colour bar. Location shown in Figure 5.8

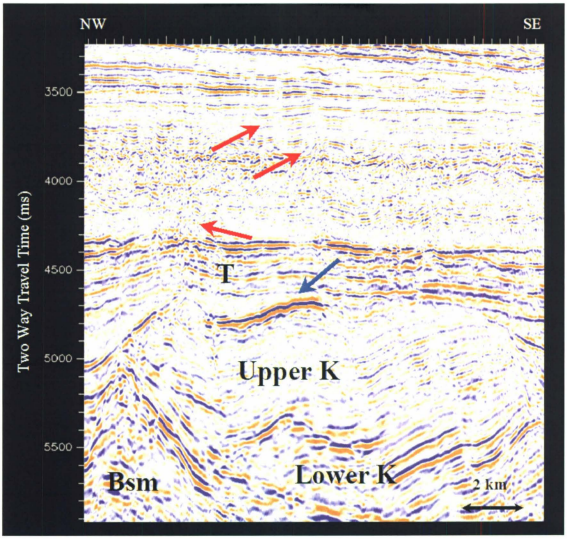

Figure 5.15: NW-SE dip seismic profile through Area B. Section shows a bright spot at the Base Tertiary Unconformity above structured Cretaceous section (Blue Arrow). Red arrows show gas chimneys through the Tertiary section. Location shown in Figure 5.8.

5.6 The Potential Hydrocarbon System

According to the structural and tectonic similarities with the Grand Banks basins and to the seismic stratigraphic and structural study performed in earlier chapters, the main petroleum system of the East Orphan Basin may include:

1. Late Jurassic-Early Cretaceous stacked sandstones for reservoir
2. A source rock equivalent to the Kimmeridgian Egret Member of the Rankin Formation
3. Seal provided by intra-formational shales, Late Cretaceous age fine clastics, likely equivalent to the Dawson Canyon shales in the Jeanne d'Arc Basin, and thick regional Tertiary shales (Figure 5.3)
4. Structural traps in the form of drape over horst blocks, extensional anticlines and rotated fault blocks of Late Jurassic-Early Cretaceous age, some modified by trans-tension (also Smee, 2003; Enachescu et al., 2005)

Similar to Jeanne d'Arc Basin, maturation of Late Jurassic source rocks may have started in the Late Cretaceous in some deep half grabens and continued to the Tertiary in the rest of the area where they were present. The migration is likely local, from deep grabens and half grabens into surrounding structural highs using fault plane conduits and porous carrier beds. As the Egret Member is a marine, high Hydrogen Index source rock, the main hydrocarbon play in the East Orphan Basin is likely oil accumulations hosted in Late Jurassic to Early Cretaceous sandstones contained in structural closures; however,

large possible natural gas accumulations should not be discounted. The most prospective plays in this sub basin are in Area B where extensional anticlines are commonly modified by later rifting events.

A potential petroleum system for the West Orphan Basin may include:

1. Basin margin and basin floor siliciclastic fans of Late Cretaceous to Early Tertiary age
2. An Early Cretaceous to Early Tertiary terrestrial or marginally marine-terrestrial source
3. Intraformational and regional seals of Late Cretaceous and Tertiary age shales
4. Structural, stratigraphic and combinational traps, most likely basin margin fans draped over some form of structure (Hardy and Enachescu, 2005 and 2007; Enachescu *et al.*, 2005)

The correlation of the West Orphan Basin geologic evolution with the Labrador rift to the north indicates that a petroleum system in this area would most likely be gas prone equivalent to the proven hydrocarbon system in the Hopedale and Saglek basins, offshore Labrador.

The validity of the Orphan Basin hydrocarbon system is currently being tested with the Great Barasway F-66 well that was drilled during the summer 2006 to spring 2007. As information from this drilling program will not become public for two years, the results of the well could not be incorporated into this study.

Chapter 6

Conclusions and Recommendations for Future Work

6.1 Justification of Study

The passive continental margin of Eastern Canada is characterized by a series of deep sedimentary basins above a wide zone of significantly thinned continental crust. Repeated extensional rift phases dissected the Avalon Terrane between the Cumberland Belt and Charlie Gibbs Transform zones into a 450 km wide tract of extensional ridges and grabens which collectively form the broad Orphan Basin. Previous petroleum exploration focused on the shallow water western part of the basin and all seven wells were unsuccessful. New seismic acquisition over the entire basin in 2000-2003 have identified the presence of two sub basins, an older (Jurassic) East Orphan Basin situated in deep water and a younger (Cretaceous) West Orphan Basin, located in shallow water. A record land sale took place in December 2003 and a new well was drilled in the East Orphan Basin during the summer of 2006.

The Orphan Basin is an underexplored area and limited studies have been completed on the structural, tectonic and stratigraphic framework of the area. Regional papers by Keen and Dehler (1993) and Chian *et al.* (2001) have focused primarily on crustal structure beneath the Orphan Basin and have been used to define the tectonic framework of the basin. Work by Enachescu *et al.* (2004 a, b, c and 2005) was used as primary references for this thesis. Regional generalizations in these papers often fail to

account for the detailed structural and stratigraphic character, architectures and relationships observed in the Orphan Basin. There have been no publicly released wells in the East Orphan Basin so information was obtained wherever possible from wells in adjacent basins.

6.2 Conclusions

Geological Evolution

The Orphan Basin is divided into two sub basins: the East and West Orphan Basins. Development began with the Late Triassic – Early Jurassic Tethys rift that affected the basin only in its eastern part. Continental clastics in the form of red beds and alluvial sands are postulated to have been deposited in the synrift phase. The absence of large diapiric structures, like those seen in the Jeanne d'Arc Basin, do not discount the possibility of salt in the basin, which may be in stratified or "salifère" form. After a long thermal subsidence phase during the Early Jurassic, the Orphan Basin was reactivated during the Late Jurassic – Early Cretaceous Atlantic rift. As the rifted area deepened, a marine incursion occurred depositing organic rich shales. Rifting propagated landward during this time affecting the western areas of the platform. Deposition of sands equivalent to the Jeanne d'Arc and Hibernia sandstones seen in the Jeanne d'Arc Basin were likely sourced from local elevated basement highs to the west, north and southeast and make up the synrift sequences of the East Orphan Basin. A postrift phase followed the Atlantic rift and deposition was dominated by shales, likely equivalent to the

Whiterose Formation. A third stage of rifting began in the Aptian – Albian. Rifting propagated even farther landward and the opening of the West Orphan Basin occurred. This rift affected the rest of the Orphan Basin only in the central regions where transtension and ridge push caused uplift of the Central Orphan High and intrabasinal ridges. Deposition in the West Orphan Basin was dominated by sands which were derived from surrounding highs (Bonavista Platform to the west and basement highs). These sediments are likely analogous to the Ben Nevis Formation sandstones deposited at this time in the Jeanne d'Arc Basin and the Bjarni Formation sandstones seen in the Labrador basins to the north. This rift was followed by a final postrift phase in the Late Cretaceous through the Tertiary where the stratigraphy is likely dominated by shales equivalent to the Nautilus Formation with intermitted periods of sands analogous to the Otter Bay and Fox Harbour members.

Seismic Stratigraphy

Within the study area six seismic boundaries were mapped and the basin fill was divided into five depositional sequences, three of which are Cretaceous sequences. The interpretation was done using the donated GSI seismic grid which encompases an area of approximately 160,000 square kilometers and contains nearly 20,000 km of 2D seismic data.

- Seismic Sequence S1 (Late Triassic – Late Jurassic) is contained in local deep sub basins and is restricted to the East Orphan Basin.

- The depositional pattern of Seismic Sequence S2 (Early Cretaceous) extends farther landward than the underlying sequence and thickens within the sub basins
- Seismic Sequence S3 (late Early Cretaceous) was deposited in the West and East Orphan basins, it thins on basement highs and thickens in the depocentres
- Seismic Sequence S4 (Late Cretaceous) was deposited in the West and East Orphan basins. This sequence is often eroded on highs by the Base Tertiary Unconformity
- Seismic Sequence S5 (Tertiary) is thickest in the West Orphan Basin and thins dramatically eastward.

Tectonics

Within the study area four fault families were identified and mapped based on regional extent, depth of detachement and timing of movement.

- The Basin Bounding Fault Family includes two major normal listric faults and their associated imbricates. The White Sail Fault is the basin bounding fault for the East Orphan Basin and marks the landward limit of the Late Triassic – Late Jurassic deposition. The Bonavista Fault acts as the basin bounding fault in the West Orphan Basin and marks the landward limit of Early Cretaceous deposition in the Orphan Basin.
- The Basement Involved Fault Family is located in the hanging walls of the basin bounding fault family. It is made up of a series of landward and seaward dipping

listric faults which sole into the basin bounding faults. These faults divide the basement into a number of grabens and half grabens, horst and rotated basement blocks.

- The Cretaceous Sedimentary Fault Family is made up of major sedimentary faults that typically link with the basement involved faults and were active until the Tertiary. They have a normal sense of dip separation, are slightly curved and dip both landward and seaward. This fault family is also made up of minor sedimentary faults which are seen in the Early Cretaceous rift sequence and are restricted in the East Orphan Basin by the K2 sequence boundary. Late movement along these faults (up to the Aptian-Albian) is seen in Area B. Due to the poor resolution of the seismic data it was not possible to extensively map this fault family with any degree of confidence.
- A fourth family of faults, the Transfer Fault Family, was implied by a change in major fault curvature to the southern parts of the Orphan Basin (from N-S in the West Orphan Basin and NE-SW in the East Orphan Basin to W-E). This change is likely attributable to movement along the southern Cumberland Belt Transform Zone; however, the extent and orientation of the seismic data does not allow for confident mapping. To the northern limit there exists the Charlie Gibbs Transform Zone, but again, the seismic grid does not extend far enough north to accurately image this zone.

Tectonostratigraphic Evolution of the Orphan Basin

Based on the mapping of the Cretaceous sequences and the orientations of major faults seen in the study area, the Orphan Basin can be divided into three distinct tectonostratigraphic regions (Areas A, B, and C).

- Area C is the most eastern part of the East Orphan Basin. This area was affected initially by the Late Triassic – Early Jurassic Tethys rift. Major basement involved faults show a general orientation to the NE-SW, in line with the direction of this original rift. This area deepened during the Late Jurassic-Early Cretaceous Atlantic rift and the major basement faults were reactivated and new faults were formed.
- Area B is located in the central region of the Orphan Basin. This area was involved in the Tethys rift and was reactivated by the Atlantic rift. The synrift sediments are dominated by large extensional anticlines of Late Jurassic – Early Cretaceous age. Major basement involved faults show a NNE-SSW orientation. The rotation of faults is attributed to the change in the extensional vector, from NE-SW to N-S. This area was again reactivated during the Labrador rift that occurred during the Aptian – Albian. As the West Orphan Basin developed the Orphan High, Orphan Knoll and adjacent intrabasinal ridges became emerged. The combination of yet another change in the extensional vector (N-S to NNE-SSW), transtension and uplift caused inversion in the Early Cretaceous sequence

in Area B. The extensional anticlines were sheared in multiple directions and are heavily faulted.

- Area A encompasses the majority of the West Orphan Basin. This area was affected by the Late Jurassic – Early Cretaceous Atlantic rift only in its most eastern parts. This region was predominantly affected by the Aptian – Albian Labrador rift stage. The basin bounding Bonavista Fault formed during this time.

The Potential Petroleum Systems

A proven petroleum system has not been identified in the Orphan Basin; however, due to the timing of rifting, two different petroleum systems are proposed for the East Orphan and the West Orphan basins. Considering all the elements and processes required for a working hydrocarbon system, the most likely plays within the study are outlined below.

East Orphan Basin

- A source rock equivalent to the Late Jurassic oil rich Egret Member of the Rankin Formation, with possibly contributions from organic rich shales of Early Cretaceous age.
- The most likely reservoirs are Late Jurassic - Early Cretaceous stacked sandstones equivalent to the Jeanne d'Arc and Hibernia sandstones in the Jeanne d'Arc Basin.

- Late Cretaceous and thick Tertiary shales age equivalent to the Nautilus and Banquereau shales may provide a seal.
- Large structural traps in the form of drape over horst blocks, extensional anticlines and rotated fault blocks of Late Jurassic – Early Cretaceous age have been identified in Area B.
- Using well information from adjacent wells and the time-depth information from the H-28 well, a Kimmeridgian Horizon (equivalent to the Egret Member source rock) was created and mapped. This map shows that the area of present maturation of this source is over most of the East Orphan Basin.
- The petroleum system for the East Orphan Basin is likely analogous to that of the adjacent Jeanne d'Arc Basin.

West Orphan Basin

- Organic rich shales of Late Cretaceous and Early Tertiary age have been drilled in the West Orphan Basin. These sources are likely gas prone and equivalent to the Bjarni and Markland formations shales in the Labrador Sea.
- Basin floor siliciclastic fans of Late Cretaceous and Early Tertiary age have been identified on the seismic data and are likely reservoirs.
- Seals of thick Nautilus and Banquereau shales
- Structural, stratigraphic and combination traps, most likely basin margin fans draped over some structural feature
- The petroleum system of the West Orphan Basin is likely analogous to that of the Labrador basins to the north of the study area.

6.3 Recommendations for Future Work

There are several areas in which future work could significantly enhance the results of this project.

1) Within the next two years the Great Barasway F-66 well will become public. The seismic interpretation presented in Chapter 3 of this study should be checked against the information from this well.
2) A basement study using gravity, magnetics and deep seismic data would help discriminate between Paleozoic sedimentary cover and crystalline basement and would provide more insight into the thickness of synrift sedimentary successions.
3) 2D balanced geological restorations of selected lines would provide additional constraints on the seismic interpretations presented in this study.
4) A provenance study using thin sections, cuttings and any available core at Blue H-28 and the Flemish Pass Basin wells would help identify the source areas for the Early Cretaceous sediments and also define areas of intrabasinal uplift.
5) A petroleum geology study including geochemical analysis of the immature organic rich shales identified in the West Orphan Basin followed by basin modeling to identify areas of potential maturity.
6) Reprocessing of regional lines and prestack depth migration.

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