DEPOSITIONAL EVOLUTION AND STRUCTURAL SYNTHESIS OF THE B MARKER (LIMESTONE) MEMBER, WHITEROSE FORMATION, JEANNE D'ARC, OFFSHORE NEWFOUNDLAND

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DEPOSITIONAL EVOLUTION AND STRUCTURAL SYNTHESIS OF THE B MARKER (LIMESTONE) MEMBER, WHITEROSE FORMATION, JEANNE D'ARC, OFFSHORE NEWFOUNDLAND

by

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Abstract

The discrepancy in the correlation of lithostratigraphy and seismic stratigraphy of the B Marker (limestone) Member on the eastern flank of the Hibernia oilfield is studied using available 3d seismic profiles and the log data from 16 wells across the Jeanne d'Arc Basin. Unlike the previous studies which suggested that the B Marker was deposited as a time synchronous lithology across basin, detailed seismic stratigraphic and well analysis revealed that the marker was in fact deposited as a mildly diachronous unit. Four seismic traces (S1-S4) are recognized within the stratigraphic range of the proposed B Marker seismic event. A Carbonate Ramp Facies Model is proposed, incorporating these traces, for the basin-wide sedimentation of the B Marker which explains in a precise manner, the notable lithological variations of the marker in various exploration wells across the Jeanne d'Arc Basin. The B Marker was deposited during a relative rise of base level within the basin, coincident with a rise of global sea level during the Valanginian. This deposition is summarized by four discrete events (S1-S4). S1 marks the end of a phase of regression in the basin, and beginning of a transgressive phase of marine deposition. Limestone deposited during S1 was confined to a narrow E-W trending belt in the northern portion of the basin. During S2 landward migration of the shoreline southward, caused the deposition of shale over a wider E-W trending belt of limestone in the north. During S3 a very broad E-W trending belt of oolitic limestone blanketed the southern shallow shelf, and shingled above thin-bedded limestones (in S1 and S2). This geometry is interpreted as a subtle depositional hinge zone, which migrated south because of the stick slip on a master fault and uplift on structural culminations in the southern areas of the basin. This resulted in the lateral gradation of B Marker limestone into sandstone further north, during ensuing transgression from S1 to S3. S4 marks the peak of transgression within the basin, and in the widest coverage of the deeper shelf across basin.

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CHAPTER 1: INTRODUCTION

1.1 Hypothesis and Objectives

The aim of this thesis is to evaluate the temporal and spatial variability within an important marker horizon in the Mesozoic-Cenozoic rift basin located offshore eastern Newfoundland. The B Marker limestone horizon is an important seismic stratigraphic unit in the Jeanne d'Arc Basin of offshore Eastern Newfoundland. Located within Early Cretaceous, syn-rift and predominantly siliciclastic sediments, the B Marker horizon delineates the top and base of several important hydrocarbon bearing reservoirs in the basin. The distinctive limestone lithologies of the B Marker are readily recognizable in well penetrations and contribute to a regionally recognizable seismic expression. Until comparatively recently, the B Marker horizon was considered a reliable chronostratigraphic unit deposited during a period of transgression and reduced clastic sediment supply within the Jeanne d'Arc Basin. However, new seismic and well data have cast doubt on the temporal continuity of the B Marker and suggest that greater temporal and spatial variability exists than previously thought. Understanding the stratigraphic context of the B Marker is of critical importance to future oil and gas prospectivity. Therefore a new evaluation of the origins of the B Marker and particularly its temporal variability was proposed by key oil companies active in the Jeanne d'Arc Basin.

New 3-D seismic and well data collected by Hibernia Management and Development Company Limited (HMDC) suggest that the stratigraphic architecture and relationship of the B Marker limestone with neighboring units is poorly understood. According to Reservoir Management at HMDC, the discrepancy associated with the B Marker is apparent on a regional scale. Sediments overlying and underlying the B Marker appear to be locally conformable, but new lithologic, biostratigraphic, and seismo-stratigraphic data clearly show that this is not always the case on a larger scale. These sediment packages may therefore show notable diachroneity. It is considered by HMDC that the resolution of this issue is of upmost importance, especially in light of new evidence of oil-bearing sands in this zone.

Thus, a detailed study undertaken as a part of this MSc thesis examines both seismic and well data over a critical part of the Jeanne d'Arc Basin. This study has an objective of constructing a predictive model for the deposition of the B Marker, focusing on the delineation of temporal and spatial relationships of the B Marker limestone and associated sandstones. The complex stratigraphic/structural architecture of the Hibernia oil field complicates the assessment of the hydrocarbon potential of the B Marker and the associated siliciclastics. Therefore, this thesis requires a multi-facet approach toward analysis, and will use the seismic database (3-D and 2-D), lithologic and biostratigraphic data from offshore wells provided by HMDC and Chevron Canada Ltd. This thesis aims to accurately delineate the following: (1) detailed seismic sequence stratigraphy, including temporal and spatial variations in acoustic character, (2) chronostratigraphic framework using borehole data and (3) a structural architecture of the B Marker limestone and associated siliciclastic pay zones in the Hibernia Oil Field.

1.2 Structural Evolution of the Grand Banks and Jeanne d'Arc Basin

1.2.1 Tectonic History

The Mesozoic-Cenozoic sedimentary successions along the continental margin of Eastern Canada record a long history dominated by tectonic events marked by the development of a mature passive margin. The Iapetus Ocean began to form ~ 540 Ma (million years ago), along a divergent margin which separated Laurentia Ocean (ancient North America) and Gondwana (ancient Europe and Africa). Over a period of 80 million years the Iapetus Ocean widened, but began closing in the Carboniferous. Final suturing in the Permian resulted in the accretion of continental terranes and the formation of the supercontinent Pangea: an irregular Early Paleozoic passive margin which developed east of the Appalachian- Caledonian mountain belt (Williams et al.1996). Subsequent rifting of Pangea over the next hundred million years resulted in the development of extensive rift zones in northwestern Europe and eastern North America. The initial phase of rifting began during the Triassic ~ 250 Ma (Tankard and Balkwill, 1989). The North Atlantic began to open in the Early Jurassic from south to north. During the Middle Jurassic, Africa and North America separated. During the Early Cretaceous the Atlantic Ocean extended northward between Iberia and the Grand Banks, dividing the European-Greenland and North American Plates in the Late Cretaceous (Sinclair, 1988; Tankard and Balkwill, 1989). Postrift thermal subsidence of the North Atlantic margins was a protracted event and was accompanied by the deposition of ~ 10 km thick seaward-thickening sedimentary wedges which blanketed the underlying extensional rift zone, leading to the development of a new classification known as the Atlantic-type margin (Tankard and Balkwill, 1989).

1.2.2 Regional Structure and Geologic Setting of the Grand Banks

The Grand Banks is one in a series of Mesozoic extensional sedimentary basins located along the continental margin of North America (McAlpine, 1990) (Figure 1.1). These basins developed sequentially as seafloor spreading propagated from south to north. South and east of the Grand Banks, seafloor spreading began in the Early Jurassic and mid-Cretaceous, respectively and extended NW to the Labrador Sea in the Late Cretaceous (McAlpine, 1990). The Grand Banks is separated from the Labrador and Scotian Shelves by two prominent transform faults: Charlie Gibbs and Newfoundland fracture zones. A series of major strike slip faults further sub-divides the Grand Banks into northern, central and southern provinces (Tankard et al, 1989) (Figure 1.2).

Morphologically, the Grand Banks is a continental shelf (36-185 m deep), which extends 450 km seaward of Newfoundland. The basement rocks in Grand Banks are composed of Late Proterozoic-Late Paleozoic sedimentary successions of the Appalachian Orogen resting over continental crust (Tankard et al, 1989).

The Grand Banks basins record a complex history of basin formation, including multiple episodes of rifting and postrift thermal subsidence related to the opening of the Atlantic Ocean (Tankard and Welsink, 1989). The first rifting event occurred from

Triassic-Early Jurassic during a period of NW-SE extension (Sinclair, 1988; Tankard, et al. 1989; Hiscott, et al. 1990; McAlpine, 1990). This event was followed by the mid-Pliensbachian break-up of North America and Africa. The second rifting event occurred from Tithonian through Early Valanginian time, during a period of E-W extension. This second event was succeeded by the breakup of Iberia from the Grand Banks in the mid-Valanginian (Sinclair, 1988). The final stage of rifting occurred from Aptian-Albian, during a phase of NE-SW directed extension. This rifting event was followed by the separation of North America from Europe in the latest Albian (Sinclair, 1988; Tankard, et al. 1989; McAlpine, 1990). Each rifting event was preceded by regional arching and succeeded by tectonically quiet episodes of thermal subsidence and sedimentation.

The Mesozoic basins on the Grand Banks have a dominant, NE trending elongate geometry, which primarily developed during the latest Jurassic to mid-Cretaceous rift episode. These basins include the Jeanne d'Arc, Whale, South Whale, Horseshoe and Carson Basins. Formation of these elongate basins coincided with the development of a broad regional arch on the Grand Banks, known as the Avalon Uplift, which coincides with the second rifting event. The Avalon unconformity is a prominent peneplain seen throughout the Grand Banks, which developed in response to latest Jurassic-Middle Cretaceous rifting and separation of Iberia and the Grand Banks. Except for in basins, Avalon basement highs in the Grand Banks are typically truncated by the Avalon unconformity (McAlpine, 1990). By the Late Cretaceous, the Grand Banks had subsided as a continental block and became buried beneath undeformed Upper Cretaceous and

Tertiary strata.

Major rifting episodes produced depositional wedges of coarse clastic sediments that filled the Jeanne d'Arc Basin from southeastern sources. These deposits act as the major reservoirs within the Jeanne d'Arc Basin. The Jeanne d'Arc Basin covers ~10, 000 km^2 in the central region of the Grand Banks and contains ~ 17 km-thick post Paleozoic rift/drift successions. Hibernia, Hebron, Ben Nevis, Terra Nova, Whiterose, Nautilus, South Mara, and South Tempest are oil fields in the Jeanne d'Arc Basin and collectively hold approximately 2 billion barrels of recoverable hydrocarbon reserves. (Tankard et al., 1989). The study area encompasses Hibernia, Hebron, Ben Nevis and Terra Nova oilfields (Figure 1.3).

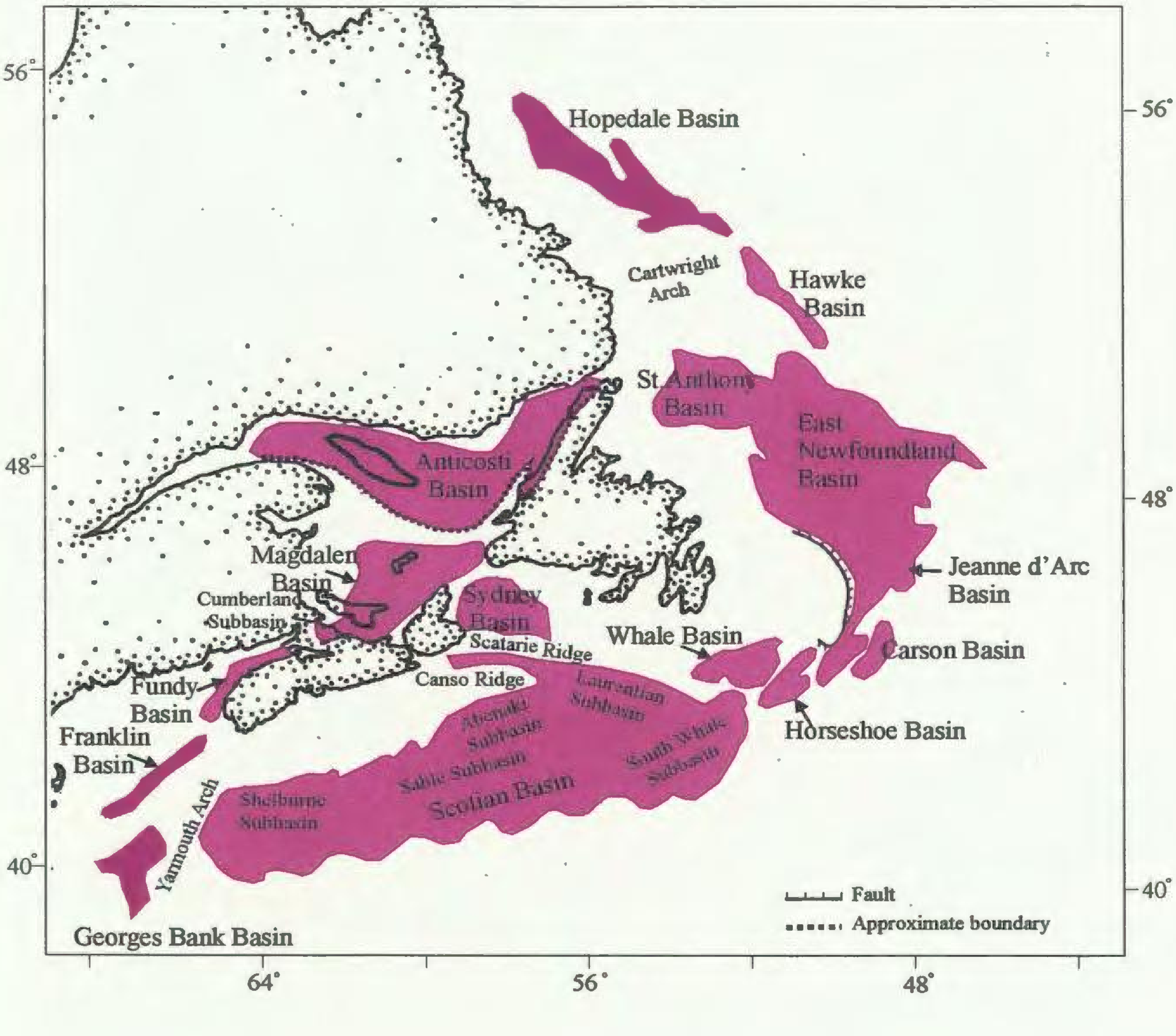


Figure 1.1. Sedimentary basins located offshore Eastern Canada (after Keen et al., 1990).

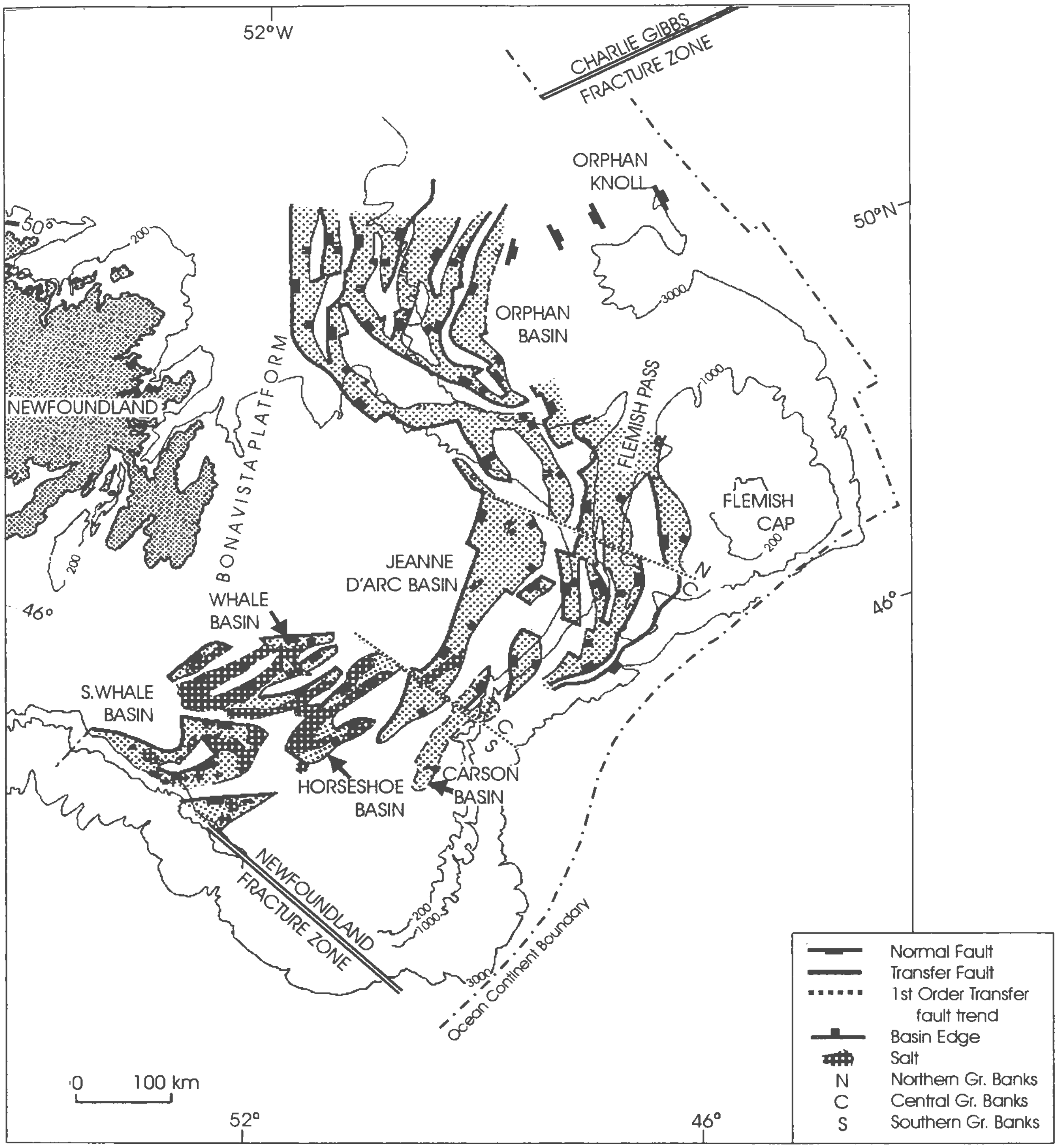


Figure 1.2. Map showing the principle structural elements of the Grand Banks and Orphan Basin (after Welsink, Srivastava, and Tankard, 1989). The Grand Banks is a continental shelf located 450 km offshore Newfoundland, separated from the Labrador and Scotian Shelves by two prominent transform faults: Charlie Gibbs and Newfoundland fracture zones. A series of major strike slip faults further subdivides the Grand Banks into northern, central and southern provinces.

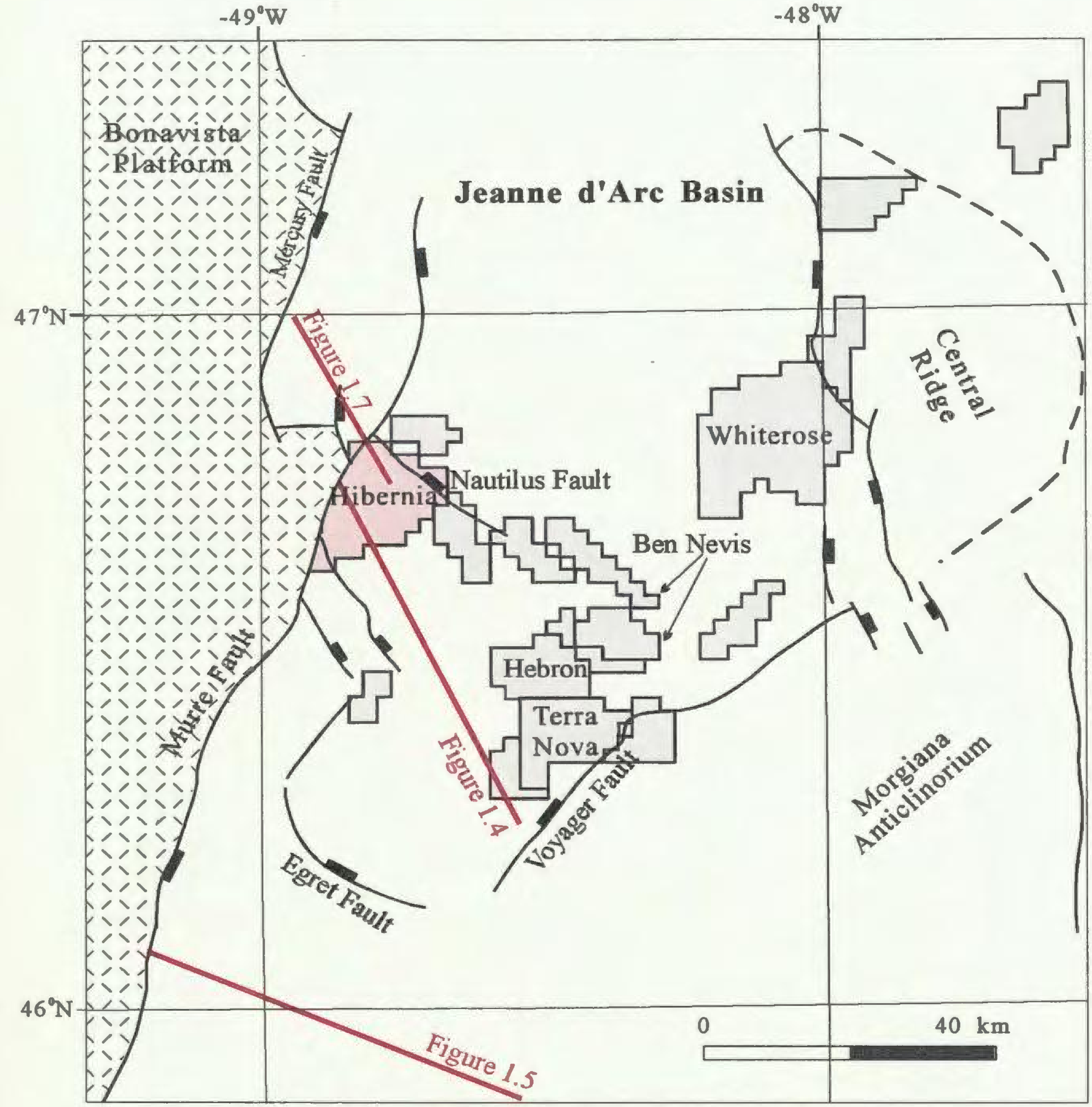


Figure 1.3. Map of the Jeanne d'Arc Basin, showing major fault trends and areas of hydrocarbon exploration; including the Hibernia, Ben Nevis, Hebron, Terra Nova and Whiterose oilfields. The basin is bound by the Murre Fault and structurally high Bonavista Platform in the west, and by the Voyager Fault and Central Ridge Complex in the east. The location of seismic lines in figures 1.4-1.6 are indicated.

1.2.3 Structure of the Jeanne d'Arc Basin

The structural architecture of the central Grand Banks is dominated by episodes of Late Callovian-Aptian rifting which preceded the separation of the Grand Banks and Iberia (Tankard and Welsink,1989; Mackay and Tankard, 1990). The Jeanne d'Arc Basin is characterized by a deep half graben, which evolved through southeast directed extension. Extensional tectonics delineated major fault patterns in the Jeanne d'Arc Basin, including NE-SW trending listric and high angle normal faults, and NW-SE trending trans-basinal faults. The presence of salt under much of the Jeanne d'Arc Basin accentuated the structural architecture of the Mesozoic sedimentary succession. A significant amount of faulting in the basin may be the result of compensatory movement for salt withdrawal and flowage.

1.2.3.1 Jeanne d'Arc Basin bounding faults

The Jeanne d'Arc Basin is flanked by a large basement platform: the Bonavista Platform, to the west, and by a series of basement ridges known as the Central Ridge Complex to the east. The Avalon uplift borders the Jeanne d'Arc Basin in the south and opens to the north into the East Newfoundland and Orphan Basins. Collectively, these structural features define the funnel-shaped geometry of the Jeanne d'Arc Basin, which is elongated in a NE-SW orientation and tapers toward the SW (Figure 1.3).

The gross morphology of the Jeanne d'Arc Basin is attributed to the reactivation of the Murre-Mercury, Egret and Spoonbill Faults. The Murre Fault is a NE-trending, listric, basin-forming fault: it defines the western boundary of the Jeanne d'Arc Basin, and flanks the pre-Mesozoic rocks of the Bonavista Platform. The Murre Fault is believed to have formed by the reactivation of pre-Mesozoic lineaments (Tankard and Welksink, 1989). The Murre Fault consists of a series of left-stepping *en-echelon* strands that are offset by very high angle transfer faults, which share the same level of detachment at depth. Seismic data suggests that the Murre Fault soles at about 22-26 km. Minor fault arrays in the basin are attributed to right-lateral shear couples. In the Hibernia oilfield, shear couples in transfer zones created dogleg-shaped R'-Riedel shears and tension fractures (Tankard and Welsink, 1989). A smaller scale example of these structural elements is illustrated by the Hibernia rollover anticline, which is enhanced by the presence of crestal collapse structures (Figure 1.4). The Hibernia rollover anticline, commonly referred to as the Hibernia structure or Hibernia anticline, is the major structural element associated with hydrocarbon bearing zones in the Hibernia oilfield. The Hibernia anticline was created by extensional faulting and rollover, and accentuated by the presence of salt (Mackay, 1990). It trends N-NE and is dissected by a series of transverse normal faults that trend NW (Arthur et al., 1982). The areal closure on the anticline is 155 km^2 with 760 m of structural closure (Arthur et al., 1982).

The eastern extent of the Jeanne d'Arc Basin is flanked by the Central Ridge Complex, which is defined by a series of basement ridges composed of deformed Triassic sediment (Tankard and Welksink, 1989) (Figure 1.5). The structurally high Central Ridge Complex forms a hanging wall, which is detached at the same level as the Murre

Fault (Tankard et al., 1989). Synrift sediment and the hanging basement collectively define an extensional ramp anticline in the Jeanne d'Arc Basin (Tankard and Welksink, 1989) (Figure 1.5). The Terra Nova anticline is located west of the Central Ridge Complex in the south-central region of the basin. The north-plunging anticline covers an area of 200 km^2, and is bound by the Trinity Fault in the north, the E-79 Fault in the east and by the basin margin in the south (Figure 1.6). The Terra Nova anticline is cut by a suite of orthogonal listric normal faults, which divides the field into three structural blocks. Formation of the Terra Nova anticline was the result of eastward-directed crustal extension and associated salt migration during the Middle Cretaceous, which caused the formation of a keystone fault on a north-plunging, salt cored pillow (Figure 1.6). Further oblique slip movement on the older north-south fault system may have resulted in the pop-up feature located on the west flank of Terra Nova. Ensuing subsidence and salt migration further emphasized the structural relief of the Terra Nova anticline (Petro-Canada, 1996).

The southern extent of the Jeanne d'Arc Basin is bound by the NW-SE trending Avalon uplift (Enachescu,1987; Jansa and Wade, 1975); a region of elevated strata, which formed in response to Tethyan plate movements (McAlpine, 1990).

1.2.3.2 Jeanne d'Arc Basin trans-basin faults

Trans-basin faults divide the Jeanne d'Arc Basin into three structural-stratigraphic regions. In the region south of the Egret Fault, Late Jurassic and Lower Cretaceous rocks are absent due to erosion and stratigraphic thinning (McAlpine, 1990)(Figure 1.3, and 1.5). In the central region of the basin, between the Egret Fault and Hibernia to Ben Nevis trans-basinal fault zone, Late Jurassic and Lower Cretaceous strata thickens significantly (Figure 1.3 and 1.4). In the northern region of the Jeanne d'Arc Basin, Middle Cretaceous strata progressively thickens northward. Upper Jurassic and Lower Cretaceous strata in the northern region of the basin suggests that the formation of the Avalon unconformity was in response to uplift, deformation and erosion within the Jeanne d'Arc Basin in the Late Kimmeridgian to Albian-Cenomanian times (McAlpine, 1990).

The Nautilus Fault is a transfer fault, which flanks the northern edge of the Hibernia oilfield (Welsink, et al, 1989) (Figure 1.7). The Nautilus Fault offsets the Murre Fault, which together define the western and northeastern limits of the Hibernia anticline. Transverse faults, which bound the Hibernia anticline in the north and south have vertical separations in excess of 450 m. Movement along the Murre Fault decreased between Lower Jurassic to Tertiary, and terminated within Tertiary strata. Most transverse faults developed during the later part of the Lower Cretaceous, and some were reactivated in the Upper Cretaceous. In the Aptian the Jeanne d'Arc Basin tilted northward, resulting in the uplift and truncation of the crestal portion of the Hibernia anticline. Sediments deposited following the Aptian unconformity are typically undeformed. Hydrocarbon bearing zones within the basin are typically confined beneath the pre-Aptian unconformity (Arthur et al., 1982).

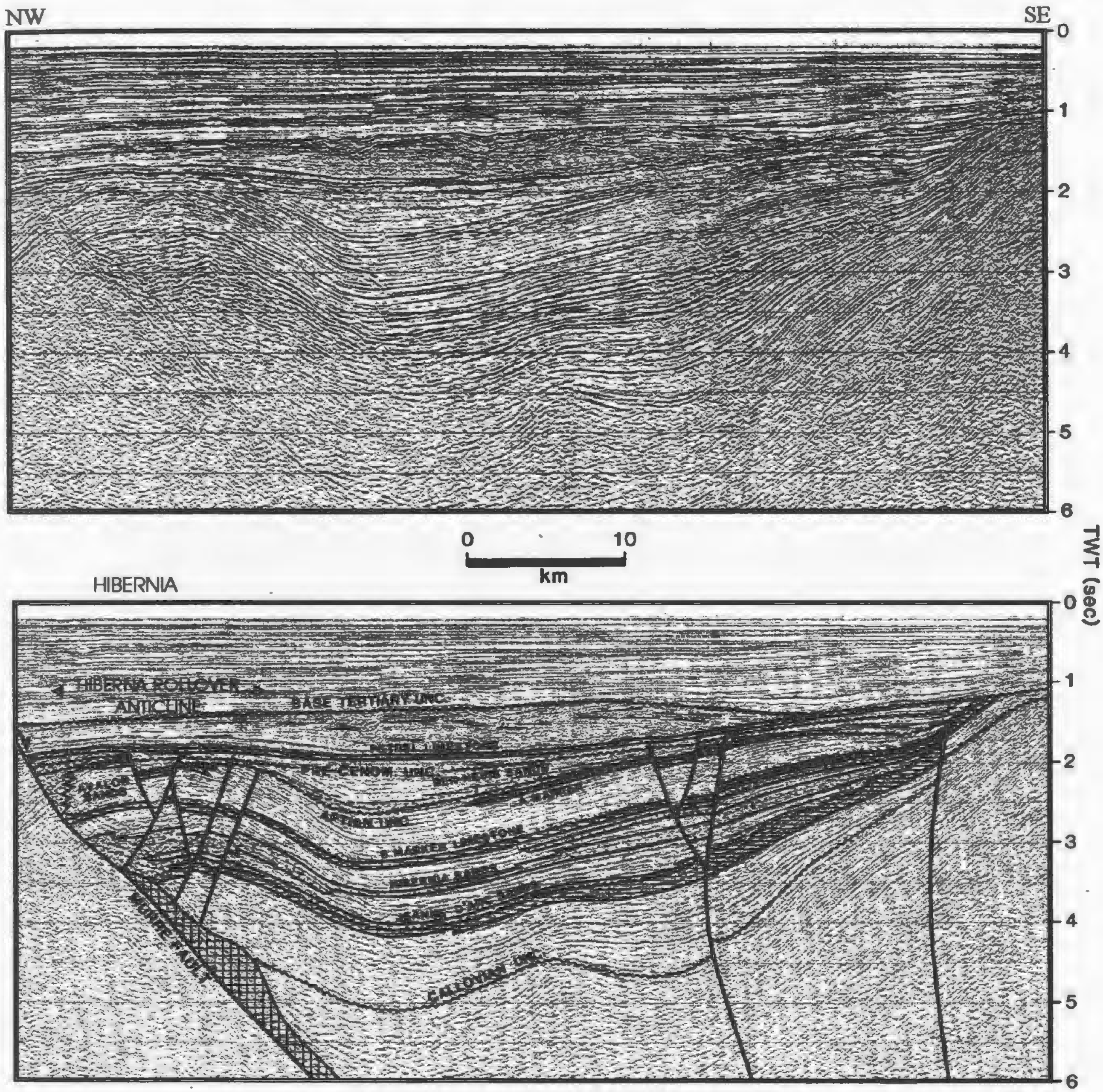


Figure 1.4. NW-SE trending seismic line (Figure 15; Tankard et al., 1989), showing the stratigraphy and half graben architecture of the Jeanne d'Arc Basin. The Hibernia rollover anticline is the major structural element associated with hydrocarbon bearing zones in the Hibernia oilfield. It was created by extensional faulting and rollover into the listric Murre Fault, and accentuated by salt. The N-NE trending anticline is dissected by a series of NW trending transverse normal faults. See Figure 1.3 for line location.

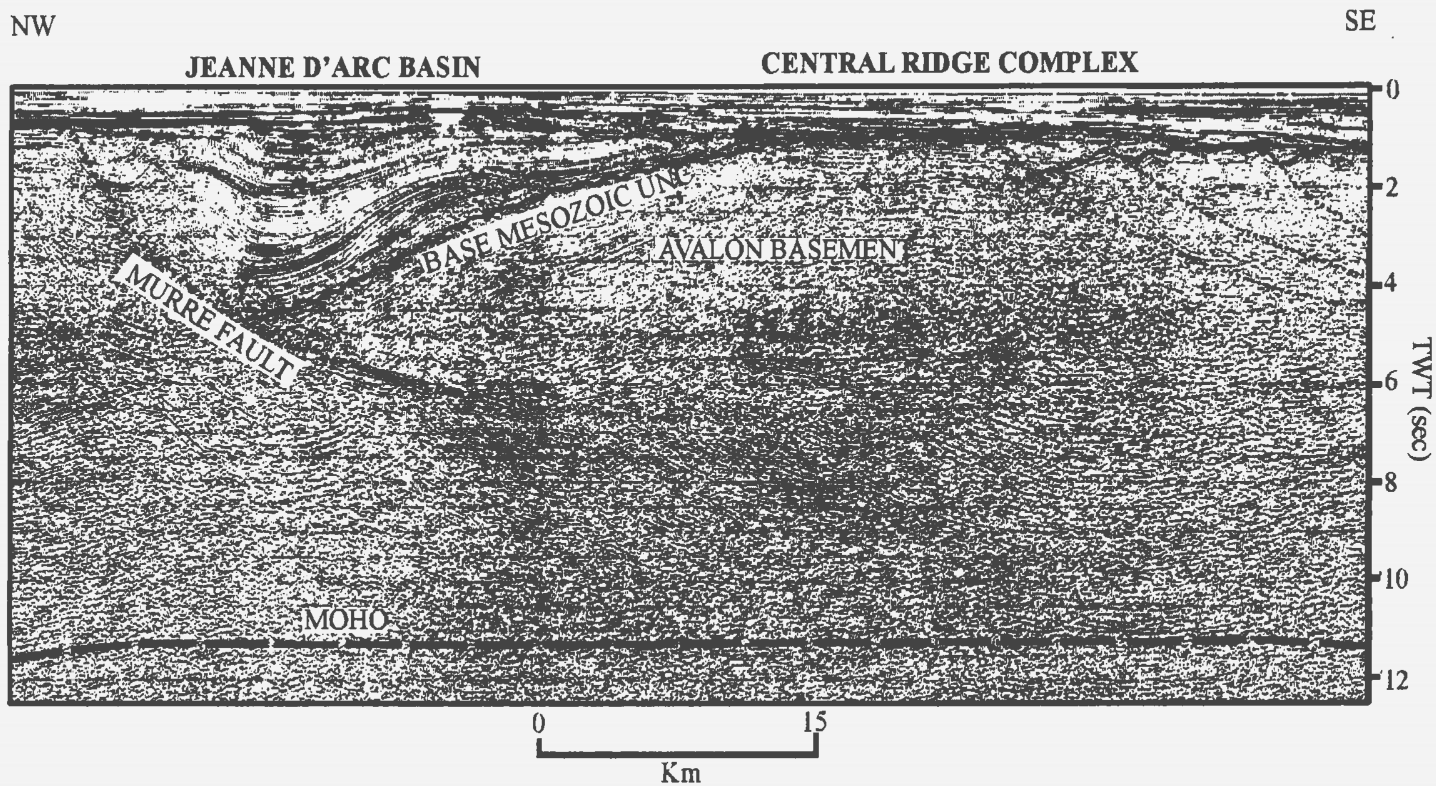


Figure 1.5. NW-SE trending seismic line (Tankard et al., 1989) located in the southern region of the Jeanne d'Arc Basin, south of the Egret Fault, showing the structural high Central Ridge Complex, which defines the western flank of the Jeanne d'Arc Basin. The complex forms a hanging wall horst of the Avalon Zone to basement, detached at the same level as the Murre Fault. The hanging basement defines an extensional ramp anticline above which synrift sediments of the Jeanne d'Arc Basin deposited in an asymmetric half graben. See Figure 1.3 for line location.

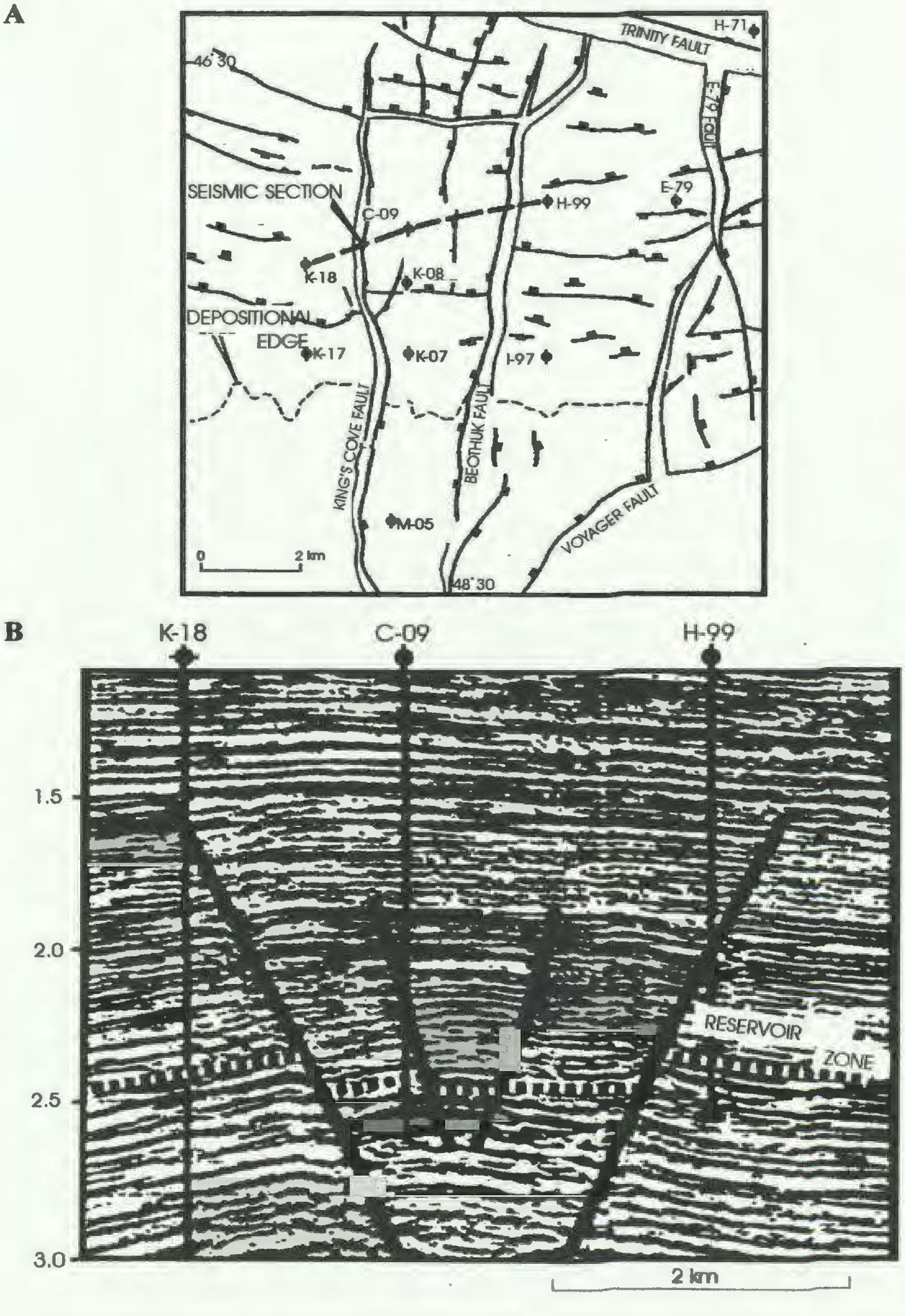


Figure 1.6.A) Map showing the fault locations at the reservoirs sands in the Terra Nova oilfield. **B)** Seismic line through the central portion of the Terra Nova oilfield, showing faults and reservoir zones (Wilcox,1991).

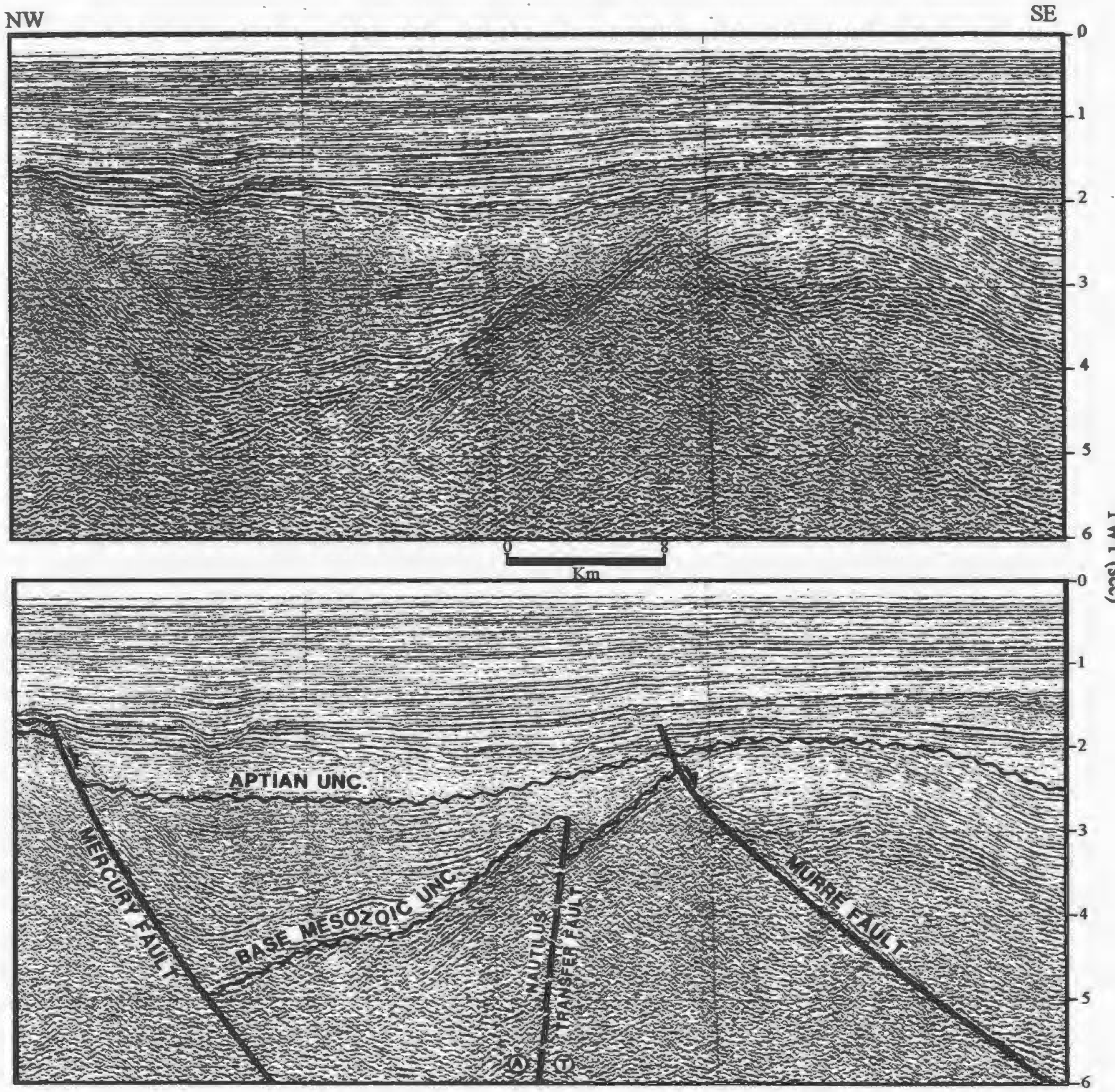


Figure 1.7. NW-SE trending seismic line showing offset of the Mercury-Murre and Nautilus faults. The Nautilus transfer fault is younger than the Mercury-Murre faults and offset the relay ramp structure in the Jeanne d'Arc Basin (Tankard et al., 1989). See Figure 1.3 for line location.

1.3 Stratigraphy of the Jeanne d'Arc Basin

In the Late Triassic, a rift system developed between the North American-Greenland Plate and the European-African Plate, which also extended as an arm into the present North Sea (McAlpine, 1990). Initiation of rifting of the Atlantic Ocean during the Late Triassic reactivated NE-trending zones of crustal weakness, which were established during Hercynian suturing of Pangea (Rice and Tankard, 1988). On the Grand Banks, continental sandstones and shales of the Eurydice Formation accumulated in the half grabens, as continental sedimentation overstepped Paleozoic strata (Figure 1.8) (Rice and Tankard, 1988; Tankard et al., 1989). As rifting progressed, marine waters from the Tethys Sea encroached the rift zone in the Jeanne d'Arc Basin and created restricted marine embayments where evaporites and sabkha carbonates of the Osprey and Argo formations were deposited (Figure 1.8) (McAlpine, 1990). Continued marine conditions resulted in the formation of anhydritic dolomite and oolitic and skeletal limestones of the Iroquois Formation in coastal sabkhas, lagoons and a warm shallow sea (McAlpine, 1990). Early Jurassic separation of North America from Africa resulted in the deposition of continental and marine sandstones along the margins. Ensuing marine transgression during the Early-Middle Jurassic in the Jeanne d'Arc Basin and the development of an epicontinental sea resulted in the deposition of carbonates and shales of the Downing Formation, and the drowning of desiccated basins (Figure 1.8). During subsequent sea level changes sandstones, shales, coals and oolitic limestones of the Voyager Formation were deposited in deltaic, and marginal marine environments in the Jeanne d'Arc Basin

(McAlpine, 1990). Oolitic limestones and sandstones of the Rankin Formation were primarily deposited in the southern part of the basin in the Late Jurassic (Figure 1.8). In the northern portion of the Jeanne d'Arc Basin, the Rankin Formation is dominated by finer-grained siliciclastics indicating distal, deeper marine conditions. In the Early Kimmeridgian, the organic-rich shales (McAlpine, 1990; MacKay and Tankard, 1990), oolitic limestones, siltstones and sandstones of the Egret Member were deposited in marine and paralic swamp conditions (Tankard and Welsink, 1987). Early-Middle Kimmeridgian organic-rich shales are the primary source of oil in the Jeanne d'Arc Basin (Powell, 1985; Tankard et al., 1989; von der Dick, 1989; von der Dick et al., 1989).

The Kimmeridgian Avalon uplift resulted in the development of a regional peneplain dotted with a number of NE trending extensional basins (McAlpine, 1990). The uplift resulted in the deposition of a significant quantity of coarse terrestrial sands of the Jeanne d'Arc Formation. The deposition of the Jeanne d'Arc Formation was terminated by the Portlandian transgression (Mackay and Tankard, 1990).

Continued growth along the Murre Fault combined with fluctuating sea levels in the Early Cretaceous resulted in deposition of lower Cretaceous transgressive-regressive deltaic reservoir sandstones in the Hibernia area. Elsewhere in the Jeanne d'Arc Basin, sandstones were derived locally from eroded highlands, such as in the Ben Nevis/Hebron region, while mudstones were deposited as distal equivalents in the north (Rice and Tankard, 1988). Hibernia and Catalina are sandstones reservoirs, which were deposited during the Early Cretaceous. The B Marker limestone occurs between the Hibernia and

Catalina reservoirs, while the A Marker separates the Catalina and Avalon reservoirs. The A and B markers are regionally extensive bioclastic limestones, deposited during times of transgression with little terrigeneous input. Hibernia reservoir sandstones were deposited during the Valanginian in a fault-controlled arcuate delta complex fed from the SW. Hibernia deltas were eventually flooded as sea level rose and the entire area was draped by the B Marker limestone. The B Marker is a regionally persistent transgressive limestone unit deposited during a time of relative basin stability in a warm, shallow, high-energy marine environment (McAlpine, 1990). In the study area it is 20 to 809 m thick, and constitutes a prominent seismic reflector (Mackay and Tankard, 1990). Above the B Marker, Avalon sandstones, shales and occasional carbonates were deposited. Unlike the B marker, the A Marker is a diachronous sequence of limestones and calcareous sandstones (Mackay and Tankard, 1990). It was deposited during the Hauterivian highstand of sea-level, and defines the base of the Avalon sandstones. These sandstones form the youngest and primary reservoir in the Hibernia oilfield. The Avalon Formation consists of a SW thickening wedge of inter-bedded mudstones and sandstones (Mackay and Tankard, 1990). The unit was deposited as retreating Barremian sea allowed deltaic sediments to prograde across the Murre Fault. As subsidence decreased, progradational thinner sandstones were deposited (Rice and Tankard, 1988).

The last period of deformation effecting the Jeanne d'Arc Basin corresponds with the separation of the Grand Banks and Iberian in the Aptian (Tankard et al., 1989; McAlpine, 1990). This phase of deformation is recorded by unconformities within strata in the Hibernia to Ben Nevis trans-basin fault trend. The prominent Aptian "break-up" unconformity caps the Avalon Formation, and is prominent near basin margins and over structures (Mackay and Tankard, 1990; McAlpine, 1990). During the Aptian, the deformation was primarily the result of salt-related activity with little basement involved faulting. Many of the faults in the trans-basin trend appear listric at depth, soling in the salt or in the Jurassic shales (McAlpine, 1990). Sediment derived from the basin margins and local structural highs was reworked in the trans-basin fault zone, and produced the Ben Nevis reservoir sandstones. The Ben Nevis Formation consists of sandstones with mudclasts and coal spar on scour surfaces (Mackay and Tankard, 1990). The top of the Ben Nevis Formation is marked by the prominent Late Albian unconformity, which was less erosive than the Late Aptian event. In the tectonically stable southern region of the Jeanne d'Arc Basin, sandstones and conglomerates of the Eider Formation were deposited in a continental to marginal-marine environment, while marls and shales of the Nautilus Formation accumulated further north (Mackay and Tankard, 1990).

By the Late Cretaceous, the Grand Banks and British Isles separated, creating a shallow seaway across the Jeanne d'Arc Basin (McAlpine, 1990). The separation of Labrador from Greenland, and Greenland from northern Europe was recorded by local unconformities in the basin during the Late Cretaceous and Tertiary periods. During the Cenomanian and Turonian, transgressive marine shales of the Dawson Canyon Formation was deposited. This sequence was overlain by the Petrel Member (McAlpine, 1990). The Petrel Member is a prominent seismic reflector that drapes the Jeanne d'Arc Basin and oversteps the Bonavista platform (Mackay and Tankard, 1990). During the Senonian, chalky limestones of the Wyandot Formation were deposited in the basin. A prominent, base Tertiary unconformity separates Cretaceous from Tertiary strata on the Grand Banks.

Paleocene aged-sandstones and prodelta turbidites of the South Mara member mark the base of the Tertiary succession (McAlpine, 1990). The Eocene marked the culmination of tectonic activity in the Grand Banks. Continued thermal subsidence and seaward tilting of the margin led to the deposition of shales, chalks, siliceous mudstone, and sandstone/siltstone beds of the Banquereau Formation (McAlpine, 1990).

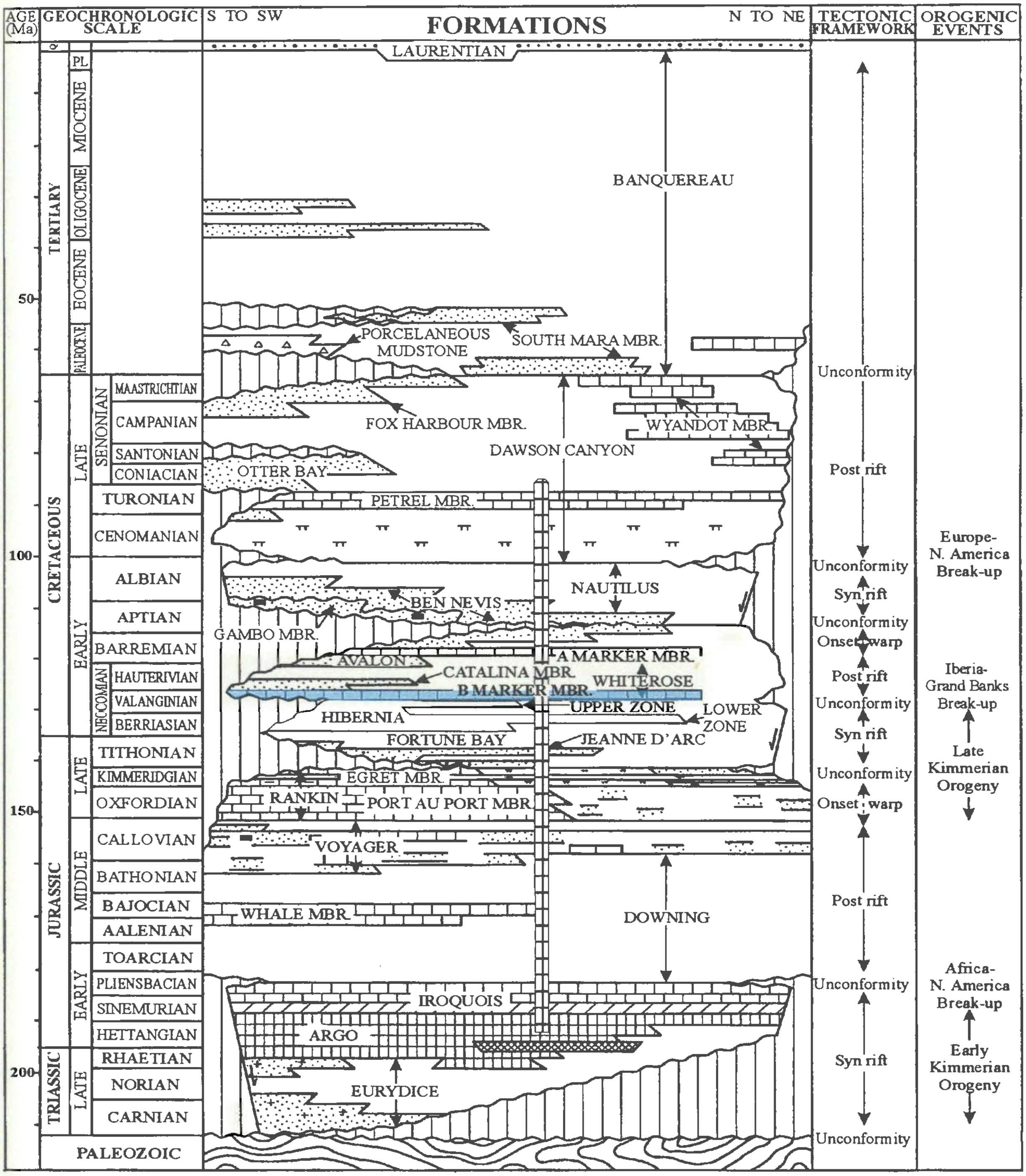


Figure 1.8. Generalized stratigraphy of the Jeanne d'Arc Basin. The highlighted region shows the position of the Late Berriasian to Early Valanginian B Marker Limestone (after Sinclair, 1988).

1.4 A and B markers and their importance within the Jeanne d'Arc Basin

The B and A markers (limestone) members occur within the Early Cretaceous oil-bearing zones of the Jeanne d'Arc Basin. These markers have been used in recent years as prominent regional lithologic and seismic events, which are correlated throughout the Jeanne d'Arc Basin, including the Hibernia and Terra Nova oil fields. Terminology referring to the B Marker was first introduced by McKenzie (1980) as a seismic event in the Hibernia oil field occurring near the top of the Lower Cretaceous sandstones of the Catalina Formation. Butot (1981) and Benteau and Sheppard (1982) later included the B Marker to the Catalina Formation. Tankard and Welsink (1987) and McAlpine (1990) redefined the B Marker Member as a limestone unit located below the base of the Catalina Formation and above the Hibernia Formation in the Jeanne d'Arc Basin. For the purposes of this study, the Lower Cretaceous Catalina sandstones are defined as a Member within the Whiterose Formation (Sinclair, 1988). This study designates the B Marker (limestone) Member as a Late Berriasian (McAlpine,1990) to Early Valanginian (Tankard and Welsink;1987) Member of the Whiterose Shale Formation (Sinclair, 1988a; CNOBP, 1990a).

McAlpine (1990) assigned the type section of the B Marker limestone as the interval from 3804 to 3909m in Mobil et al. Ben Nevis I-45 well. The type section consists of massive, buff to light grey, oolitic/skeletal, limegrainstones and packstones and displays low gamma-ray and high acoustic velocity response on well logs (McAlpine, 1990).

Ooids found within the limestone commonly have quartz nucluei and are sandy, silty and locally argillaceous. Fragments of bivalves, echinoderms, gastropods and coralline algae occur in the limestone. Near the base of the unit, thinly bedded light to dark grey calcareous sandstones, siltstones and shale are intercalated with limestone (McAlpine, 1990).

There are numerous interpretations associated with the definition of the A Marker. It was defined by Rayer (1981) as a thin carbonate stringer near the base of the Avalon sandstones. This definition was complicated by the existence of the A Marker seismic event near the top of the Avalon sands (McKenzie,1980; Butot, 1981) and disagrees with the lithostratigraphic descriptions of Tankard and Welsink (1987) and Sinclair (1988). The A Marker defined by McApline (1990) is a thin, Late Hauterivian-Early Barremian limestone marker located near the base of the Eastern Shoals Formation (McAlpine, 1990); this interpretation agrees with general industry use of the term "A" Marker in the eastern and southern portions of the Jeanne d'Arc Basin (Sinclair, 1992). The basal boundary of the Avalon Formation is assigned herein to the A Marker limestone Member. In regions where the A Marker Member is not identifiable, the Avalon Formation may be interpreted as continuing downward until the next identifiable lithostratigraphic unit is encountered (Sinclair, 1992). The basal contact of the Avalon Formation/A Marker limestone is abrupt at many locations on the southeastern margin of the Jeanne d'Arc Basin, as seen in Ben Nevis I-45. The unit is predominantly composed of limestone, but locally shows intercalation of calcareous sandstone. The A Marker is defined by low gamma-ray and high sonic response in logs, where the lower and upper boundaries of the marker are conformable with neighboring units.

The Jurassic-Cretaceous successions between the B and A markers typically encompass the Catalina Member and Whiterose Formation (Figure 1.8). The Catalina Member is composed of a thinly bedded sandstone/carbonate sequence, overlying the B Marker limestone. The lower boundary of the Catalina Member is easily picked on the gamma-ray log, but demonstrates a gradational relationship with the overlying Whiterose Formation. The Whiterose Formation is defined as a massive shale unit, which is the distal equivalent of Hibernia Formation, Catalina Member and Eastern Shoal Formation. It intertongues with these units and can be subdivided into upper and lower tongues, which may occur both above and below the Catalina Member and the B Marker Member. Well logs show the formation as having gradational contacts with both the underlying Catalina Member and the overlying A Marker Member (McAlpine, 1990).

1.5 Tectonic Models: Grand Banks and Jeanne d'Arc Basin

The structural architecture of the Jeanne d'Arc Basin was shaped by multiple phases of ocean opening, which began in the latest Triassic and continued through the latest Cretaceous. There is significant disagreement in published literature concerning the duration and number of rifting events on the Grand Banks. Tankard et al. (1989) recognized two periods of rifting and a protracted post-rift thermal subsidence on the Grand Banks. The first stage of rifting commenced in Late Triassic-Early Jurassic, while the second dominant stage spanned from Middle Jurassic to Early Cretaceous (i.e. Late Callovian to Early Aptian).

McAlpine (1990) delineates two dominant fault trends in the Jeanne d'Arc Basin. He interpreted the major fault types as listric, and high-angle normal basin bounding faults, which predominantly occur parallel to basin margins in a NE-SW orientation. Basin bounding faults were most active from Early Jurassic to Early Cretaceous (Aptian). Trans-basinal, NW-SE trending normal faults were most active from Late Jurassic through Neocomian. Faults from both systems were reactivated in the Late Cretaceous and Early Tertiary as Orphan Knoll and Flemish Cap subsided.

Hiscott et al. (1990) identified three stages of extension in the North Atlantic rift basins. The initial phase of rifting in the Late Triassic is typically associated with basins containing continental siliciclastics and thick sequences of marine evaporites. This was followed by a period of Early to Middle Jurassic thermal subsidence. The second stage of rifting commenced in the Kimmeridgian, and may have resulted in the separation south of Galicia Bank, of southern Iberia and southern Grand Banks. The third stage of separation, of the Flemish Cap and Galicia Bank, was recorded by the Early Aptian anomaly MO (Group Galice, 1979; Sullivan, 1983; Masson and Miles, 1984; Mauffret and Montadert., 1987).

Sinclair (1994) also proposed three episodes of Mesozoic rifting for the Grand Banks region. The first stage of ocean opening began in Late Triassic to Early Jurassic. This resulted in the formation of a series of NE-SW trending, *en-echelon* normal faults, which define the original half-graben geometry of the Jeanne d'Arc Basin. During a second stage of tectonism in the latest Oxfordian, rifting in the upper crust commenced as the growth of these northly-trending faults continued in the Tithonian to Early Valanginian. After a third stage of tectonism in the Barremian, Mid-Aptian to Late Albian rifting resulted in the growth of NW-SE trending normal faults. This third stage of rifting initiated the compartmentalization in the Jeanne d'Arc Basin, through reactivation of oblique slip and linkage to older NE-SW trending *en-echelon* faults.

CHAPTER 2: DATA AND METHODS

2.1 Seismic and Well Data

The seismic data used in this thesis are composed of two separate 3D surveys merged into one seismic project. These are: 1991 Hibernia survey provided by Hibernia Management and Development Company Ltd. (HMDC), St.John's, NF, and the 1997 Cape Pine survey provided by Chevron Canada Resources, Calgary, AB (Figures 2.1 and 2.2). The seismic data are calibrated by 16 exploration wells. Well data include an array of petrophysical well logs, lithological descriptions and biostratigraphic analysis. These data are interpreted in the light of previously interpreted work and together with invaluable support from HMDC.

2.1.1 1991 Hibernia 3-D survey

The Hibernia survey covers approximately 22 km x 25 km. The Hibernia seismic data were acquired by Halliburton Geophysical Services Canada Ltd. between May and October 1991. The data were collected from *R/V Indian Seal* using dual source - dual streamer (Table 2.1) for the Hibernia Management and Development Company Ltd.

2.1.2 1997 Cape Pine 3-D survey

The Cape Pine survey was acquired by Petroleum Geo-Service in May 1997. The *M/V Ramform Explorer* shot approximately 35 km x 10 km of dual source data in the north-south direction (Table 2.1). Chevron Canada Resources (CCR) provided the Cape Pine data for this thesis.

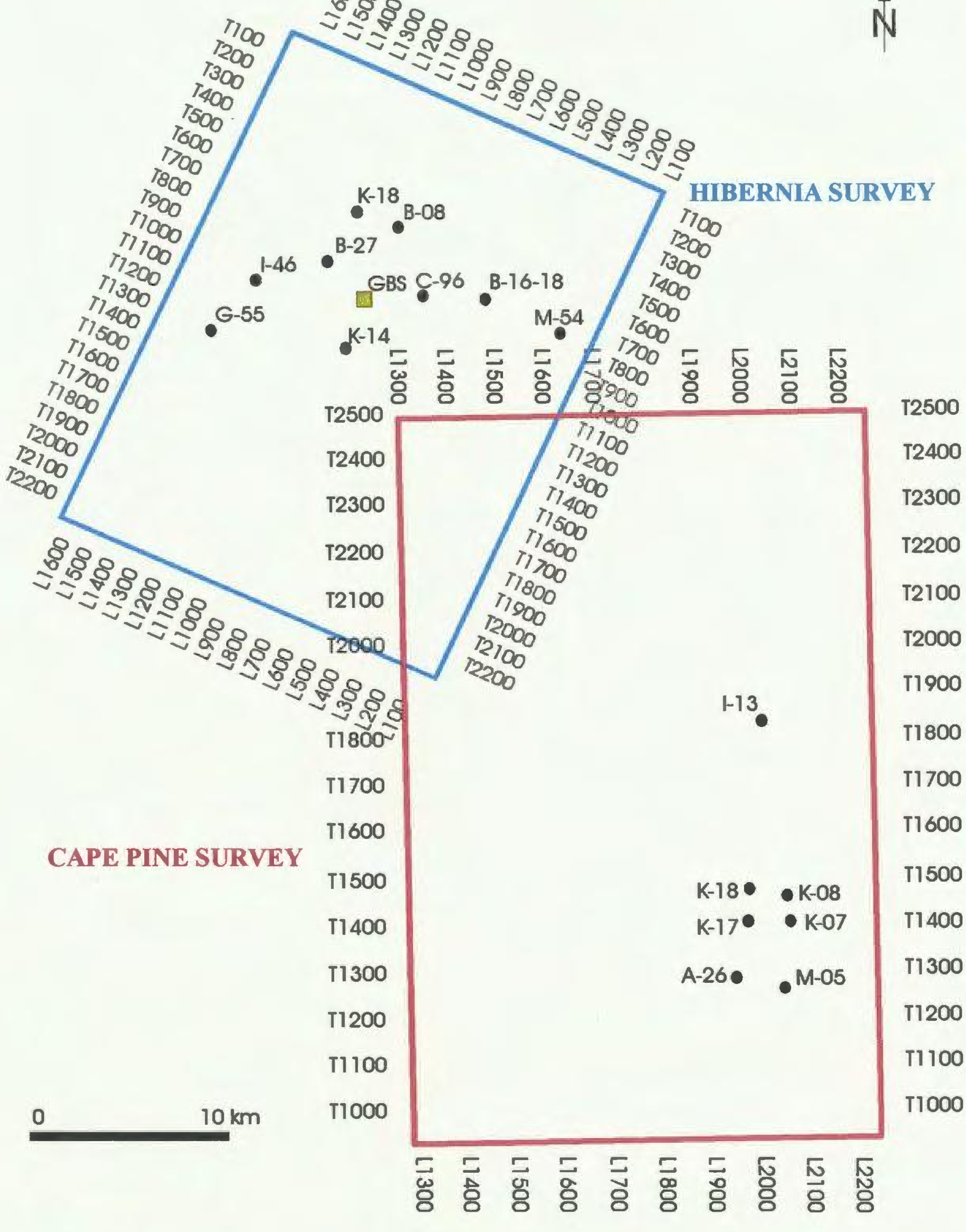


Figure 2.1. The ~1500^{2}km of seismic data used in this thesis are composed of the 1991 Hibernia survey, provided by HMDC, and the 1997 Cape Pine survey, provided by CCR.

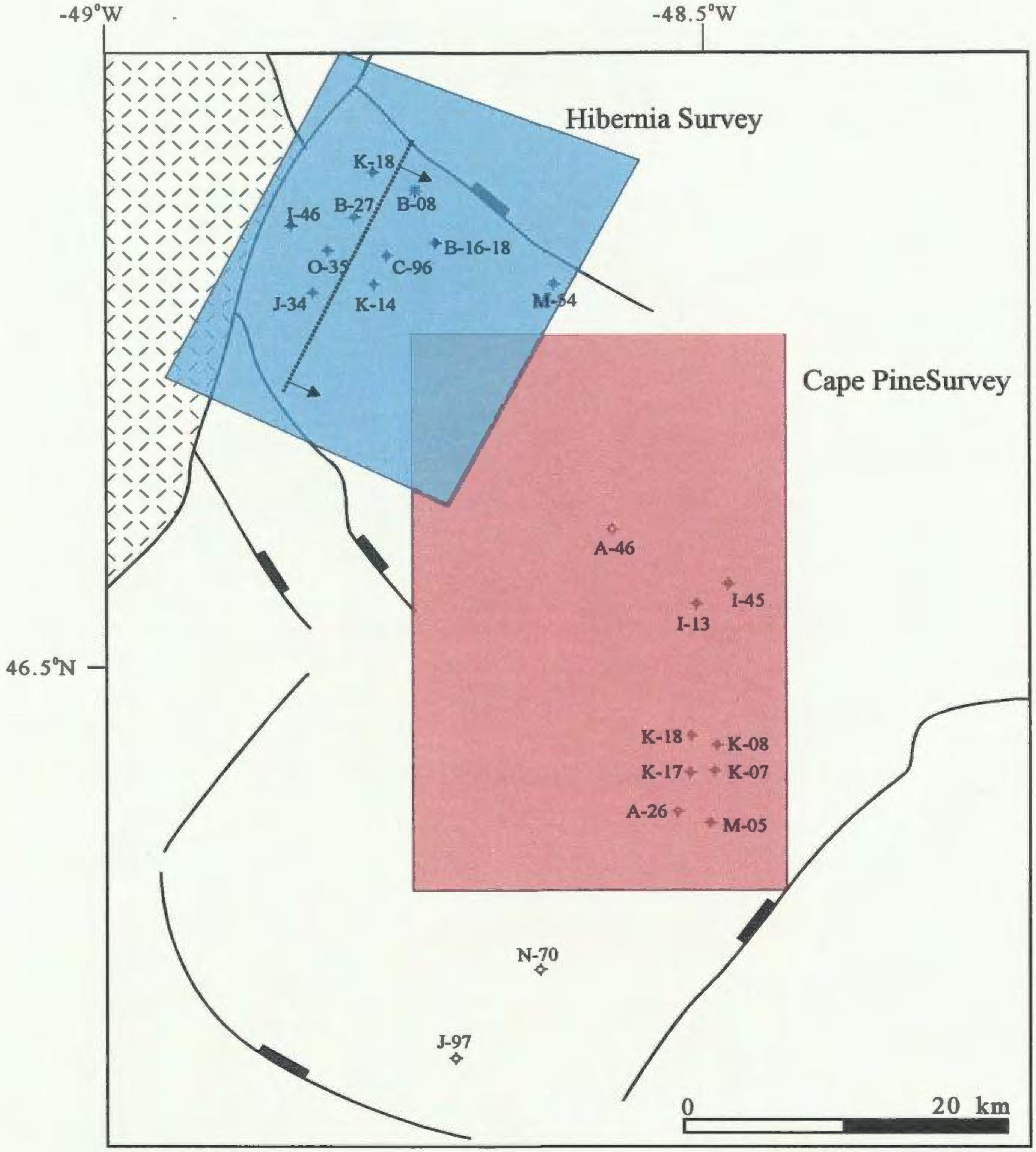


Figure 2.2. Study area of this thesis includes the Hibernia and Cape Pine 3d seismic surveys, in central and southern portions of the Jeanne d'Arc Basin, respectively. The location of wells used in this study are indicated. Seismic stratigraphic analysis focused on the regions east and south of the dashed line shown in the Hibernia survey.

Source Data	Hibernia 1991	Cape Pine 97
source	dual airgun array separation = 50 m	dual airgun array separation = 50 m
source volume	2 x 1910 cubic inches	2 x 3090 cubic inches
average source depth	6 m	7.5 m
shotpoint interval	25 m	25 m
Instrument Data		
sample rate	2 ms	2 ms
record length	6 s	7.2 s
recording system	Titan 1000	Dual Syntrak
recording format	SEG D	SEG-D
filter Low Cut High Cut	out 128 Hz/72 dB/oct	3Hz, 6 dB/oct 206 Hz, 276 dB/oct
primary navigation	DGPS	N/A
time delay	51.2 ms	N/A
multiplicity	30 fold	41 fold
Streamer Data		
cable length	2 x 2975 m	4050 m / 100 m
cable depth	7 m	9 m
group interval	25 m	25 m
number of groups	240 (120 x 2)	1296
near group offset	230 m	270 m

Table 2.1. Summary of the main acquisition parameters for the Hibernia 1991 3D survey, (modified after Wright,1998), and Cape Pine 97 survey (Magesan, 2000).

2.2 Borehole Data

Well data for this thesis (Table 2.2) were provided by Hibernia Management and Development Company Ltd. and Chevron Canada Resources. Wells located in the 1991 Hibernia 3-D survey are tied to seismic data based on geologic tops provided, for the most part by geoscientists at Hibernia Management and Development Company Ltd. and Canadian Newfoundland Offshore Petroleum Board (Table 3.1; CNOPB). Wells in the Cape Pine 3-D survey were tied to seismic by synthetic seismograms, generated from sonic and density data provided by Chevron. Geologic tops for the wells were provided by the CNOPB (2001). The well picks used is this thesis are chosen with confidence, are substantiated by the data presented herein and in conjunction with the geologists and geophysicists at HMDC. The generation of synthetic seismograms is discussed in *Methodology*. The list of time shifts applied to the wells is listed in Table 3.5.

Provider	Well	Datum	B Marker interval (TVD)	Total Depth
HMDC	Hibernia B-16-18	76 m (KB)	3617-3662 m	8180 m
HMDC	Hibernia C-96	33.2 m (KB)	3437-3467 m	4420.2 m
HMDC	Mara M-54	24.4 (RT)	3645-3737 m	4445.9 m
Chevron	Petro-Canada et al Terra Nova K-07	23 m (RT)	2363-2463m	3350 m
Chevron	Petro-Canada et al Terra Nova K-08	24.7 m (KB)	2385-2483m	4499.8 m
Chevron	Canterra PCI et al Terra Nova K-17	24 m (RT)	2170-2258m	3250 m
Chevron	Petro-Canada et al Terra Nova K-18	24.4 m (KB)	2275-2371 m	3925.6 m
Chevron	Canterra PCI et al Beothuk M-05	23.8 m (RT)	2313-2408 m	3779 m
Chevron	Petro-Canada et al King's Cove A-26	23.8 m (RT)	2098-2185 m	3092 m
Chevron	Petro-Canada et al Hebron D-94	22.9 m (RT)	not penetrated	2105 m
Chevron	Mobil et al Hebron I-13	27.4 m (KB)	2795-2887 m	4723.5 m

Table 2.2. Datum, total depth and interval of the B Marker Member limestone of the Whiterose Formation, for wells used in this thesis (CNOPB, 2001).

2.3 Methodology

The analytical phase of this thesis began in January 2000, with mapping of seismic reflectors and major faults in the eastern region of the Hibernia oilfield (Figure 2.2). These features were interpreted in a seismic cube defined by time, not by depth. Mapping of seismic reflectors was conducted using the seismic stratigraphic approach defined by Vail and Mitchum (1977). Section 2.3.1 describes the framework employed during the seismic stratigraphic analysis in this thesis.

2.3.1 Seismic reflection terminations and delineation of depositional units

Seismic stratigraphy is a geological approach to the stratigraphic interpretation of seismic data (Vail and Mitchum, 1977). It is theoretical and interpretative rather than descriptive, and the geological interpretations are expressed in terms of relative sea-level fluctuations (Walker and James, 1992). The first step in seismic stratigraphy is to divide the seismic reflection data into discrete stratigraphic packages or depositional units. The unconformities are delineated on the basis where a depositional unit is defined by a seismic package consisting of genetically related reflectors that are bounded at their tops and bases by unconformities or their correlative conformities.

Unconformities are determined by the onlap, toplap, and downlap reflection terminations, terms which where introduced by Mitchum *et al* (1977a). In addition to the criteria discussed above, the units discussed herein were also chosen on the basis of their temporal and spatial distribution throughout the Jeanne d'Arc Basin and their lithostratigraphic position in relation to the B Marker limestone. The terms described below are used to describe reflection configurations. *Lapout* is the lateral termination of a reflector at its depositional limit. *Truncation* implies that the reflector originally extended further but has been either eroded or truncated. Truncation termination types include: *erosional, apparent* and *fault truncation* (Mitchum *et al.*, 1977a,b). The lapout of reflections against an underlying seismic surface is known as *baselap*. Baselap can consist of *downlap;* where dip of the older surface is less than the dip of the overlying strata, or *onlap;* where the dip of the older surface is greater (Mitchum *et al.*, 1977a,b). Downlap is commonly seen at the base of prograding clinoforms, and represents a change from marine (or lacustrine) slope deposition to marine (or laucustrine) condensation or non-deposition. On seismic data, onlap is recognized by the termination of low-angle reflections against a steeper seismic surface. Two types of onlap can be recognized on seismic data; marine and coastal (Mitchum *et al.*, 1977a,b). *Toplap* is the termination of inclined reflections (clinoforms) against an overlying lower angle surface, where this is believed to represent the proximal depositional limit (Mitchum *et al.*,1977a,b).

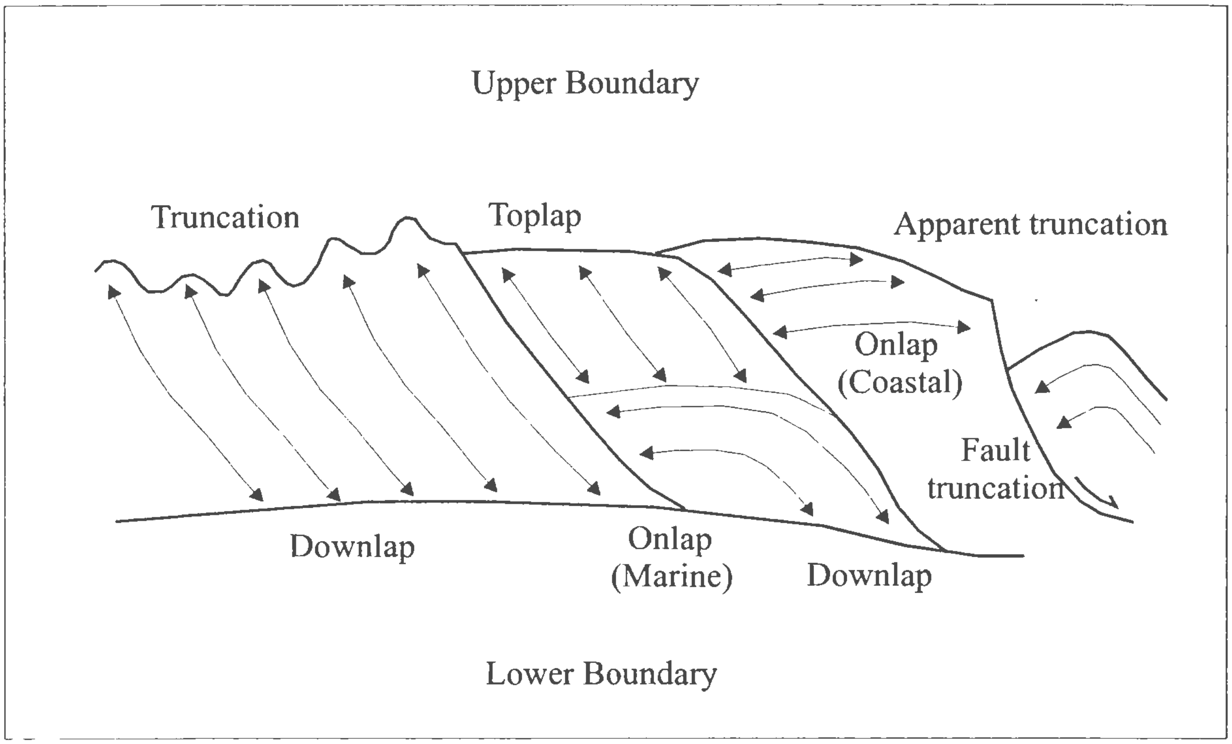


Figure 2.3. Types of reflection terminations as defined by Mitchum et al., (1977a).

2.3.2 Thesis Workflow, Mapping and Interpretative procedures

Seismic stratigraphic analysis initially focused on the area between the Hibernia C-96 well and the Mara M-54 well, because of the uncertain correlation of seismic and well data. Discrepancies between well and seismic data in this area defines this M.Sc thesis. Preliminary interpretations were preformed to identify and characterize these discrepancies. Once the problem was delineated, mapping continued. To aid in interpretation at this stage, additional horizons were mapped on a finer vertical scale.

Seismic mapping established ties between geologic, well and seismic data. Where appropriate, horizons were autotracked and autopicked (zapped) for coarse resolution mapping. Data manipulations, such as zapping, are discussed below in *Programs used.* These horizons were analyzed and further refined by additional horizon interpretation. Horizon interpretation was followed by map generation. Maps created from horizons include time-structure, amplitude, and continuity. These maps, generated using a localized dataset within the eastern extent of the Hibernia survey, provided the geologic framework on a local scale. The local framework was subsequently extrapolated to generate preliminary geologic models of the Jeanne d'Arc basin.

After the initial Hibernia area phase of mapping, it became apparent that additional data south of the Hibernia survey would be beneficial for the project. With the cooperation of Chevron Canada Resources (CCR), the study area grew from the Hibernia oilfield proper, into the central region of the Jeanne d'Arc Basin, an area covering approximately 1500 ^{2}km of seismic data. In May 2001, seismic and well data from the Cape Pine merged survey was received from Chevron Canada Resources, Calgary. At this time the Hibernia and Cape Pine surveys were merged into one 3-D seismic project, using Landmark Seisworks software. Synthetic seismograms were generated from wells in the Hibernia and Cape Pine surveys, and tied with adjacent wells and seismic data. Mapping in the Cape Pine region was integrated with the Hibernia survey. Wells in the Hibernia region were re-examined in conjunction with Cape Pine synthetics. Maps were then created from the larger merged dataset, and old geologic models were modified to encompass new interpretations and the newly defined area. Four seismic traces have been recognized (S1-S4; discussed in Chapter 4) within the stratigraphic range of the proposed B Marker seismic event. The sedimentary evolution of the time interval represented by the B Marker is described using four schematic depositional models corresponding to S1-S4 (Chapter 4).

CHAPTER 3: RESULTS

This chapter examines the seismic stratigraphic and structural architecture of the B Marker (limestone) Member and adjacent depositional units. The regional structural framework of the Jeanne d'Arc Basin is presented first. This is followed by the delineation of depositional units (Unit A and Unit B), both above and below the B Marker Member. The next section takes a closer look at the fault systems in the basin and the architecture of the depositional units across these systems. Details of the seismic reflection character of the B Marker across the basin are presented next. The next two sections examine the character of synthetic seismograms, and correlates seismic, synthetic and lithologic well data. The chapter concludes with a description of the lithologic character and biostratigraphy of the B Marker Member and adjacent units in wells across the basin.

3.1 Regional Structural Framework

The architecture of the Jeanne d'Arc Basin records an intricate history of basin formation. Regional tectonic events which shaped and subsequently effected the Jeanne d'Arc Basin are echoed, locally, in the strata and structures within the study area (Figures 3.1 and 3.2). The major structural elements observed in the study area include: 1) regional synclinal and anticlinal structures, and 2) two dominant fault trends, comprising various fault geometries and associated structures. The regional architecture is presented in the following subsections, primarily in the context of the morphology of the B Marker structure contour map (Figure 3.2). The two fault systems are described in Section 3.3.

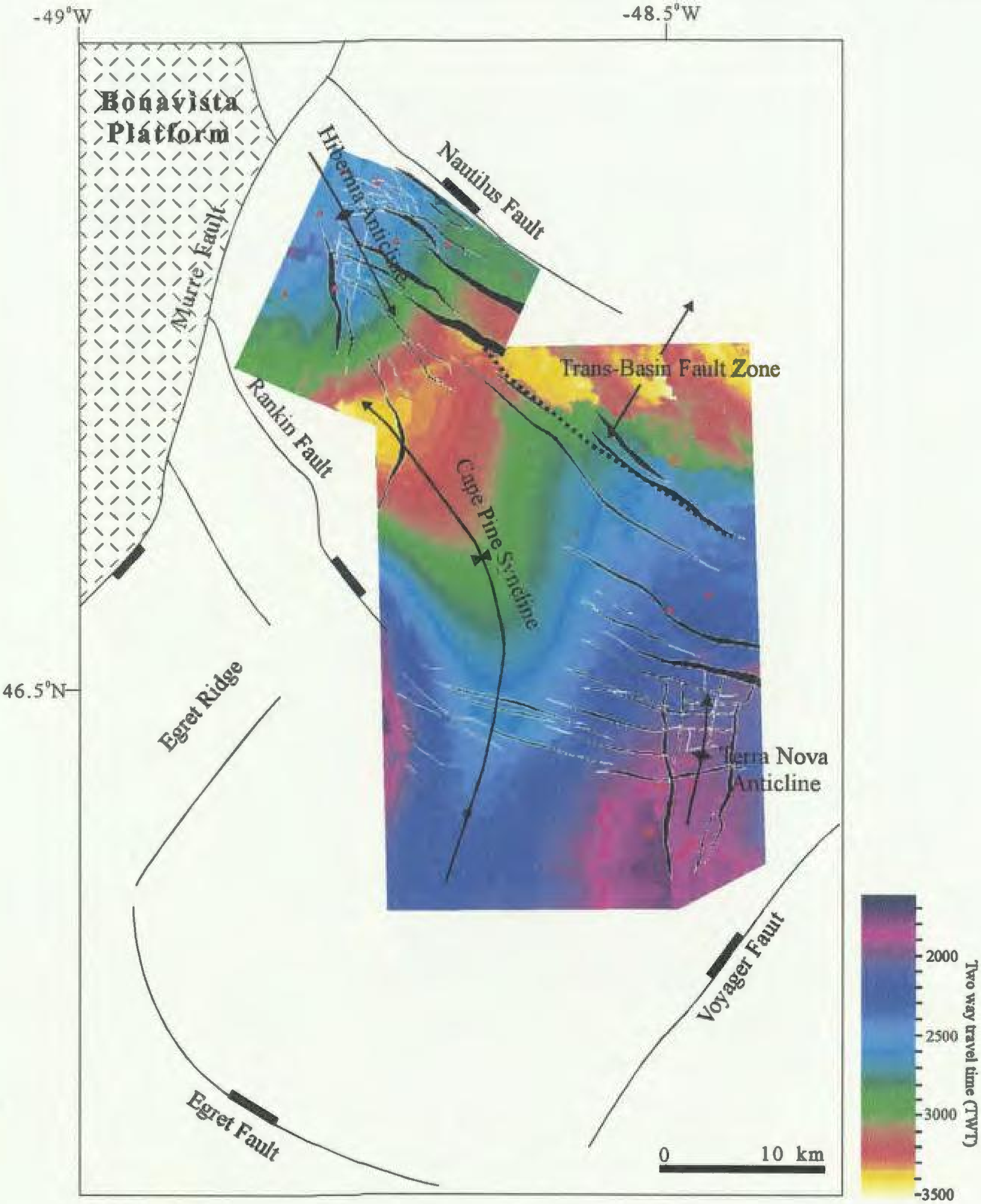


Figure 3.1. B Marker time structure map across the study area, which includes both Hibernia and Cape Pine 3d seismic surveys and wells. Major structural features within the Jeanne d'Arc Basin are indicated. Wells used in the study are marked by red circles.

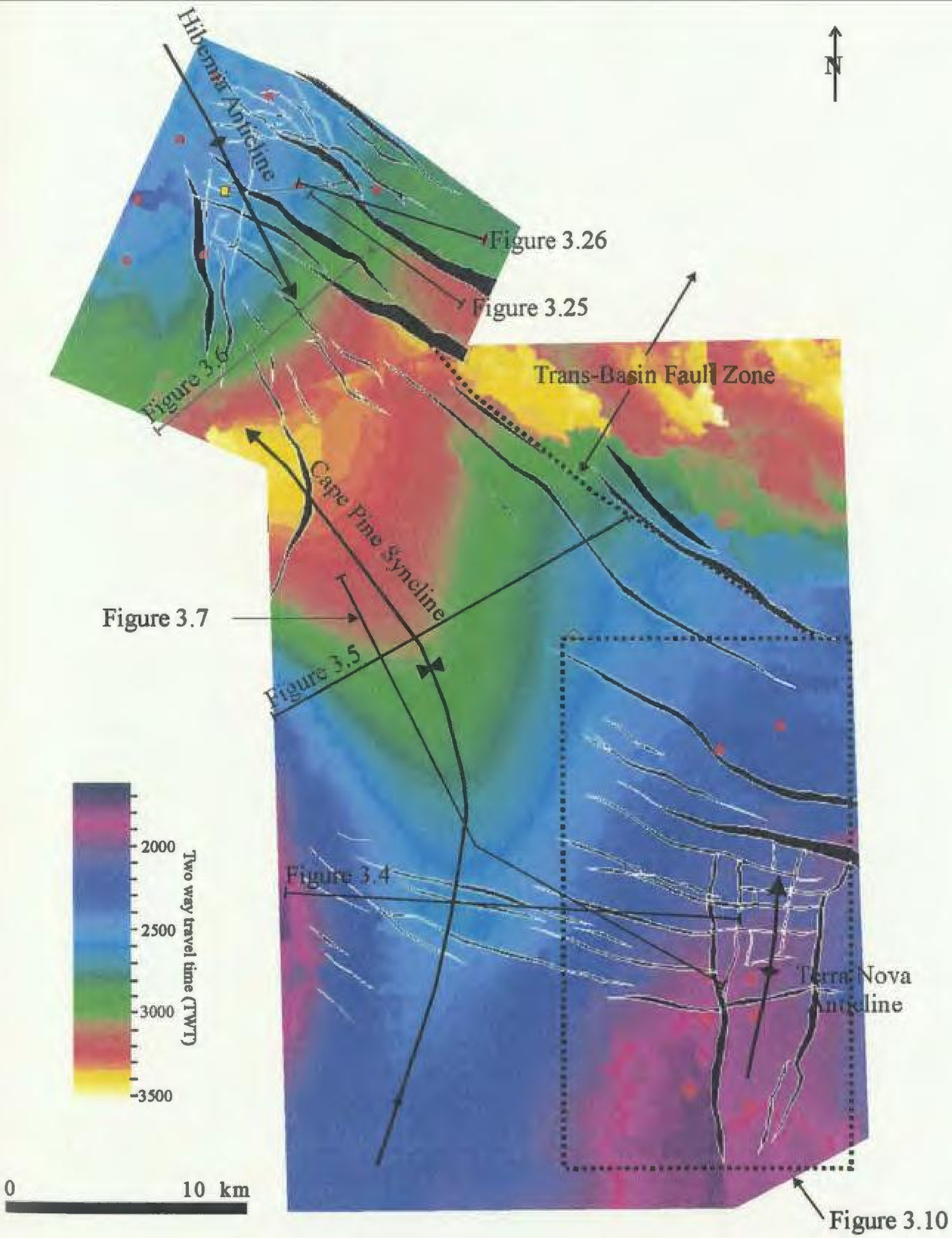


Figure 3.2. Time-structure map of the B Marker limestone, across Hibernia, and Cape Pine 3-D seismic surveys. Major structural elements include the Cape Pine syncline, Hibernia and Terra Nova anticlines. Horizontal fault separations are represented by fault polygons, outlined in white. The location of seismic lines shown in Figures 3.4-3.7, 3.25, 3.26 and the map shown in Figure 3.10 are indicated.

3.1.1 Regional Syncline, Anticlinal Structures and Structural Highs

The Jeanne d'Arc Basin has a funnel-shaped geometry in map view. It is elongate in a NE-SW orientation and tapers toward the SW. The prominent structural features of the Jeanne d'Arc Basin and its surrounding highs are: the Murre Fault, which is the western basin-bounding fault; the Hibernia roll-over anticline in the NW; the Egret Ridge in the SW; the Cape Pine syncline, which defines the main basinal structure; the anticline defined by the Terra Nova arch in the east; and the trans-basin fault zone in the north (Figure 3.1). The Hibernia survey is located in the west-central region of the Jeanne d'Arc Basin. The N-NW trending Hibernia anticline is located in the central region of this survey (Figure 3.2). It is a variably plunging structural culmination dissected by a complex array of fault systems dominated by NW-SE trending faults (Mackay et al., 1990; Tankard et al, 1989; Arthur et al., 1982). The anticline is a large roll-over structure developed during extension in the hanging wall of the listric, east-dipping Murre Fault (Tankard et al, 1989). In this thesis, the seismic stratigraphic analysis of the B Marker is limited to the eastern flank of the culmination, and therefore, the structure of the Hibernia anticline is not further described in detail. The anticline is located N-NE of the northern tip of a prominent arcuate syncline, referred to in this thesis as the Cape Pine syncline. This syncline trends NW along the southern flank of the Hibernia anticline toward the Murre Fault; it extends toward the SE within the Cape Pine survey. The Egret Ridge is a NE-trending structural high located east of the Murre Fault, and forms the west flank of the Cape Pine syncline; it mostly lies beyond the seismic dataset. This high is defined by a basement-cored rider (Gibbs, 1984) in the immediate hanging wall of the Murre Fault. In its northeastern portion, this rider terminates against the Rankin Fault and a NW-SE trending transfer zone (Figure 3.2; Sinclair et al., 1994). The northward-plunging Terra Nova anticline is located east of the Cape Pine syncline, in the SE region of the Cape Pine survey (Figure 3.1). Similar to the Hibernia anticline, the Terra Nova anticline is a major target of hydrocarbon exploration in the Jeanne d'Arc Basin. In the NE region of the Cape Pine survey there is a zone of NW trending normal faults, referred to as the Trans-Basin Fault zone (Sinclair, 1993, 1994; Grant et al., 1990; Enachescu, 1987). This zone extends from the Hibernia oilfield to Ben Nevis and north beyond seismic coverage (Figure 3.1).

The western basin-bounding fault of the Jeanne d'Arc Basin is the Murre Fault, which is a deeply rooted easterly dipping extensional fault with a ramp - flat - ramp geometry (Figure 1.4). The Hibernia culmination lies in the immediate, upper hanging wall portion of the Murre Fault. It is a roll-over anticline, with associated crestal collapse graben (McClay and Ellis, 1987), that developed mainly in the Late Jurassic - Early Cretaceous succession. Over the crest of the anticline the upper portion of the Avalon Formation is notably truncated by the Aptian erosional unconformity (Figure 1.4). This marks either a significant drop in base level in the basin, or a dramatic increase in the rate of uplift relative to the rate of erosion/deposition during growth of the structure in the Barremian to Aptian. The upper portion of the southeast limb of the roll-over anticline is overlain by the wedge-shaped, westerly onlapping succession of the Aptian-Albian Ben

Nevis Formation (Figure 1.4). This upper succession in the Cape Pine syncline was deposited in a so-called hanging wall syncline (Gibbs, 1984), which formed as a consequence of the hanging wall moving over a bend in the upper ramp - flat portion of the Murre Fault. This bend is postulated to lie at a level within the Rankin Formation of the hanging wall (T. Calon, personal communication, 2002). The crest of the roll-over anticline, and the adjacent hanging wall syncline are capped by the nearly horizontal pre-Cenomanian unconformity and the overlying Petrel Limestone Member (see below; Figure 1.4).

The main portion of the Jeanne d'Arc Basin consists of a series of Early Jurassic to Early Cretaceous (pre-Aptian) growth strata wedges, which lie above late Triassic Argo Salt and show considerable westward thickening (Figure 1.4). This succession is punctuated by a number of unconformities representing several phases of rift activity. In the eastern portion of the Jeanne d'Arc Basin, the growth strata wedges show dramatic eastward thinning over the western flank of the Terra Nova arch, notably the Rankin, Jeanne d'Arc, Hibernia, and Avalon formations, but also the Ben Nevis Formation of the younger hanging wall syncline. Within individual wedges the thinning is mainly accomplished by onlap, while overstep onto the crest of the arch is rare, and thin offlap wedges are present on the uppermost portion of the western flank of the arch (e.g., Fortune Bay and upper Hibernia formations; Figure 1.4). The Mesozoic wedge defines the fill of a large asymmetric half-graben which developed in the hanging wall of the Murre Fault during successive phases of rift-related extension. Its complicated architecture on the flank of the Terra Nova arch records considerable variation in the rate of uplift versus the rate of deposition/erosion, not taking into account variations in base level during the evolution of the basin. Asymmetric growth of the basin fill is most pronounced in the Middle-Late Jurassic, but continued at a lesser pace during the Early Cretaceous as indicated by the eastward wedging of the Hibernia, Avalon and Ben Nevis formations.

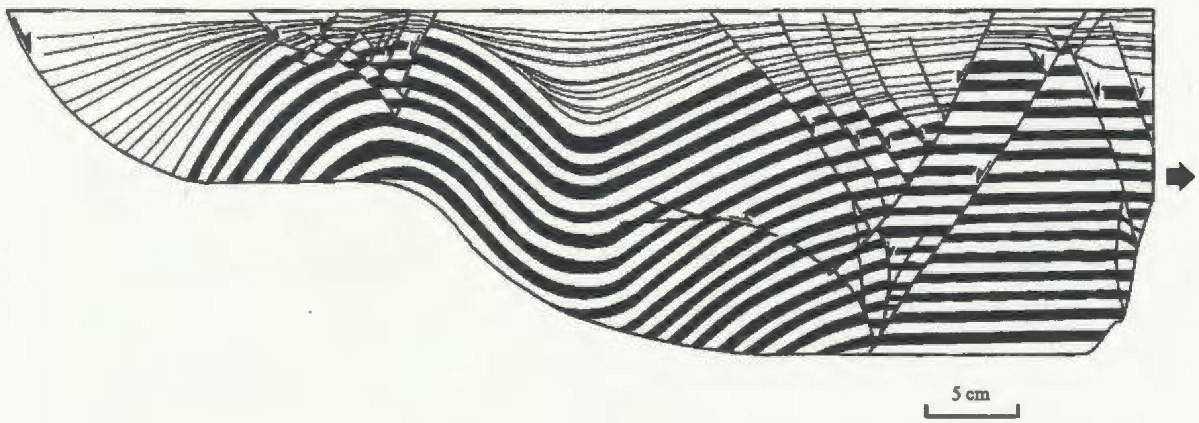
The overall synclinal shape of the Mesozoic basin fill (i.e., the Cape Pine syncline; Figure 1.4 and 3.1) is related to the presence of the Terra Nova arch in the east, and the Hibernia anticline associated with the ramp-flat-ramp geometry of the Murre Fault in the west. The largest structural relief in sections across the syncline is seen in the lowest portion of the growth strata wedges, and relief decreases up-section through the wedges. In addition, the locations of trough points for successive wedges migrate upwards in a westerly direction. This results in a westward side-stepping pattern of the synclinal axial traces, that is compatible with the geometry predicted for folding asymmetric wedges with an easterly taper (T. Calon, personal communication, 2002).

The Terra Nova arch is a huge roll-over anticline that developed in the pre-rift basement of the Jeanne d'Arc Basin, including late Precambrian and Paleozoic units of the Avalon Zone, and possibly Triassic early rift successions. This anticline formed in relation to continued extension during the Mesozoic by bending of the main hanging wall over the deep ramp portion of the listric Murre Fault. The progressive growth of this roll-over structure is recorded in the eastward thinning of the Mesozoic growth strata wedges.

The architecture of the Jeanne d'Arc Basin and its bounding highs is remarkably well illustrated in analog sand box experiment models of extensional faults with ramp-flat-ramp geometries, such as McClay's experiment E14 (Figure 3.3A; McClay, 1989; see also Tankard et al., 1989). This model shows the development of a proximal roll-over anticline above the bend between the flat and lower steep ramp segments, the related development of the hanging wall syncline in the growth strata succession, and the main roll-over anticline in the distal hanging wall portion of the fault system above the lower flat. These features can be directly related to the main structural elements of the Jeanne d'Arc Basin (Figure 3.3B). Moreover, the model clearly shows the pattern of sidestepping of the axial traces of growth strata wedges in the hanging wall syncline. Two important differences are noted between the analog model and the Jeanne d'Arc Basin architecture. First, the Murre Fault does not have the same degree of listricity as the model fault, because it is a variably dipping surface with no real flat segment. Second, all hanging wall strata in the upper and intermediate portion of the Murre Fault are growth strata, therefore creating a different geometry for the roll-over structure above the upper flat.

The Cape Pine seismic survey covers the tapered, southwestern region of the Jeanne d'Arc Basin. The Late Jurassic and Cretaceous strata in this region define an arcuate northerly plunging syncline. Prominent structural highs are present in the southern region of the Cape Pine survey. These highs define the southern, western and eastern flanks of the syncline. They delineate a lobate-shaped geometry for the syncline in plan

A)



B)

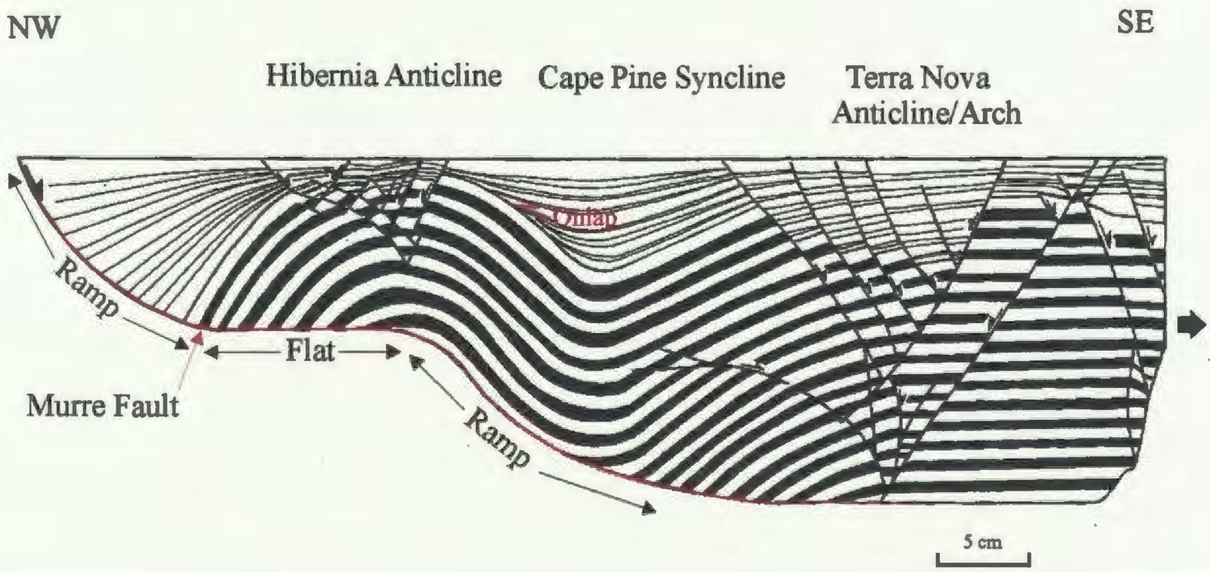


Figure 3.3 A. Experiment E14 (McClay, 1989) shows a line drawing of the sand and mica layered model showing sequencing of faulting. Pre-rift sediments are shown in bold black and white layers. **B.** Experiment E14 related to the Jeanne d'Arc Basin

view, and define the closure of the syncline toward the SW. In map view, the synclinal axis curves from a SW trend in the NW corner of the survey near the Hibernia anticline, to a southerly trend in the central region of the survey, and then to a S-SW trend in the southern region of the survey (Figure 3.1). The variation in the plunge of the synclinal axis is expressed by the B Marker which reaches its greatest depth (3.4 s TWT) in the NW portion of the survey (Figure 3.2). In this region the syncline defines a small SE trending, doubly plunging structural depression nestled against the southern flank of the Hibernia anticline, which quickly loses its expression on the NE limb of the syncline. To the west of the depression, the syncline becomes a broad and shallow easterly plunging trough situated between the southern flank of the Hibernia anticline and the prominent high that occupies the SW portion of the survey (i.e. south of the Rankin Fault; Figure 3.1). The B Marker then rises from ~2.9 s TWT in the central region of the syncline and to ~ 2.0 s TWT in the southern portion of the survey (Figure 3.2).

The Cape Pine syncline has a variable expression, that is most apparent in seismic sections which extend regionally across the basin (Figures 1.4 and 3.4-3.6). The syncline is capped at its top by the unconformity at the base of the Late Cretaceous Petrel Member and overlying Cenozoic successions (Figure 1.4). Throughout the central domain of the syncline, the Petrel Member is a prominent, very high-amplitude, continuous, and nearly horizontal event lying at depths between 1650 - 1900 ms TWT (Figures 3.4-3.6). However, the base of the Petrel Member rises toward the structural highs in both the east and west. Therefore, the Petrel Member defines a shallow and broad syncline below the base Tertiary unconformity (Figure 1.4). In detail, the almost symmetrical architecture of the syncline is shown in Figure 3.4, where there is a vertical relief of ~200 ms TWT between the center and the anticlinal flanks of the "Petrel syncline". In the cross section located further north (Figure 3.5) the base of the Petrel Member rises over an elevation difference of ~500 ms TWT onto the structural high defining the western flank of the Cape Pine syncline. In the NW, the Petrel Member caps the doubly plunging trough of the Cape Pine syncline with a gentle northeasterly dip displaying a relief of ~ 300 ms TWT (Figure 3.6). The basal strata of the Petrel Member lie with apparent conformity over the strata above the A Marker, along the axis of the Cape Pine syncline (Figures 3.4-3.6). In contrast, the base Petrel unconformity typically truncates the greatest thickness of underlying strata along the highs flanking the syncline.

Figure 3.4. W-E oriented seismic line shows the broadly synclinal architecture of the Petrel Member, and succession below, which demonstrate the curved architecture of the Cape Pine syncline. The Petrel event, has a synclinal shape (200 ms TWT vertical difference), which curves toward eastern and western structural highs. See Figure 3.2 for line location. The colored circles indicate cross line correlation points of seismic stratigrapic surfaces.

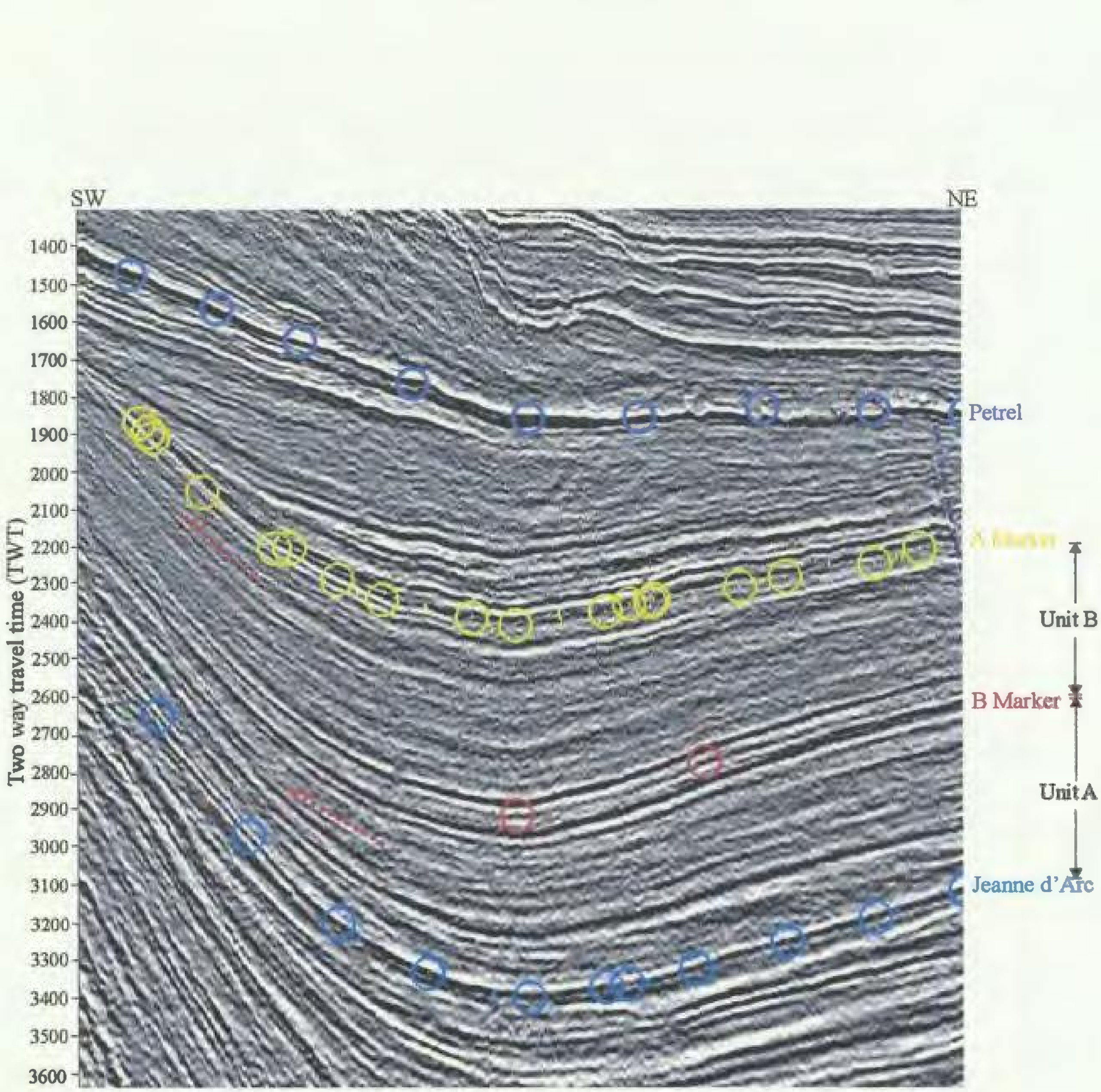


Figure 3.5. SW-NE trending seismic line across the central region of the Cape Pine syncline. Successions below the Petrel Member demonstrate the curved architecture of the Cape Pine syncline. The Petrel event, tilts from a structural high in the west towards horizontal in the east. See Figure 3.2 for line location.

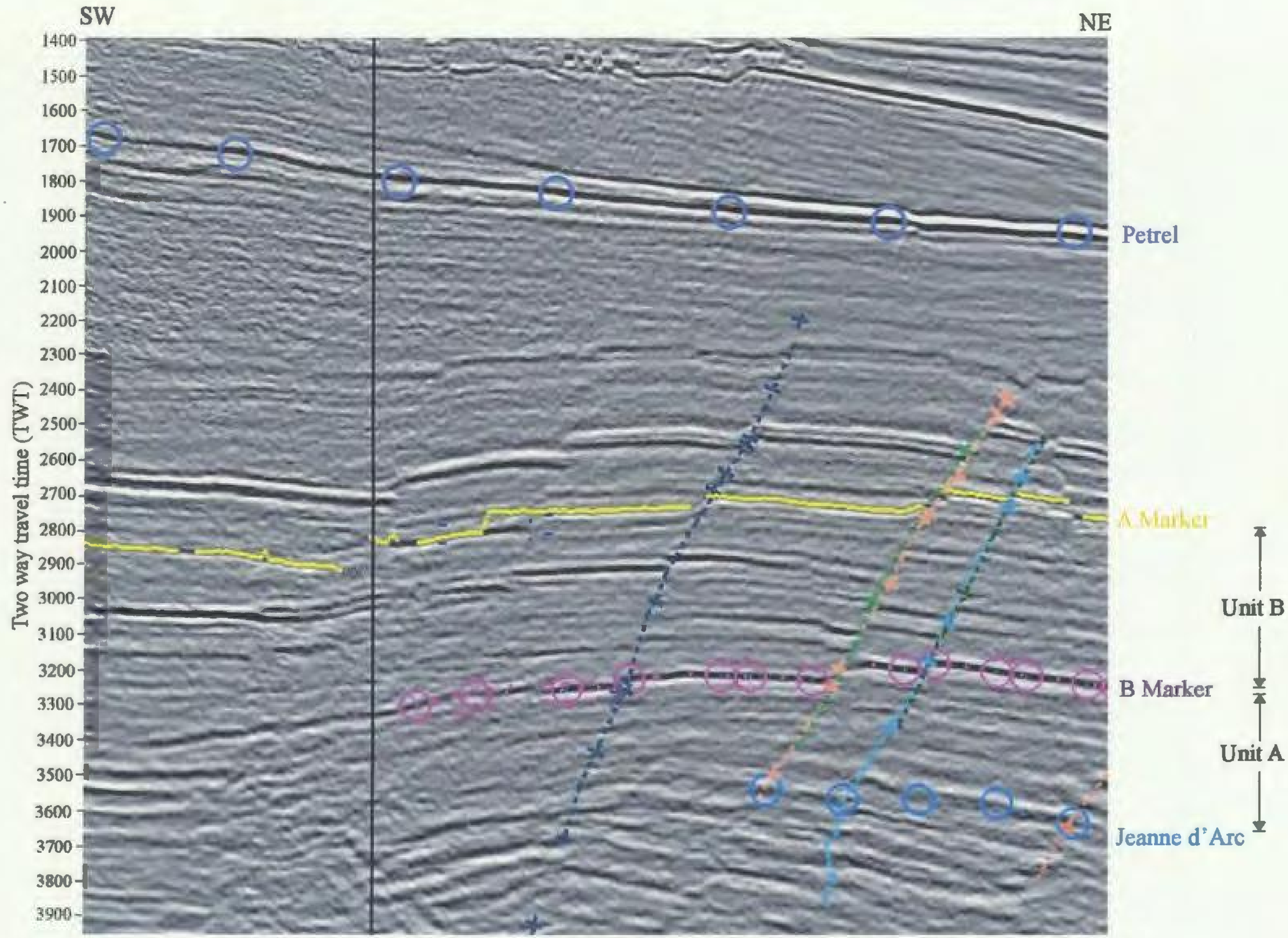


Figure 3.6. SW-NE oriented seismic line across the northernmost extent of the Cape Pine syncline. Succession below the Petrel Member no longer show pronounced the curved architecture of the Cape Pine syncline, but thickening of units above the B Marker towards the Egret Ridge is still observed. The Petrel event tilts downward from the SW-NE. See Figure 3.2 for line location.

3.2 Description of Seismic Units: Stratigraphic Architecture of Basin Fill

This section examines the sedimentary structure of the depositional units representing the Middle Jurassic through Late Cretaceous period. The units were chosen based on the seismic stratigraphic principles defined by Vail and Mitchum (1977; see Section 2.3).

Two seismic units (Units A and B) are identified in the study area. The intent of mapping these units is to determine package thicknesses, document the seismic reflection patterns of both individual seismic reflectors and seismic units, and to decipher the stratigraphic and structural events recorded in the Jeanne d'Arc Basin, with particular focus on the Middle Jurassic through Late Cretaceous periods. Collectively, Unit A and Unit B comprise a succession of sedimentary rocks which rest mostly conformably above the upper surface of the Jeanne d'Arc Formation, and are sealed unconformably at the top by the A Marker limestone. The thickest accumulation of this succession is found in the main plunge depression of the Cape Pine syncline (Figure 3.2). The location of the seismic sections discussed in this part of the text are displayed on the map in Figure 3.2.

3.2.1 Unit A

Unit A is typically the lowermost package within the Late Jurassic - Early Cretaceous sedimentary succession. The unit is characterized by medium- to high-amplitude, coherent internal reflections which show moderate lateral continuity throughout the region. The base of Unit A is delineated by a moderate- to high-amplitude reflector which corresponds to the top Jeanne d'Arc Formation (Figure 3.7). The progressive but mild onlap of lower reflectors in Unit A over the Jeanne d'Arc event is evident along structural highs in the study area, suggesting that the Jeanne d'Arc event is an unconformity along structural highs, becoming a conformable or disconformable surface in deeper regions of the basin. The seismic top of Unit A is delimited by a high- to very high-amplitude coherent reflector which represents the B Marker limestone at the base of Unit B.

Isochore mapping shows that Unit A displays a circular to lobate shape in plan view, and the unit thins uniformly toward structural highs (Figure 3.8). Unit A is thickest along the central axis in the N-S trending portion of the Cape Pine syncline, where package thickness ranges between from 500 ms TWT in the north, to 580 ms TWT along the axis of the syncline, thinning toward 412 ms TWT in the south. Likewise, from east to west, Unit A thickens from 284 ms TWT in the west, to 522 ms TWT in the center, to 375 - 436 ms TWT in the east. Changes in Unit A's thickness are most obvious along E-W trending seismic lines in the Cape Pine survey, which demonstrate both westward and eastward thinning with maximum thinning against the flank of the Egret Ridge (Figures 3.4-3.7). In addition, some thickness variation of Unit A is seen in narrow belts bounded by E-W trending faults across the southern part of the Cape Pine syncline (Figure 3.8). In this area, the isochore map defines a discontinuous horst-block impinging on the western flank of the syncline.

Within the deeper portions of the sedimentary succession, in the trough and along the eastern flank of the Cape Pine syncline, Unit A is divided into two sub-units. The base of the lower sub-unit is bound by the reflector, which corresponds with the top of the Jeanne d'Arc Formation. The surface between the two sub-units correlates with the seismic event defining the top of the Fortune Bay Formation (Figure 3.7). The upper sub-unit includes the Hibernia formation, and the top of this sub-unit corresponds to the base of the B Marker (limestone) Member. The lower sub-unit is thinner than the upper sub-unit, and ranges between 75 and 150 ms TWT in the thickest portion of the sedimentary succession. It displays moderate- to high-amplitude reflectors which primarily are laterally continuous in the deeper portions of the Cape Pine syncline. The upper sub-unit ranges from 250 to 400 ms TWT thickness in the thickest portion of the sedimentary succession. It shows low- to moderate-amplitude reflectivity and is typically laterally continuous. This two-fold character is most pronounced in the deeper regions of the basin, and typically not recognized in sections of the sedimentary succession lying higher on the flanks of the syncline, where the strong seismic expression of the contact is lost (Figure 3.7).

Seismic reflection profiles within the study area reveal minor erosion at the top of Unit A. McAlpine (1990) recognized toplap in beds underlying the B Marker limestone along the margins of the Jeanne d'Arc Basin, associated with minor erosional truncation of the upper portion of the Hibernia Formation along the base of the B Marker limestone.

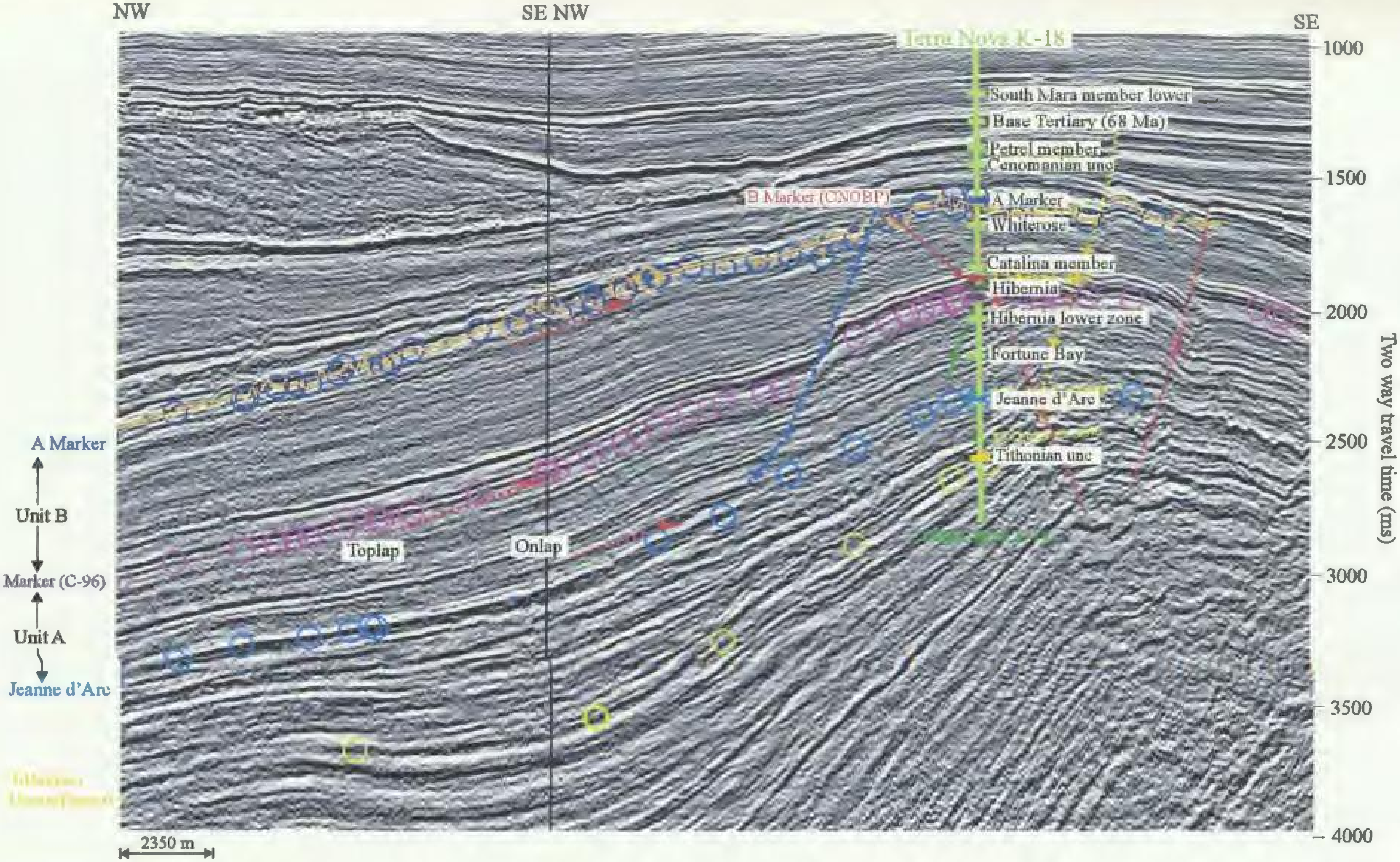


Figure 3.7. This NW-SE trending seismic line shows the variation in thickness of Unit A and Unit B across the Cape Pine syncline and the Terra Nova arch. Onlap and thinning of the unit between Tithonian and Jeanne d'Arc markers suggests there was a phase of rapid growth, which terminated below the base of the Jeanne d'Arc. Onlap and overstep of Unit A is less pronounced than seen below the Jeanne d'Arc base, indicating a slower phase of growth both before and during the time of B Marker deposition Unit B also shows onlap and overstep, and associated package thinning, suggesting significant growth occurred prior to the time that A Marker was being deposited. See Figure 3.2 for line location.

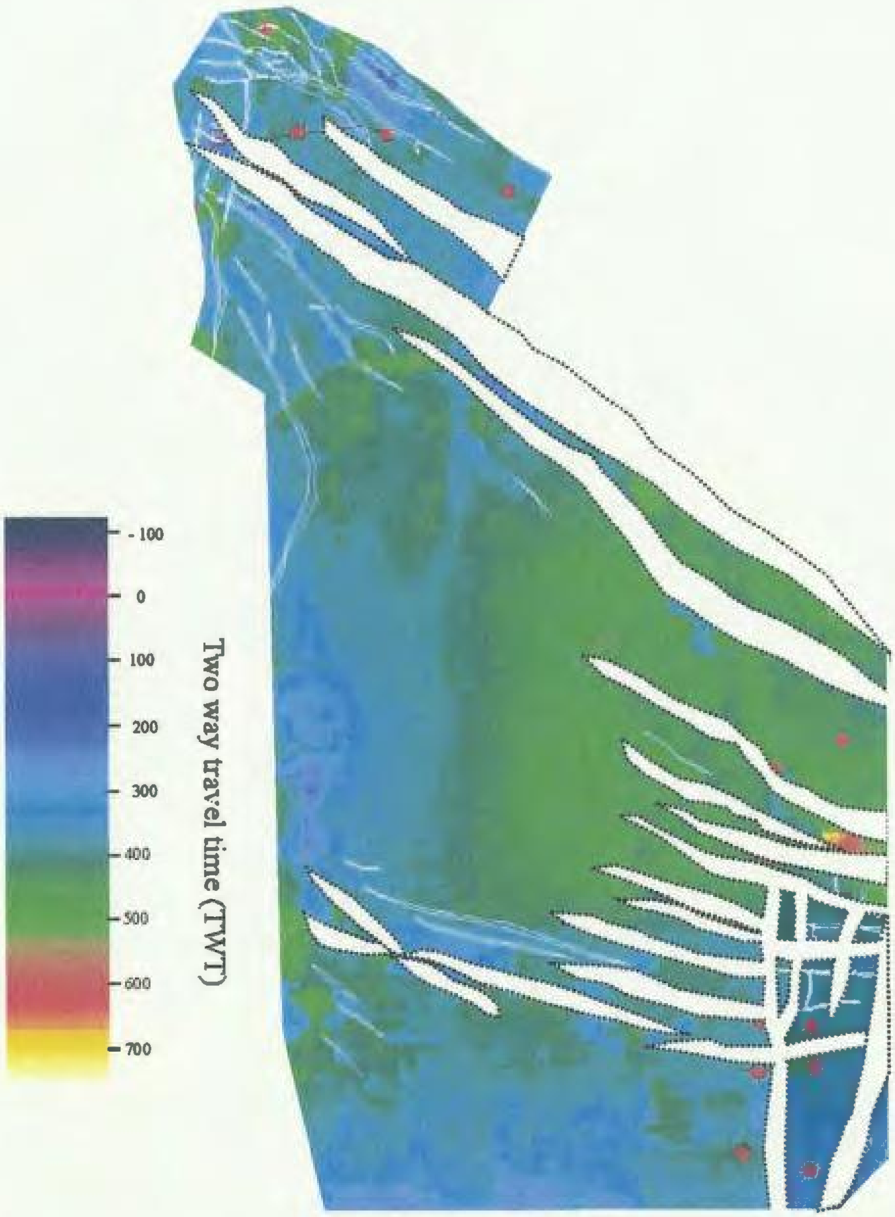


Figure 3.8. Unit A (top Jeanne d'Arc Formation to B Marker limestone) isochore map. Fault separations between the Jeanne d'Arc and B Marker are measured between B Marker in the hanging wall and Jeanne d'Arc in the footwall, and are marked by a dashed line. B Marker fault separations are outlined by solid white lines. Unit A displays a circular to lobate shape in plan view, and the unit thins uniformly toward structural highs. It is thickest along the central axis in the N-S trending portion of the Cape Pine syncline.

3.2.2 Unit B

The base of Unit B is defined by the B Marker (limestone) Member, whereas strata at the top of the unit lie below the A Marker (limestone) Member. Unit B thus includes the B Marker Member, the Catalina Member and shales of the Whiterose Formation. The unit appears in the seismic sections as a regularly reflective package of acoustically moderate reflectors which show significant lateral continuity. In deeper regions of the Jeanne d'Arc Basin Unit B conformably overlies Unit A. However, along the flanks of the Cape Pine syncline, the lower portion of Unit B shows mild onlap to the west onto the lower flank of the Egret Ridge. However, onlap to the east against the Terra Nova arch is not evident, and the lower portion of the unit appears to overstep the flank of the arch with constant thickness (above the unconformity at the base of the B Marker). Seismic reflections in the upper portion of Unit B show toplap against the overlying A Marker indicating that the base of the A Marker is an unconformity (Figure 3.7). In addition, locally the Avalon unconformity excises the A Marker and lies in the top of Unit B.

Unit B is also lobate in plan view, like Unit A, and is thickest along the axis of the Cape Pine syncline; it ranges from 508 ms TWT in the NW, to 650 ms TWT in the center of the syncline, and to 340 ms TWT in the south (Figure 3.9). Unit B thickens from 420 ms TWT on the western flank of the syncline, to 680 ms TWT in the middle, tapering to 412 ms TWT in the east. Significant thinning and progressive onlap of seismic reflectors above Unit B, i.e. on top of the A Marker limestone, as seen on the flanks of the Cape

Pine syncline (Figure 3.7), suggests that the top of the A Marker is also an unconformity in these regions.

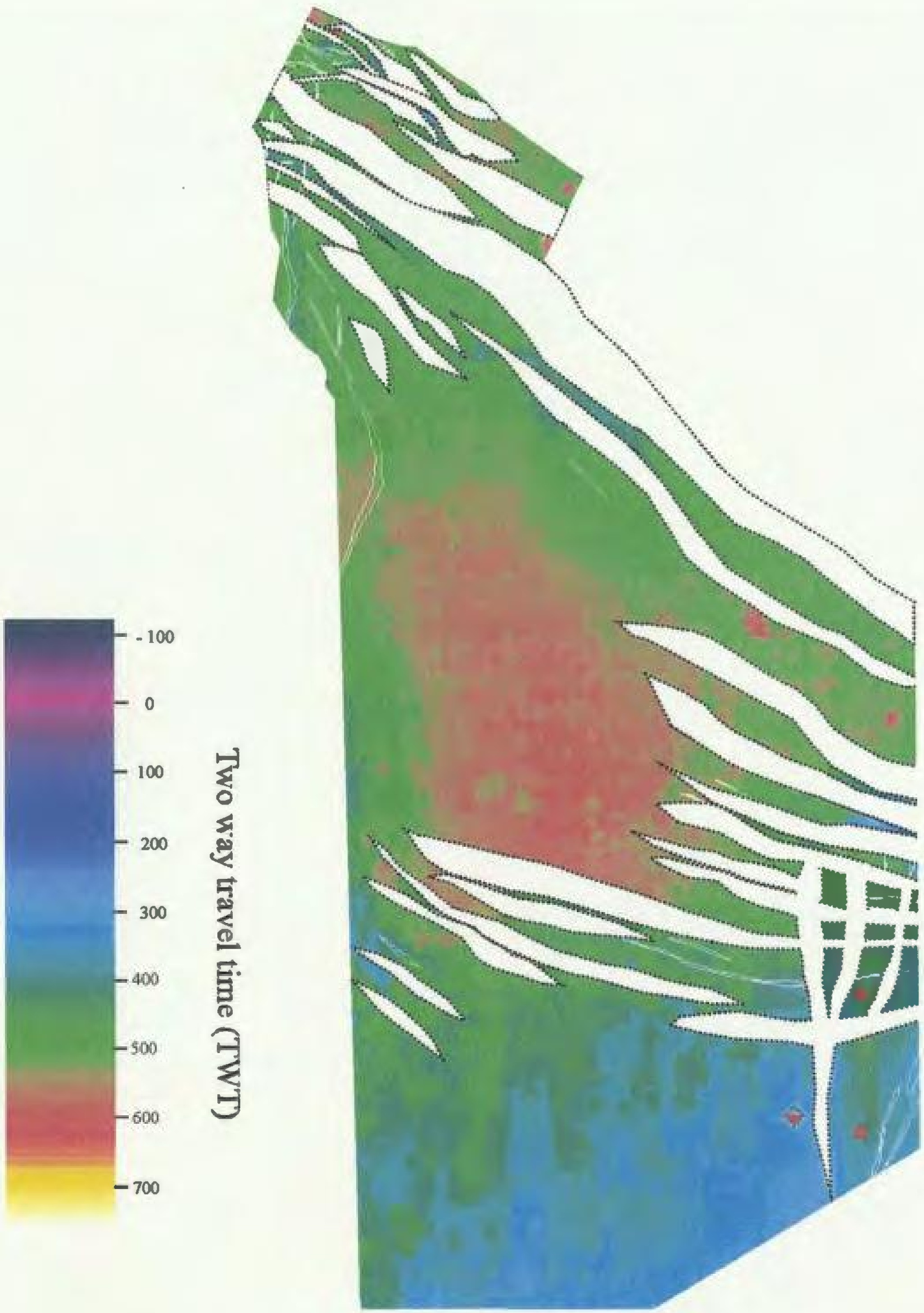


Figure 3.9. Unit B (B Marker to A Marker) isochore map. Fault separations are measured between B Marker in the hanging wall and the Jeanne d'Arc in the footwall. B Marker fault separations are outlined by solid white lines. Unit B is lobate in plan view, like Unit A, and is thickest along the axis of the Cape Pine syncline.

3.3 Fault Systems

The flanks of the Jeanne d'Arc Basin are bound by: 1) the Murre Fault, a NE trending fault which defines the western limit of the basin; 2) the NE trending Voyager Fault, which lies west of the Central Ridge Complex; 3) the NW-SE trending Egret Fault which defines the southern extent of the Jeanne d'Arc Basin (Figure 3.1). The Hibernia survey is bound by the Nautilus Fault in the NE, and Murre Fault along the NW extent.

Two dominant fault trends are evident in the study area. In this thesis, the N-S and NE-SW trending faults are discussed as the NE-SW fault system; similarly, the NW-SE and E-W trending faults are discussed as the NW-SE fault system.

3.3.1 NE-SW fault system

NE-SW trending faults occur in a ~ 55 km wide zone within the study area, and are particularly concentrated in the SE region of the Cape Pine survey (Figure 3.10). Faults in this system trend both NE-SW and N-S. NE-SW faults are oriented parallel to the basin-bounding Murre and Voyager faults. Individual fault segments have linear to slightly curved map traces, which extend laterally from 0.5 - 12 km across the study area. With regard to terminations of these fault segments, both tip points and terminations against cross faults are evident. The faults dip between 40 - 60°, typically averaging between 40 - 50°, toward both the east and west (Figures 3.11-3.13). They form arrays consisting of conjugate sets of planar faults with mainly normal sense dip separation in cross-sectional view. There is no clear evidence for strike separations on faults at the B

Marker level. This is to be expected considering that the stratigraphic markers in the basin generally have horizontal cut-off lines on the fault planes, because their orientation is either horizontal or gently dipping towards the basin axis with trends nearly parallel to the strike of the fault system.

In cross sectional view, curved trajectories observed along some fault planes occur because of the listric geometry of the fault surface, or indicate the presence of a geophysical artifact where velocity pull-up distorts the seismic image, as commonly observed in the foot walls of faults (Fagin, 1996). As illustrated by Figure 3.11, the traced fault surface appears to be listric at depth, but this is actually an example of the intersection of two faults with slightly different dips and strikes. In the Hibernia survey, as illustrated by the basin-bounding Murre Fault zone, both listric and high-angle planar NE-SW trending faults occur (Figure 1.4).

The largest dip separations of the B Marker on NE-SW faults, excluding the Murre Fault, occur in southern regions of the Cape Pine survey. In these southern areas, the greatest displacement of the B Marker is seen on those faults which define the flanks of the structural highs. This is particularly so for the faults on the structural high that defines the eastern flank of the Cape Pine syncline. In Figure 3.12, at ~1.93s TWT in the SE region of the survey, the B Marker intersects a N-S striking, east dipping fault plane *e1500*. Fault *w1340* strikes NE, and dips westward. Fault *e1500* is correlated with the King's Cove Fault and fault *w1340* is correlated with the Beothuk Fault, as defined by the

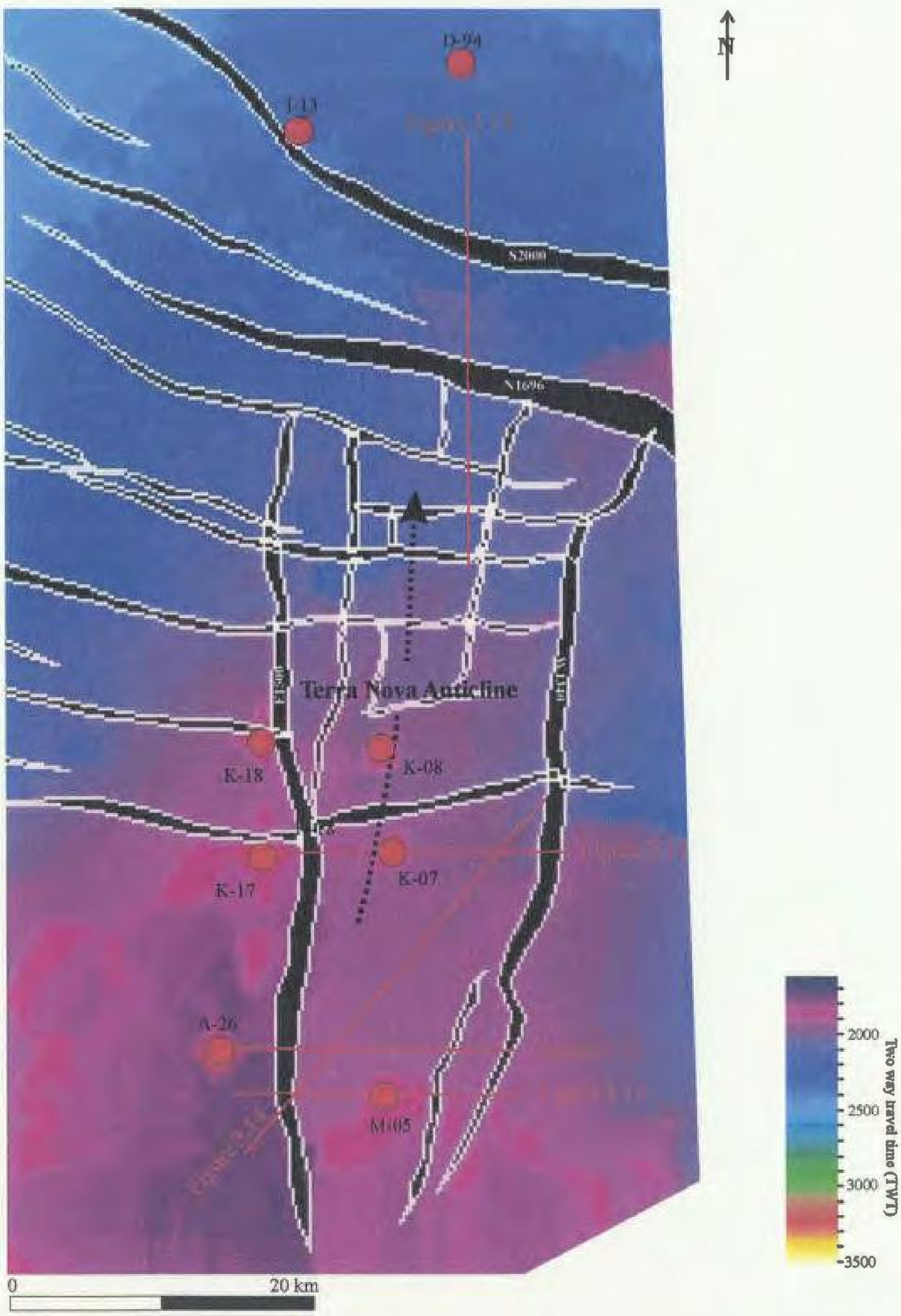


Figure 3.10. Time structure map of the B Marker limestone in the Terra Nova oilfield shown in the inset in Figure 3.2. The location of seismic lines and wells shown in Figures 3.11-3.15 are indicated.

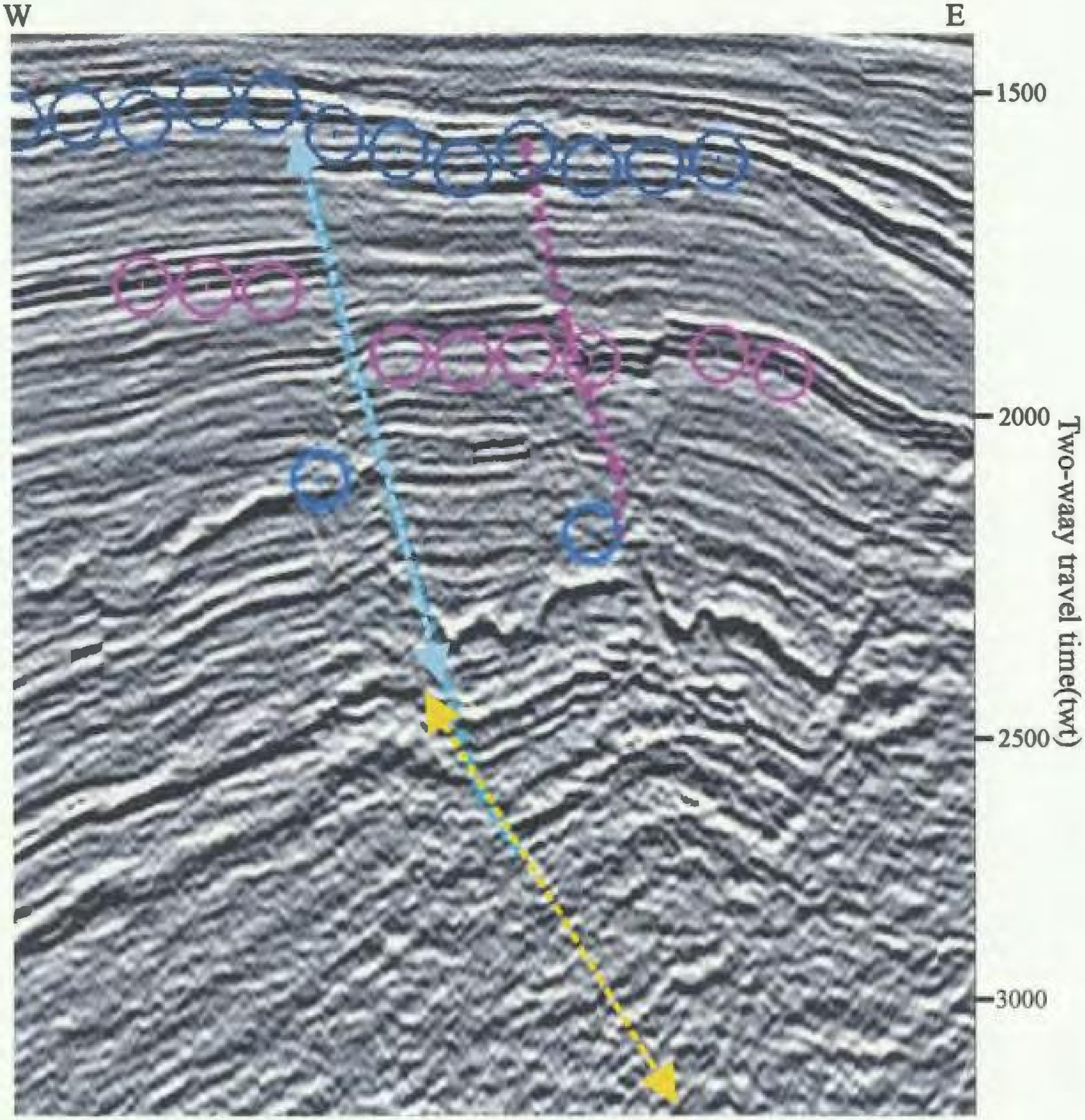


Figure 3.11. E-W trending seismic line illustrating an apparent listric fault, which is actually two faults (highlighted in blue and yellow) intersecting with slightly different dips. See Figure 3.10 for line location.

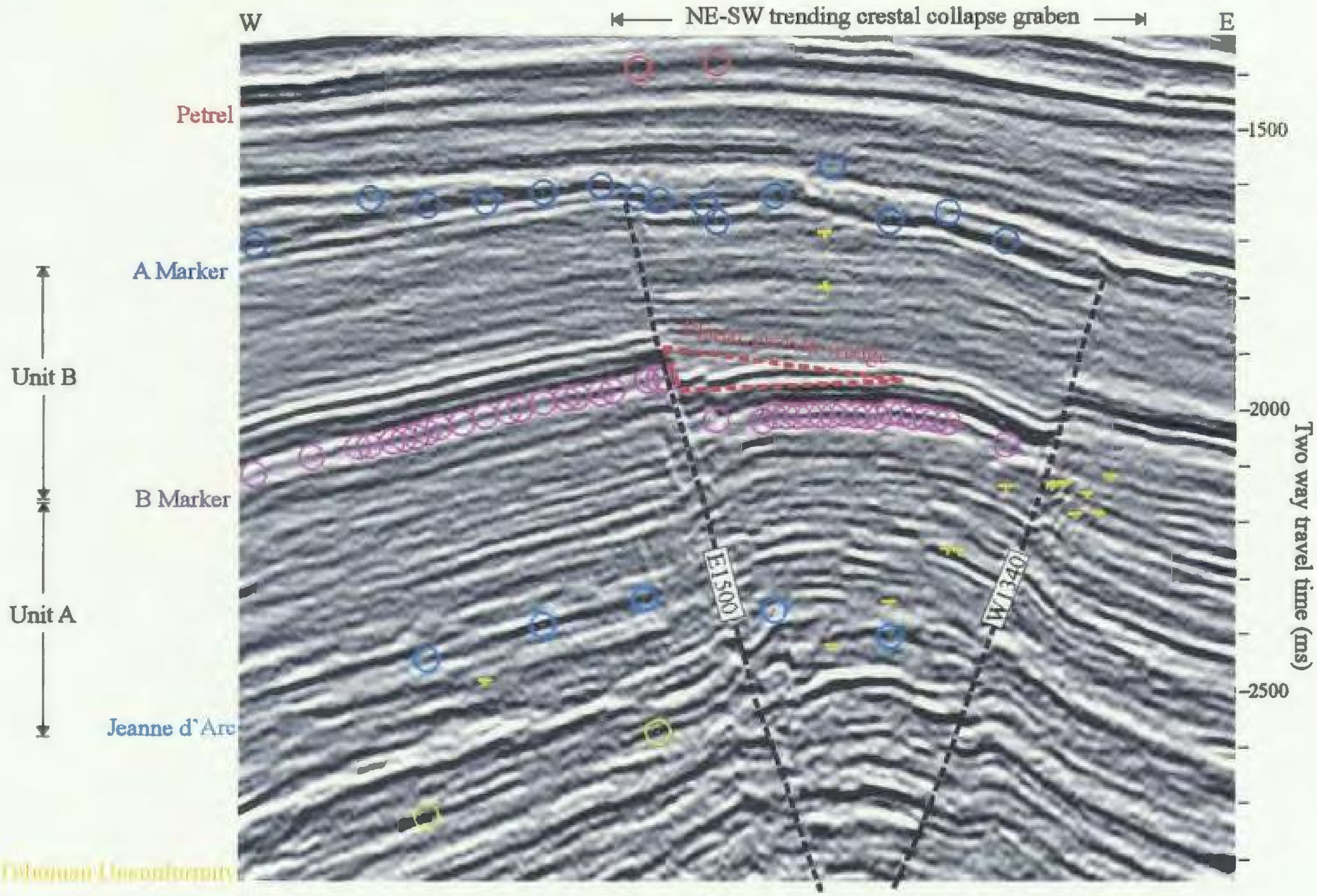


Figure 3.12. Seismic line shows the NE-SW trending crestal collapse graben located in the Terra Nova oilfield region. The stratal architecture in the graben has a broad anticlinal form, with ~ 80 ms TWT of structural relief on the arch above the graben axis. Seismic Unit A demonstrates very little to no growth across the graben. Seismic Unit B shows growth strata which typically form a planar shaped wedge with a thickness of ~ 40 ms TWT. This wedge occurs within the lowest portion of Unit B immediately above the B Marker, and thickens westward against fault *e1500* . See Figure 3.10 for line location.

mapping of Petro-Canada (1996). These two faults are here interpreted to define the western and eastern flanks, respectively, of a crestal collapse graben. A crestal collapse graben has the geometry of a keystone graben bound by planar antithetic and sigmoidal synthetic faults; they are produced by outer arc extension of the evolving roll-over anticline above a listric (ramp-flat) fault surface (McClay, 1989; McClay and Ellis, 1987). Maximum vertical separation of the B Marker across the bounding faults of this graben is ~150 ms TWT. The width of the graben tapers from a distance of ~ 5.1 km in the north, to 2 km in the south. The longitudinal axis of the graben is oriented NE-SW and extends at least 12.0 km (Figure 3.10). Graben highs trend longitudinally, parallel to the graben axis. The graben probably extends further southward, beyond the seismic coverage in this area. In between faults *e1500* and *w1340*, there are sets of smaller scale conjugate faults, extending between 1-5 km along strike; these mimic the graben-bounding faults. The stratal architecture in the graben has a broad anticlinal form. The structural relief of this arch above the graben axis is approximately 80 ms TWT.

The seismic section in Figure 3.13 lies immediately north of the cross section of the crestal collapse graben shown in Figure 3.12. The section shows the crest of an active salt diapir wall, where salt has risen through the lower portion of the stratigraphic successions contained in the keel of the graben (i.e. up to the Jeanne d'Arc marker), and along the eastern foot wall of the graben structure. Salt movement is clearly linked to the extensional faulting that created the graben (Jackson and Vendeville, 1992a). The salt diapir typically pierces the immediate foot wall domain of the fault, due to unloading in the hanging wall. In this structure, the main extensional fault is therefore considered to be the eastern graben-bounding fault. The arching of the strata in the graben, seen in both cross sections, is interpreted to be related to the rise of the salt (Jackson and Vendeville, 1992b). Subsequent fall of the salt is shown by the presence of the small graben developed across the eastern wall of the main graben (Jackson and Vendeville, 1992a). This event clearly effects the strata extending to a level above the A Marker and is, therefore, younger than the formation of the main graben (Figure 3.13).

The Terra Nova arch and associated NE-SW trending fault system and related salt structures shown in Figures 3.12 and 3.13, are located ~20 km west of the basin-bounding Voyager Fault (Figure 3.1). Petro-Canada (1996) proposed that the Terra Nova anticline formed in response to Middle Cretaceous, west-east crustal extension and associated deep-seated salt migration, to form a keystone fault on a north-plunging, salt-cored pillow. This, combined with reactivation of the north-south trending fault system, led to detachment of cover rocks in the salt zone resulting in the uplift seen on the west flank of the Terra Nova oilfield (located west of the King's Cove fault in the block containing Terra Nova wells K-17 and K-18; see Figure 1.6). Continued salt migration combined with subsidence in the keystone graben, further accentuated irregular relief on the Terra Nova anticline (Petro-Canada, 1996). The origin of the crestal collapse graben identified in the Cape Pine grid is similarly thought to be fault-driven. It developed over the crest of a roll-over anticline lying above a westerly dipping, listric extensional fault which tapped

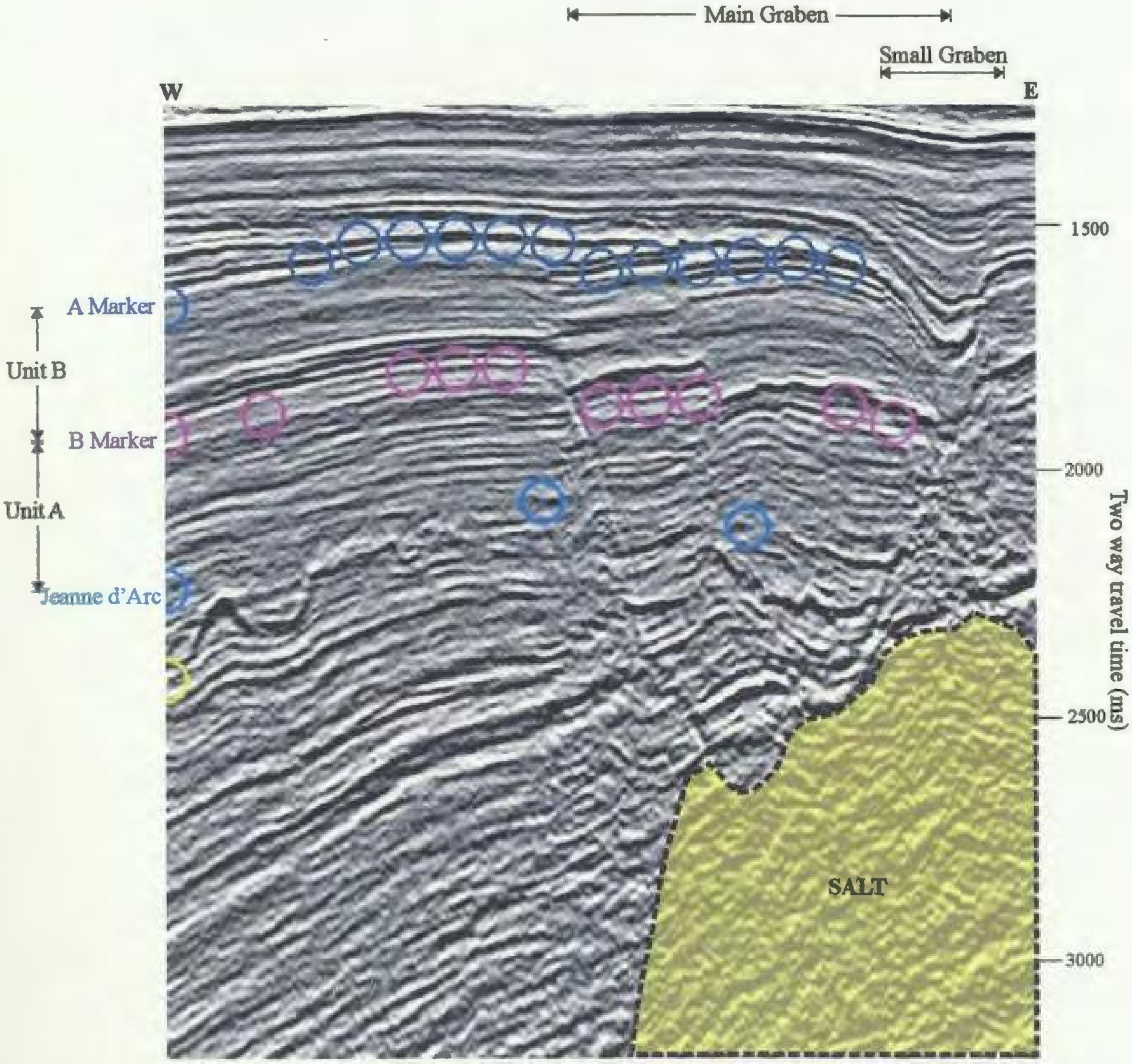


Figure 3.13. W-E trending seismic line in the southern region of the Terra Nova anticline. The Terra Nova anticline formed in response to Middle-Cretaceous, west-east directed crustal extension and associated deep salt migration, to form a keystone graben on a salt cored pillow. The salt plugging the west dipping fault is highlighted in yellow. See Figure 3.10 for line location.

into the Triassic salt horizon, and mobilized the salt because of unloading in the hanging wall of the master fault (i.e. Beothuk Fault) (Figures 3.12 and 3.13).

The stratigraphic successions involved in the crestal collapse graben can be divided into pre-growth and syn-growth strata packages (Figures 3.12 and 3.13). Unit A includes strata between the Jeanne d'Arc and B Marker. This package demonstrates very little to no growth across the graben. Unit B contains strata between the B Marker and the A Marker. This package shows growth strata which typically form a planar shaped wedge with a thickness of ~ 40 ms TWT. This wedge occurs within the lowest portion of Unit B immediately above the B Marker, and thickens westward against fault *e1500* (Figure 3.12). In the cross section shown in Figure 3.13, growth is also seen in the seismic package B, but in this case the thickest growth strata are encountered in the central and eastern portion of the graben. Growth above the A Marker is confined to the small salt withdrawal graben situated above the crest of the salt diapir. This structure contains growth strata with a thickness of 50-100 ms TWT situated mainly in the lower part of the package contained between the A Marker and the base of the Petrel member. In the region between King's Cove A-26 and Terra Nova K-07 wells, a significant amount of growth strata is present within unit B (Figure 3.14). Approximately 120 ms TWT of growth is present across the western graben-bounding fault (*e1500*) where Unit A thickens from 300-420 ms TWT, toward the NE. Furthermore, between the A Marker and the base of the Petrel member, additional growth strata are present, with a thickness in excess of 80 ms TWT. This package of growth strata defines a wedge, which thickens northeastward from 200-290 ms TWT. This growth strata package is correlated with the younger growth strata package associated with salt withdrawal, imaged in Figure 3.13.

3.3.2 NW-SE fault system

NW-SE trending faults are present throughout the entire study area, but are most concentrated in the northern, eastern and southern regions (Figure 3.2). The width of the system span ~ 46 km, and presumably extends east and northeast, beyond the limits of the seismic dataset. East of the Hibernia anticline, in the northeast region of the Cape Pine survey, NW-SE trending faults define a prominent regional fault system, corresponding with the Trans-Basin Fault zone, defined by Mackay and Tankard (1990), McAlpine (1990) and Enachescu (1987) (Figure 3.2). Here the structure contour map for the B Marker shows strong segmentation of the unit in an array of NW-SE trending symmetric and asymmetric NW-SE trending graben with considerable structural relief (Figure 3.2). This region extends north, beyond the seismic dataset , towards the northerly dipping Nautilus Fault (Figure 3.1). An analysis of the B Marker in this complicated fault zone was kept outside the scope of this thesis. Therefore, discussion of the NW-SE fault system focuses on faults observed in the southern and eastern regions within the Cape Pine survey (Figure 3.10).

Fault traces predominantly trend NW-SE in the northern and western regions of the study area, but E-W in the SE, over the Terra Nova arch (Figure 3.10). Fault traces

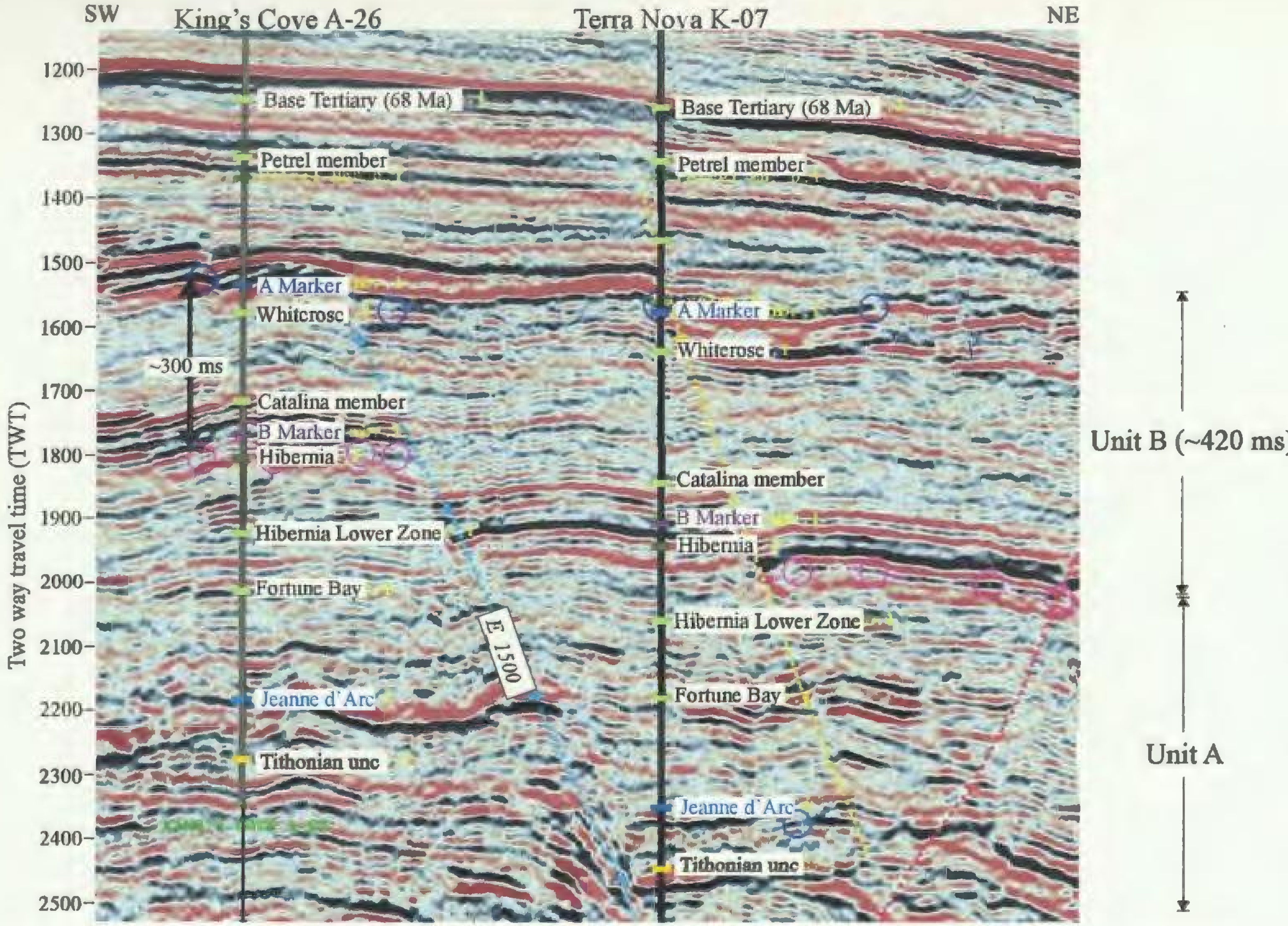


Figure 3.14. SW-NE trending seismic line is located southwest of the Terra Nova oilfield. The well trajectory of Terra Nova well K-07and King's Cove A-26 are highlighted in green . There is ~120 ms of growth in Unit B across NE-SW trending fault system. This is the largest amount of growth strata observed in Unit B within the study area. See Figure 3.10 for line location.

have straight to arcuate geometries in plan view and show evidence of splaying. NW-SE trending faults extend between ~ 0.5-14.8 km along strike. Smaller scale faults, with strike length between 0.5-3.0 km, are mostly concentrated along the flank of the structural high (Egret Ridge) in the SW region of the survey. Large scale faults, with strike length between 10.0 -14.0 km, are evident throughout the survey and cross the entire syncline and its flanking structural highs. Faults have dips between 55-60° toward both the NE and SW. In cross-sectional view, they are typically faults with normal sense dip separation (Figures 3.10 and 3.15). The faults are generally planar surfaces, and commonly arranged in conjugate sets.

Dip separations on the B Marker across NW-SE faults increase in north and northeastward directions. The larger dip separations coincide with faults which define flanking structural highs in the Cape Pine region. At ~ 1950 ms TWT in the east-central region of the survey, the B Marker is intersected by fault plane *n1696* (Figure 3.15). This is a normal fault, which trends NW-SE and dips northward. Similarly, fault *s2000* extends from NW to SE, dipping SW. These two faults define the northern and southern flanks, respectively, of the graben depicted in Figures 3.10 and 3.15. Maximum throw of the B Marker across the bounding faults of this graben is ~ 400 ms TWT. The width of the graben increases from ~ 1.4 km in the east, toward 4.5 km near the center of the Cape Pine survey. The longitudinal axis of the graben is oriented NW-SE and extends at least 14 km, and probably further beyond the limit of the seismic grid.

NW-SE trending structural highs show no evidence of growth strata in units A or B. However, the presence of growth strata above Unit B, between the A Marker and Petrel Member, is observed on both uplifted blocks and graben associated NW-SE trending faults. Figure 3.15 shows growth within the NW-SE trending graben located along the eastern flank of the syncline within the Cape Pine survey. However, determination of the quantity of growth strata between the A Marker and Petrel Member is complicated by erosion above the A Marker, which occurred after the tilting of pre-growth units A and B, and the thin package of strata above the A Marker. In some regions within the Jeanne d'Arc Basin, the A Marker and base of the Avalon Formation define the same horizon (Tankard and Welsink,1987; Sinclair, 1988). As illustrated in Figure 3.15, the A Marker and "base Avalon" are two separate horizons, which display varying amounts of erosion within the package of strata lying between them. South of the graben, an ~100 ms TWT thick package of strata lies between the A Marker and the erosive Avalon horizon, while north of the graben the package is ≤50 ms TWT thick (Figure 3.15). Within the graben strata between the "base Avalon" and A Marker reaches ~ 200 ms TWT thickness, suggesting the Avalon unconformity was less erosive within the confines of the graben. Similarly, more strata is preserved between the Avalon Formation and Petrel Member in the down-faulted succession within the graben, than on the adjacent foot wall blocks (Figure 3.15). Although the amount growth strata preserved within the NW-SE fault system is probably less than the amount deposited initially, it is obvious that notable growth occurred between the A Marker and Petrel Member.

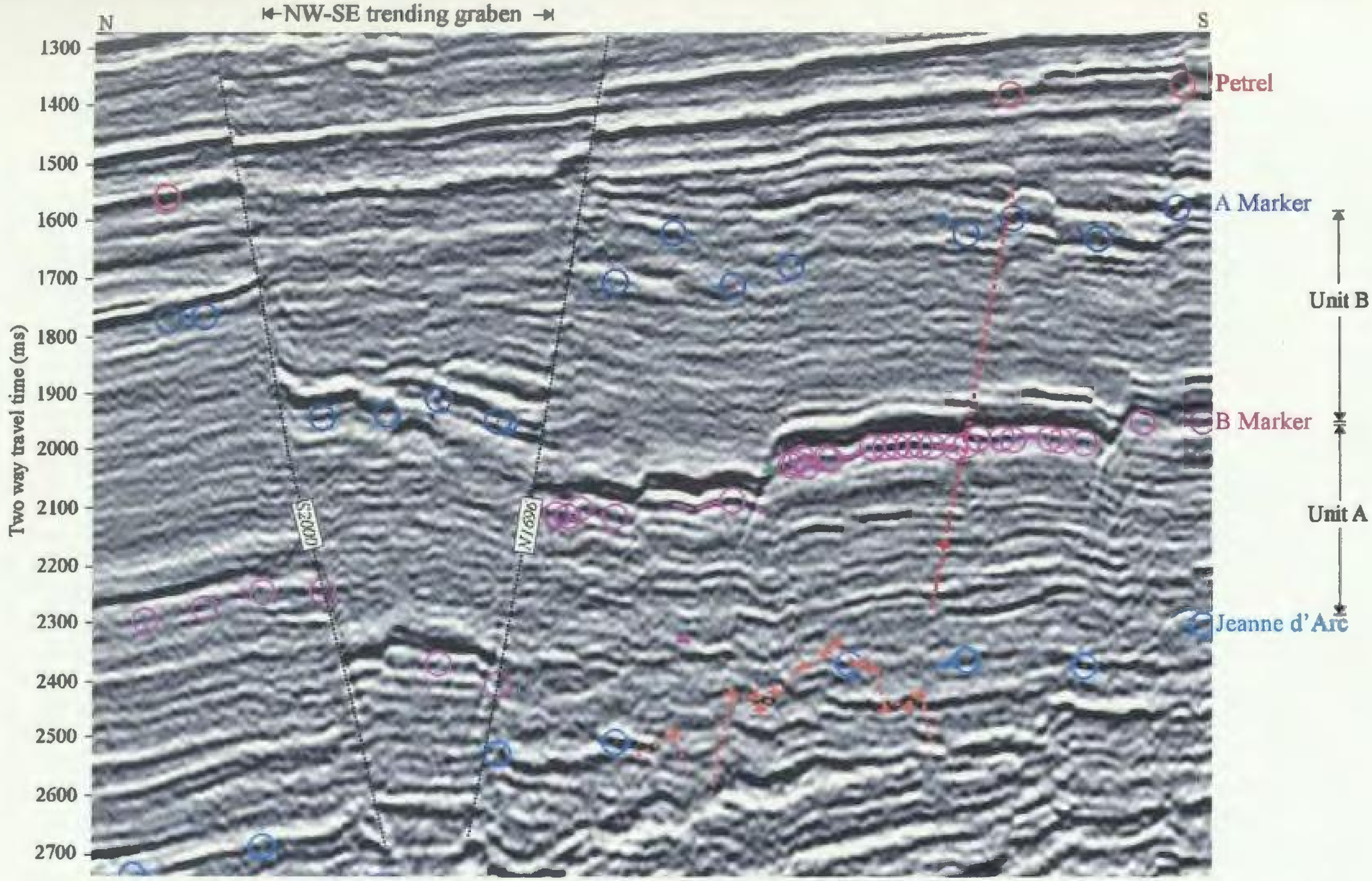


Figure 3.15. N-S trending seismic line shows the NW-SE trending graben located along the eastern flank of the syncline within the Cape Pine survey. Structural highs bounded by NW-SE trending faults show no evidence of growth strata in units A or B. Growth strata between the A Marker and Petrel Member is observed on both uplifted blocks and the graben associated NW-SE trending faults. See Figure 3.10 for line location.

3.4 Seismic Character of the B Marker Member

3.4.1 Seismic Reflector Continuity

Continuity extractions are useful in 3-D seismic analysis which allows the identification of the zones where reflectors are laterally continuous. By calculating localized waveform similarity in both line and trace orientations, estimates of 3-D seismic coherence can be obtained (Bahorich and Farmer, 1995). Typically, fault planes and localized stratigraphic features appear on continuity maps as zones of discontinuity. Similarly, in the study area, zones of seismic reflector discontinuity correlate well with mapped fault traces (Figures 3.16 and 3.17).

A continuity extraction was generated in SeisWorks for the B Marker horizon, which corresponds with the B Marker seismic event (Figure 3.18 and 3.19) and B Marker geologic well pick of CNOPB in C-96 (Figures 3.16 and 3.17).

Along the eastern flank of the Hibernia survey the B Marker continuity extraction reveals a ~ 3 km wide zone of discontinuity. This zone correlates with the hanging wall of a major NW-SE trending normal fault (see Figures 3.2, 3.16 and 3.17). This area of discontinuity has an abrupt contact in the west with a zone of high continuity. It is bound to the south by another NW-SE trending normal fault and possibly extends east beyond the survey limits (Figure 3.17). In the western region of the Hibernia survey, there is a large ≥7km wide zone of discontinuity which spans from north to south over a distance of ≥8 km. This zone of discontinuity has a gradational contact with adjacent zones of continuity.

In the Cape Pine survey, zones of discontinuity are present along faults and in areas immediately adjacent to the faults, extending ~ 200-300 m beyond the fault trace, ie., in the hanging walls and footwalls. In the central to NW region of the Cape Pine survey there is a large zone of discontinuity, which is shaped like the letter "T", and slightly tilted toward the NW (Figures 3.16 and 3.17). The "cross" of the "T" is ~ 4km wide over a distance of 10 km, and the "stem" is ~ 2 km wide, extending ~ 14km. This zone of discontinuity has an abrupt contact with adjacent zones of higher continuity.

Careful seismic tracing, mainly in the Cape Pine region demonstrates the lateral discontinuity of high amplitude events associated with the B Marker (Figures 3.18 and 3.19). Most notable are patterns of overstepping/splitting and shingling of discontinuous reflections defining the B Marker. This zone of discontinuity can be clearly recognized throughout the survey area, but is most pronounced in the "T" shaped region in the Cape Pine survey (Figure 3.17).

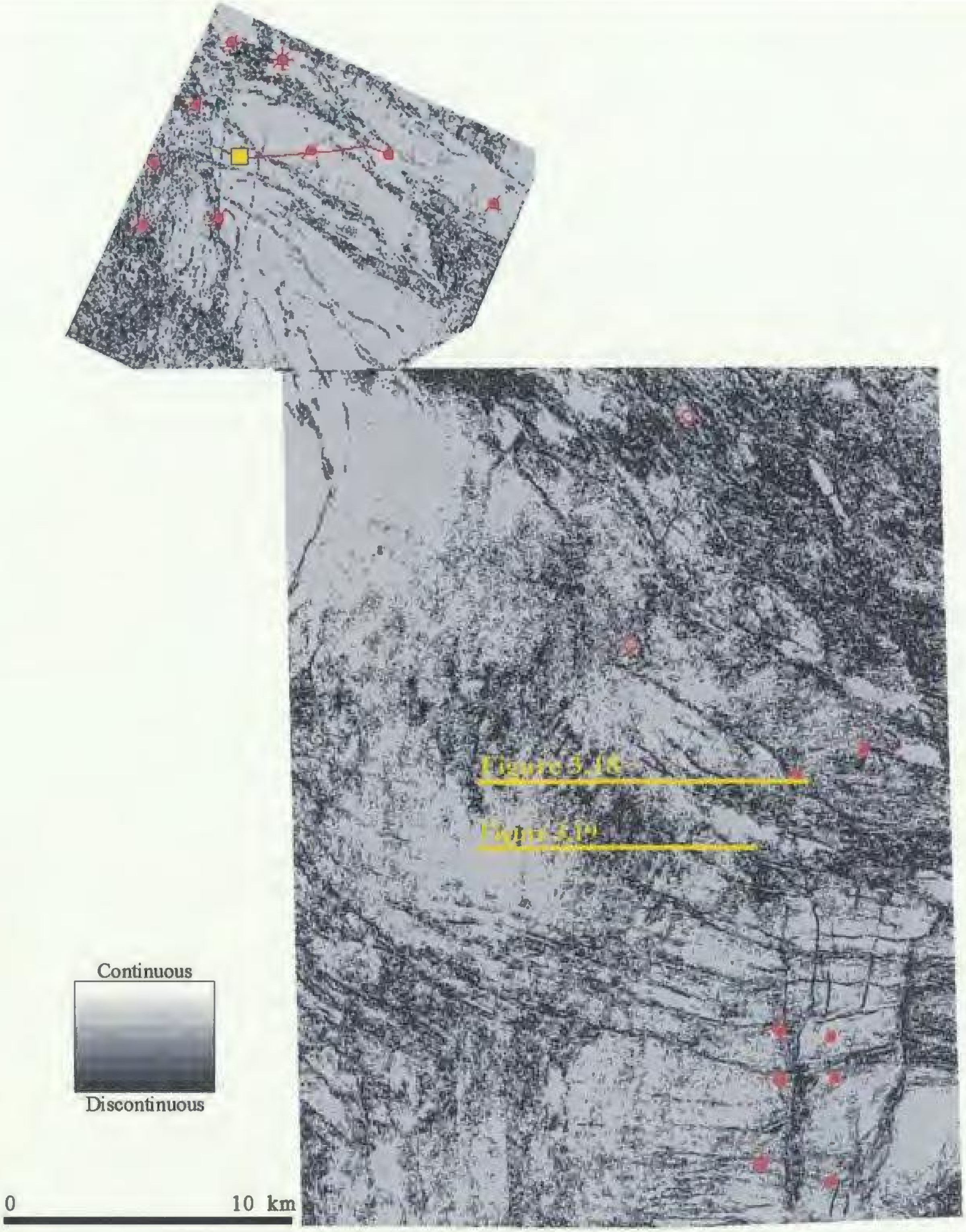


Figure 3.16. Continuity map of the B Marker event extrapolated from the Hibernia C-96 well. Areas containing highly continuous seismic reflectors are grey in color, and discontinuous zones are black The location of the seismic lines shown in Figures 3.18 and 3.19 are highlighted in yellow.

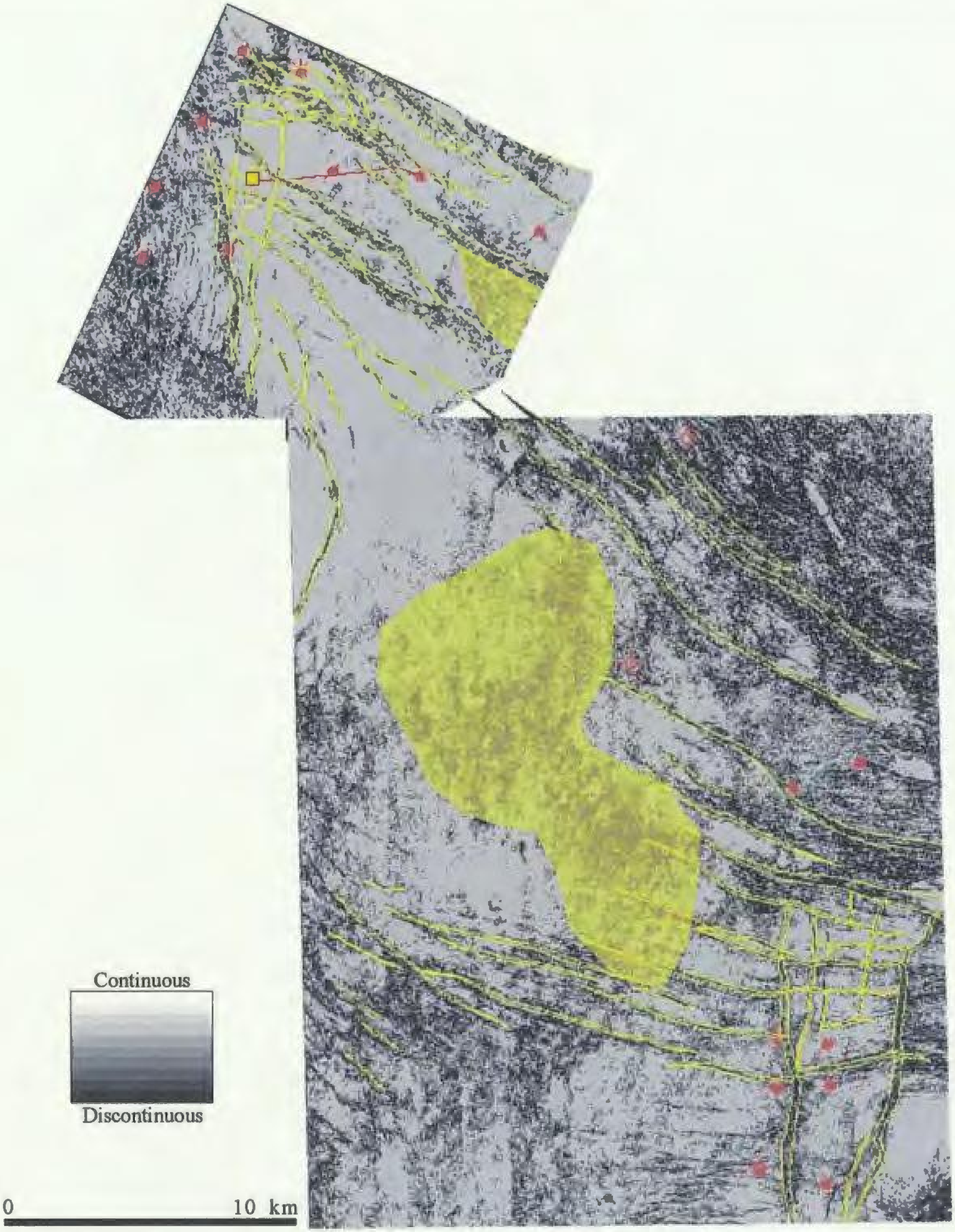


Figure 3.17. Continuity map of the B Marker limestone extended from the Hibernia C-96 well. Areas containing highly continuous seismic reflectors are grey in color, and discontinuous zones are black. The most notable areas of discontinuity are colored yellow, including; fault traces, ~ 3km wide N-S zone along the eastern flank of the Hibernia survey, and the "T" shaped zone in the central region of the Cape Pine survey.

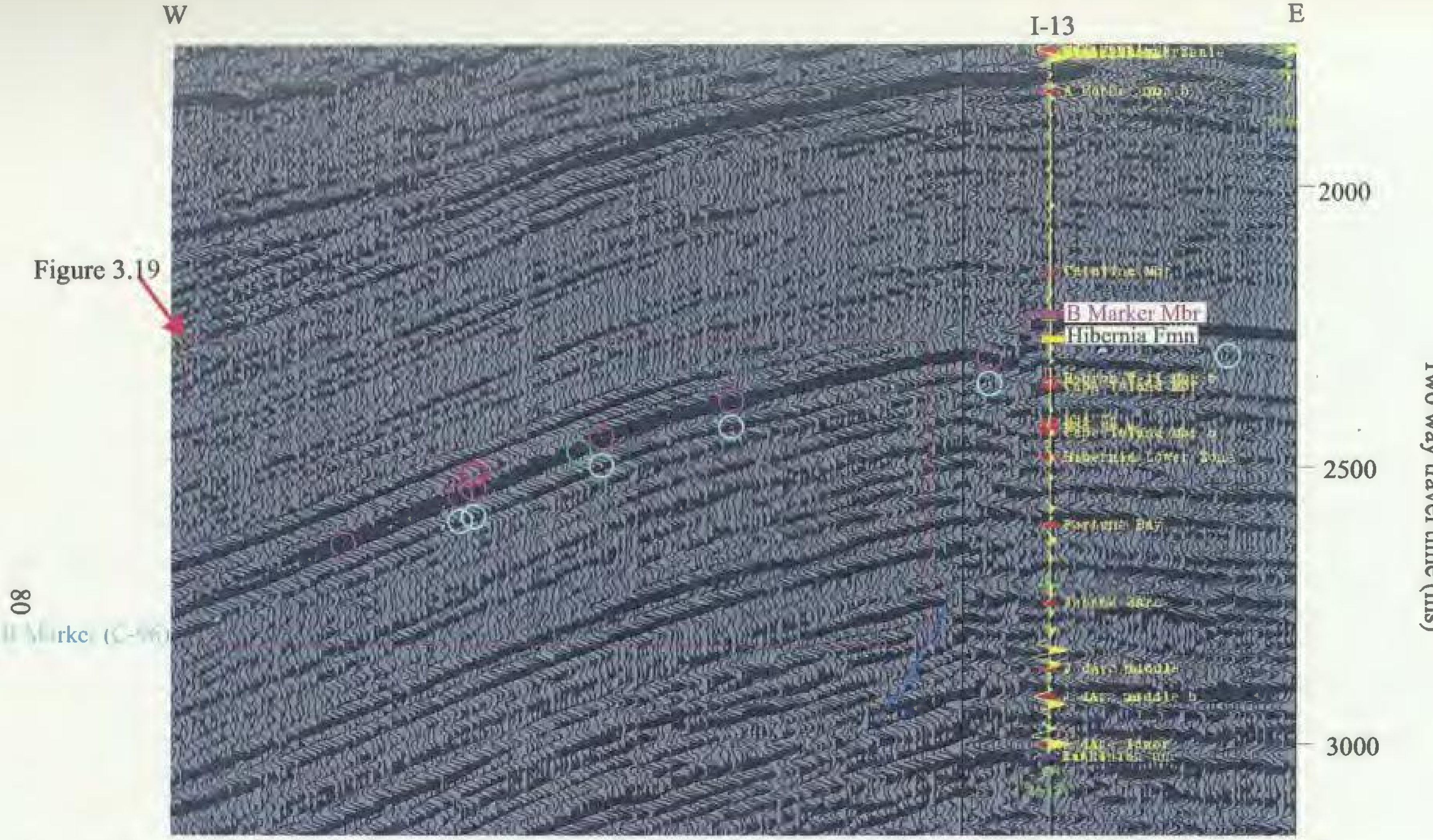


Figure 3.18. This W-E oriented seismic section taken across the central region of the Cape Pine survey, illustrates the dual character of the B Marker, (shown in purple) extended from the Hebron I-13 well. The blue circles represent the B Marker seismic event extended from the Hibernia C-96 well. The B Marker event extended from the Hibernia C-96 well, clearly lies below the B Marker lithologic pick in the Hebron I-13 well, and is more accurately interpreted to be located lower along the well section, below the Hibernia lithologic pick. See Figure 3.16 for line location. The red box outlines the approximate location of the seismic section shown in Figure 3.19.

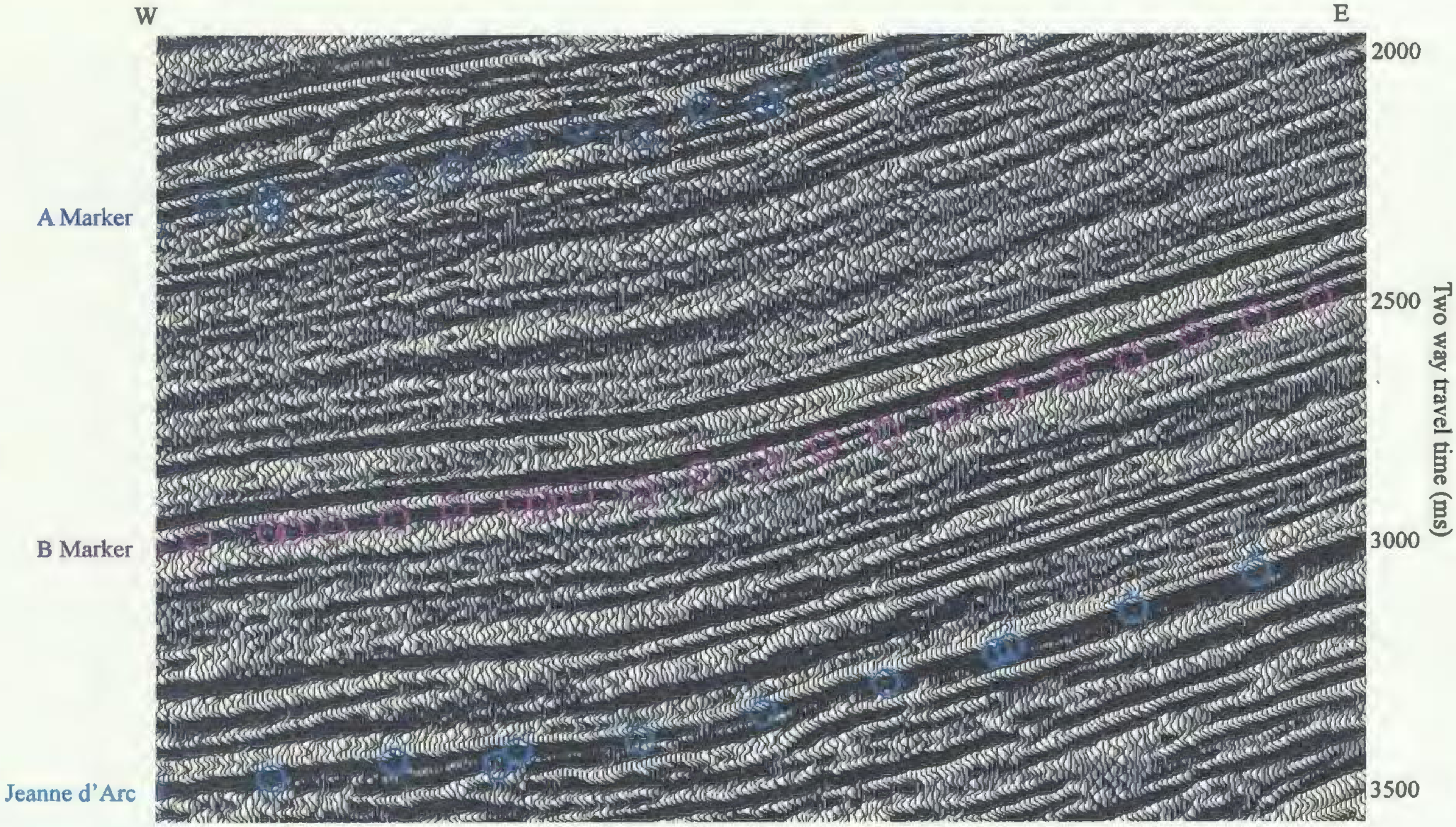


Figure 3.19. This W-E trending seismic line demonstrates the variation in B Marker amplitude in the Cape Pine syncline. Near the center of the syncline (~3 s TWT), the B Marker is a high amplitude reflector. Further east, the amplitude of the B Marker reflector decreases (from 2.7 - 2.9 s TWT), and then increase in amplitude as it rises along the eastern flank of the syncline. See figure 3.16 for line location.

3.4.2 Seismic Reflector Amplitude

The amplitude of a seismic reflection depends on the acoustic impedance contrast at the reflecting interface (Sheriff and Geldart, 1995). Amplitude maps accentuate similar amplitude trends, and when displayed in multi-colored gradation maps, show sharp lateral variations in amplitudes for detailed stratigraphic work. Display techniques used to display data like amplitude strongly effect the ease with which features can be seen. The optimum display for one interpreter may not be optimum for another. The brighter the colors of orange and red stand out, and are often perceived as good - high amplitude, amplitude increasing with offset, low velocities, etc. (Sheriff and Geldart, 1995). The color bar used in Figure 3.20 displays white, yellow, red, and green as areas of very high to moderate amplitude reflectivity, while aqua and blue areas define zones of low to very low amplitude reflectivity.

The files used to generate amplitude extractions in Hibernia and Cape Pine surveys are separate, therefore, zones of similar amplitude in Cape Pine and Hibernia are displayed as slightly different colors in each survey. This difference is illustrated in the area where the surveys merge (Figure 2.2 and 3.20). Here, B Marker amplitude is very high, however, it appears the amplitude diminished across the surveys.

An amplitude map was generated in SeisWorks for the B Marker horizon (Figure 3.20). The map reveals a large, ~ 8 km wide zone of high amplitude reflectivity which spans across both the Hibernia and Cape Pine surveys, extending ~35 km from NW-SE.

This zone is by surrounded by areas of low amplitude reflectivity. In addition, two low amplitude trends are evident in the central and southern regions of the Cape Pine survey. In the central region of the survey there is a zone of lower amplitude trending NE-SW. It is ~10 km in length and 3 km width. The second area of discontinuity extends southward from the center of the survey, and ranges between 2 -15 km width, over ~ 20 km. In this area, the B Marker climbs along the Cape Pine syncline eastward, toward shallower depths (Figure 3.19).

In the Terra Nova region there is an ~11 km wide zone of moderate to high amplitude reflectivity trending north-south over a distance of ~13 km surrounded by regions of low amplitude (Figure 3.20). This zone of moderate to high reflectivity corresponds with the location of the Terra Nova graben (Figures 3.2 and 3.10).

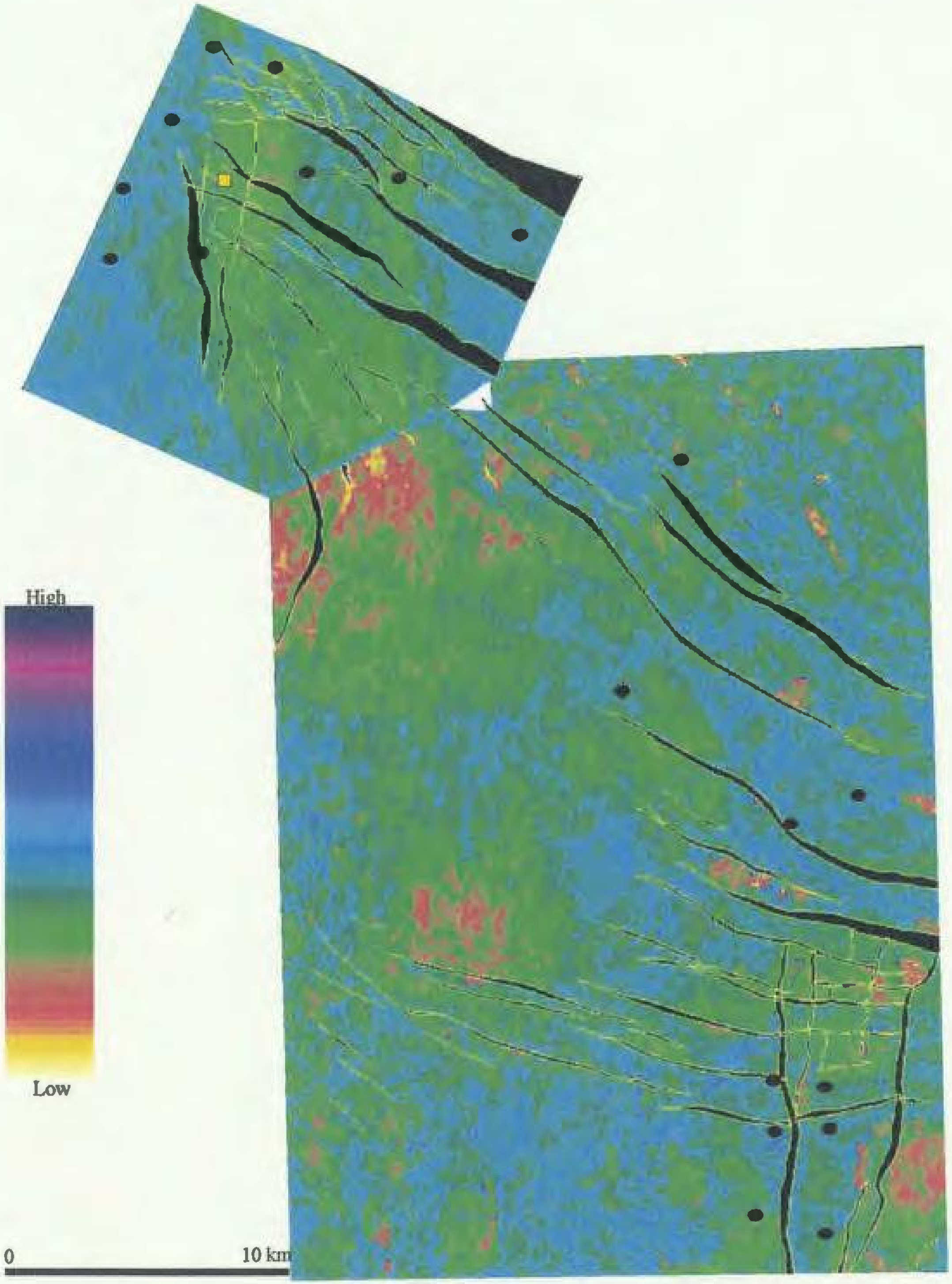


Figure 3.20. Amplitude map of the B Marker event, extended from the Hibernia C-96 well. The map reveals a large zone of high amplitude reflectivity across the Hibernia and Cape Pine surveys, extending ~35 km from NW-SE. There are two zones of lower amplitude in the Cape Pine survey; 1) NE-SW trending zone in the central region, and 2) N-S trending zone in the southern region. Here the B Marker climbs along the Cape Pine syncline (Figure 3.19). In the Terra Nova region there is a N-S trending zone of moderate amplitude corresponding with the location of the Terra Nova graben (Figure 3.2).

3.4.3 Superimposed Amplitude and Continuity data

Superimposed map displays may help in seeing the interrelationship of various data aspects (Sheriff and Geldart, 1995). When the B Marker amplitude map is overlain by the continuity map a major trend is apparent, showing zones of high amplitude reflectivity corresponding with zones of high continuity (Figures 3.17, 3.20 and 3.21). This relationship is most prominent from north-south, beginning near the crest of the Hibernia anticline, trending south along the axis of the Cape Pine syncline, and in the Terra Nova oilfield region (Figure 3.17 and 3.21). Similarly, zones of low amplitude reflectivity correlate with zones of discontinuity. This relationship can be seen along the eastern flank of the Hibernia survey, where the B Marker continuity extraction reveals a ~ 3 km wide zone of discontinuity and low to moderate amplitude reflectivity (Figures 3.17, 3.20 and 3.21). In the central region of the Cape Pine survey there are two prominent zones of low amplitude and discontinuity, which collectively form a "T" shape. As shown in Figures 3.17 and 3.21, the NE-SW trending zone extends ~14 km, ranging between >1-5 km width. The second, NW-SE trending zone is ~4 km width, 8 km height.

In summary, the amplitude and continuity data show that the main "T" shaped region is an area of seismic stratigraphic variability, whereas, the NE-SW trending zones of discontinuity are clearly fault-controlled regions.

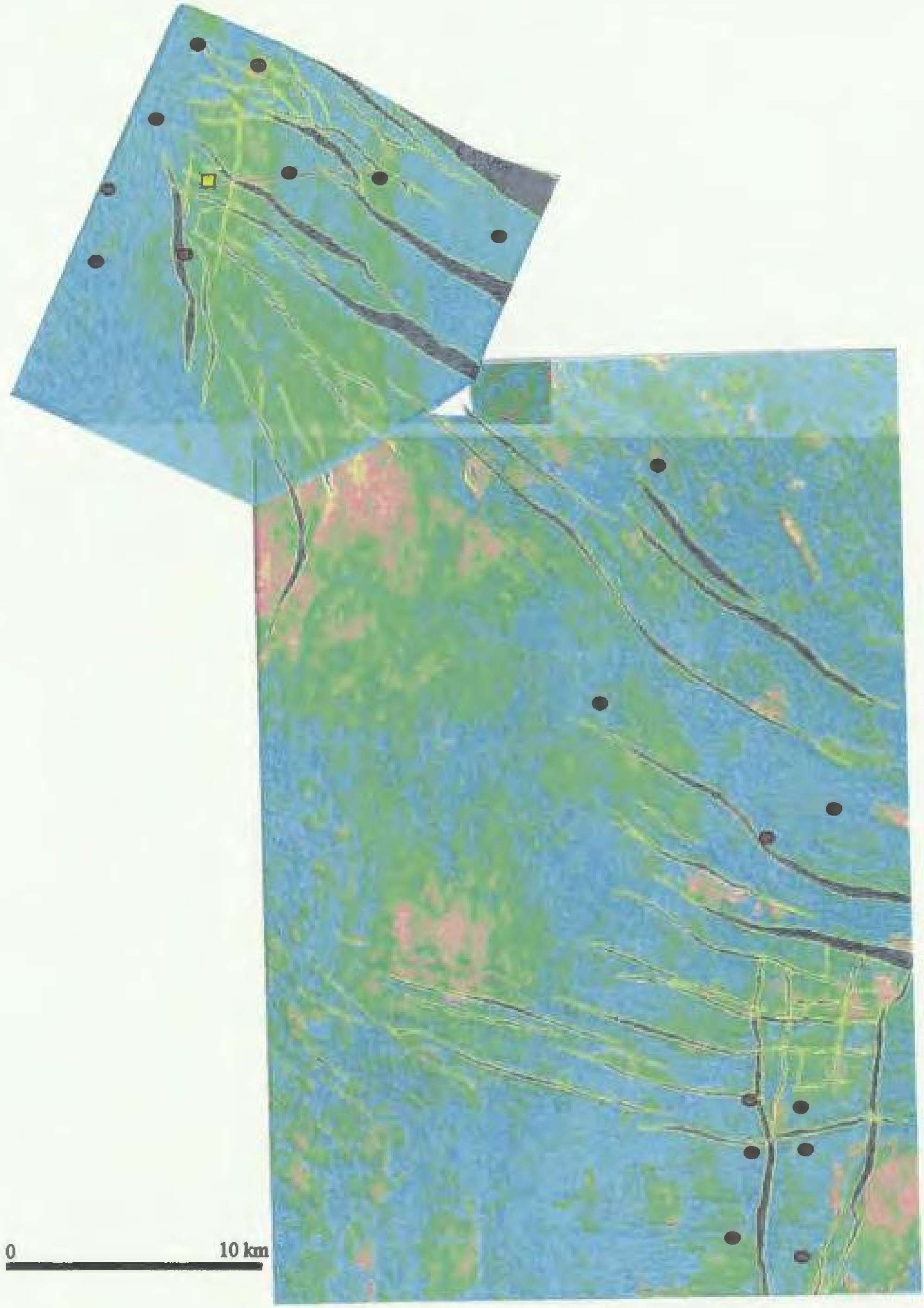


Figure 3.21. Superposition of the B Marker amplitude and continuity maps. Major trends are evident where zones of high amplitude reflectivity corresponding with zones of high continuity (Figures 3.16-3.20). This relationship is most prominent from north-south, from the Hibernia anticline, south along the axis of the Cape Pine syncline, and in the Terra Nova oilfield region (Figure 3.2 and 3.10). Similarly, zones of low amplitude reflectivity correlate with zones of discontinuity, as seen along the eastern flank of the Hibernia survey, and in the central region of the Cape Pine survey, where two prominent zones of low amplitude and discontinuity, form a "T" shape.

3.5 Synthetic Seismograms

Synthetic seismograms are a common type of forward modeling used in hydrocarbon exploration based on fundamental concepts in geophysics with the following assumptions: 1) wavelets reflected from an acoustic impedance discontinuity have the same waveshape as the incident wave, and that a seismic trace records the unit of such wavelets and thus the unit of impedance discontinuities, and 2) a seismic trace is the superposition of individual seismic reflections (Sheriff and Geldart, 1995).

The distribution of sonic and density data along a borehole can be determined and a synthetic seismogram be generated (Sheriff and Geldart, 1995). Sonic data are typically used because they are standard logs run down the borehole. Density logs are sometimes available and can also be input as constant values, such as Gardner's Rule[1], or assume a relation to velocity.

Synthetics seismograms are usually created to compare with actual seismic data and to identify reflections associated with particular interfaces. They can also be used to distinguish primary reflections from multiples (Sheriff and Geldart, 1995).

Synthetic seismograms were generated using either sonic logs, density logs or both (Table 3.1). Generation of synthetic seismograms for wells in the Cape Pine survey area was vital because the well data was loaded into the survey area without a datum. Once synthetic seismograms were tied to seismic reflection profiles and correlated with

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[1]*Gardner's Rule*: $\rho = aV^{1/4}$ where density ρ is in g/cm^3, a=0.31 when velocity V is in m/s and a=0.23 when V is in ft/s (Sheriff and Geldart, 1995).

adjacent wells in the Terra Nova oilfield, seismic horizons were mapped throughout the Cape Pine area and were tied with the Hibernia survey.

Well	Synthetic time shift (ms)
GBS origin/center	0
C-96	-16
B-16-18	24
Mara M-54	0
Ben Nevis	0
Beothuk M-05	0
Hebron D-94	n/a (B Marker horizon not penetrated)
Hebron I-13	-70
Terra Nova K-07	-88
Terra Nova K-08	-142
Terra Nova K-17	-80
Terra Nova K-18	-82
Kings' Cove	-240

Table 3.1. Time shifts applied to the synthetic seismograms generated in Syntool for wells used in this thesis. Negative numbers indicate an increase in time and depth.

3.5.1 C-96 Synthetic Seismogram

The synthetic seismogram generated for the Hibernia C-96 well matched well with the actual seismic reflection data in the Hibernia survey. High amplitude events such as the A Marker limestone, the Catalina sandstone Member and the B Marker limestone were easily correlated with the seismic reflection data (Figure 3.22). The synthetic seismogram generated for C-96 is displayed in normal polarity where positive kicks trend right and negatives trend left. The B Marker horizon, which corresponds with the B Marker seismic event and B Marker geologic well pick of CNOPB (2001) occurs as a single, positive, very high amplitude event. In the cross basin seismic tracing, this event in the western portion of the basin is assigned to Tr 1. It is bounded by very high amplitude negative events within the overlying Basal Catalina Member and underlying Hibernia Formation, respectively (Figure 3.22).

3.5.2 M-54 Synthetic Seismogram

The synthetic seismogram created for the Mara M-54 well partially matches with the seismic reflection data. The synthetic event for the B Marker horizon in the Mara M-54 well represents a synthetic couplet (Figure 3.23). The couplet is defined by two positive events, an upper very high amplitude event and lower moderate amplitude event. In the Hibernia oilfield region, the upper surface of the high amplitude pick is assigned to Tr 4. The lower surface of the high amplitude event is assigned to Tr 3 (Figure 3.23). The high amplitude event is overlain by a negative basal Catalina Member event, and underlain by a negative, a two very low amplitude events which coincide with HMDC's 128 Ma maximum flooding surface pick, and the top of the Hibernia Formation. Tr 1 and Tr 2 correspond to lower and upper portions, respectively, of the couplet designated the B

Marker couplet. The base of the couplet is a moderate amplitude event, while the upper portion of the couplet is higher amplitude. The base of the couplet lies above a negative, very high amplitude event which corresponds with top of the Hebron Well Member, Hibernia Formation (Figure 3.23).

The B Marker geologic and seismic picks defined by the CNOPB and HMDC differ from the interpretation presented herein. The B Marker event identified in this study, based on detailed seismic tracing through the basin, occurs lower in the M-54 well section, below the Hibernia Formation as shown in Figure 3.23. The synthetic seismogram created for M-54 places the B Marker pick between the Hibernia Formation and Hebron Well Member and corresponds with a single, positive, very high amplitude event. This event exhibits similar character to the B Marker event (Tr 1)generated in the C-96 synthetic seismogram (Figure 3.22).

3.5.3 Terra Nova Synthetic Seismograms

Synthetic seismograms were created for Terra Nova wells K-07, K-08, K-17 and K-18. Data for these wells were loaded into Landmark without a datum resulting in large time shifts. Tying of synthetic seismograms to seismic data in the Terra Nova region was primarily based on recognizing similarities in synthetic character identified in the Hibernia C-96 and Mara M-54 wells.

In synthetic seismograms generated for the Terra Nova wells, the B Marker event occurs as a couplet (Figures 3.24). The couplet identified in the Terra Nova wells corresponds to the couplet recognized in the Mara M-54 well (Figure 3.23). The upper portion of the couplet is a positive, moderate-high amplitude event which corresponds to Tr 2. The lower portion of the couplet is a positive, moderate amplitude event, which corresponds to Tr 1. The couplet overlies a negative, high amplitude reflector which corresponds with the top of the Hibernia Formation. The couplet is overlain by positive and negative kicks contained within the Catalina Member.

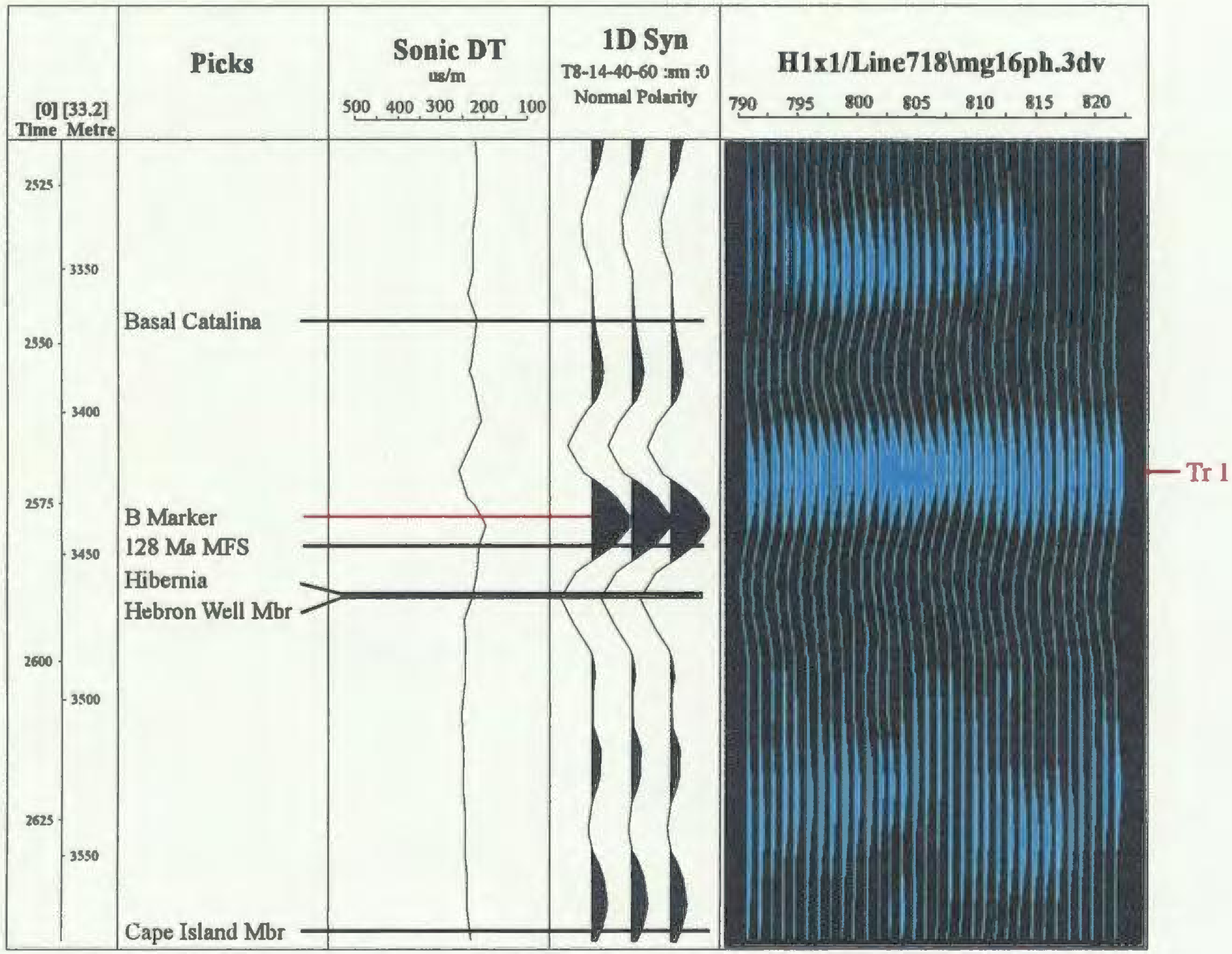

Figure 3.22. Synthetic seismogram generated for the Hibernia C-96 well. The B Marker horizon, corresponds with the B Marker seismic event and B Marker geologic well pick (CNOPB, 2001), as a single, positive, very high amplitude event, labeled Tr 1. It is bounded by very high amplitude negative events within the overlying Basal Catalina Member and underlying Hibernia Formation. The frequency trapezoid used to create the synthetic in C-96 is defined by frequencies of 8, 10, 30, and 50 Hz.

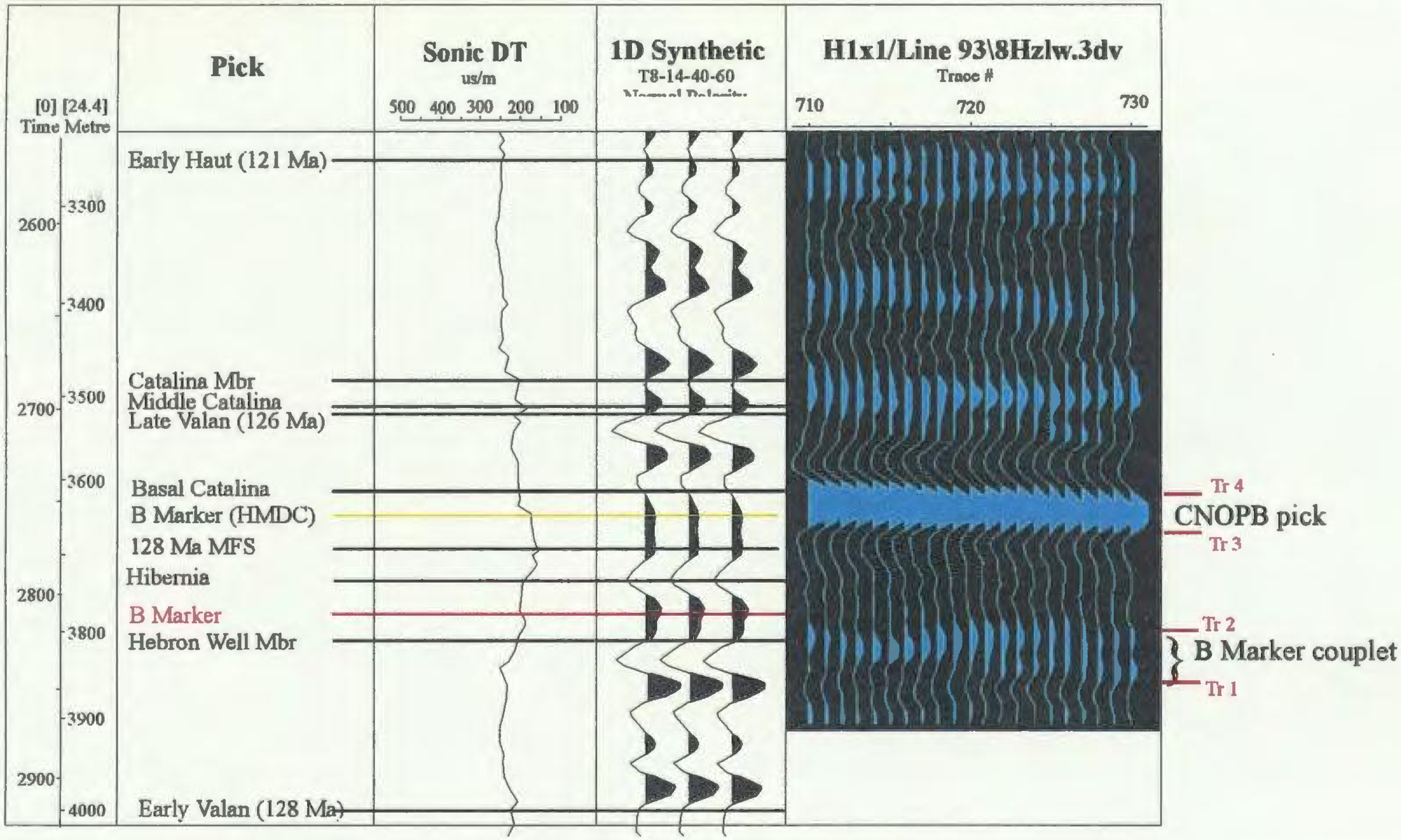

Figure 3.23. Synthetic seismogram generated for the Mara M-54 well. The synthetic event corresponding to the B Marker geologic well pick (CNOPB, 2001), shown in yellow, is as a positive high amplitude event. Traces Tr 3 and Tr 4 are assigned to this event. The B Marker event extended from the Hibernia C-96 well is highlighted in red. It corresponds to a synthetic couplet, which is defined by an upper high amplitude event (Tr 2) and lower moderate amplitude event (Tr 1). The couplet is overlain by a negative, high amplitude event , which corresponds with the top of the Hibernia Formation, and lies above a negative, high amplitude event, which corresponds with the Hebron Well Member. The frequency trapezoid used in the M-54 well is defined by 8, 14, 40 and 60 Hz.

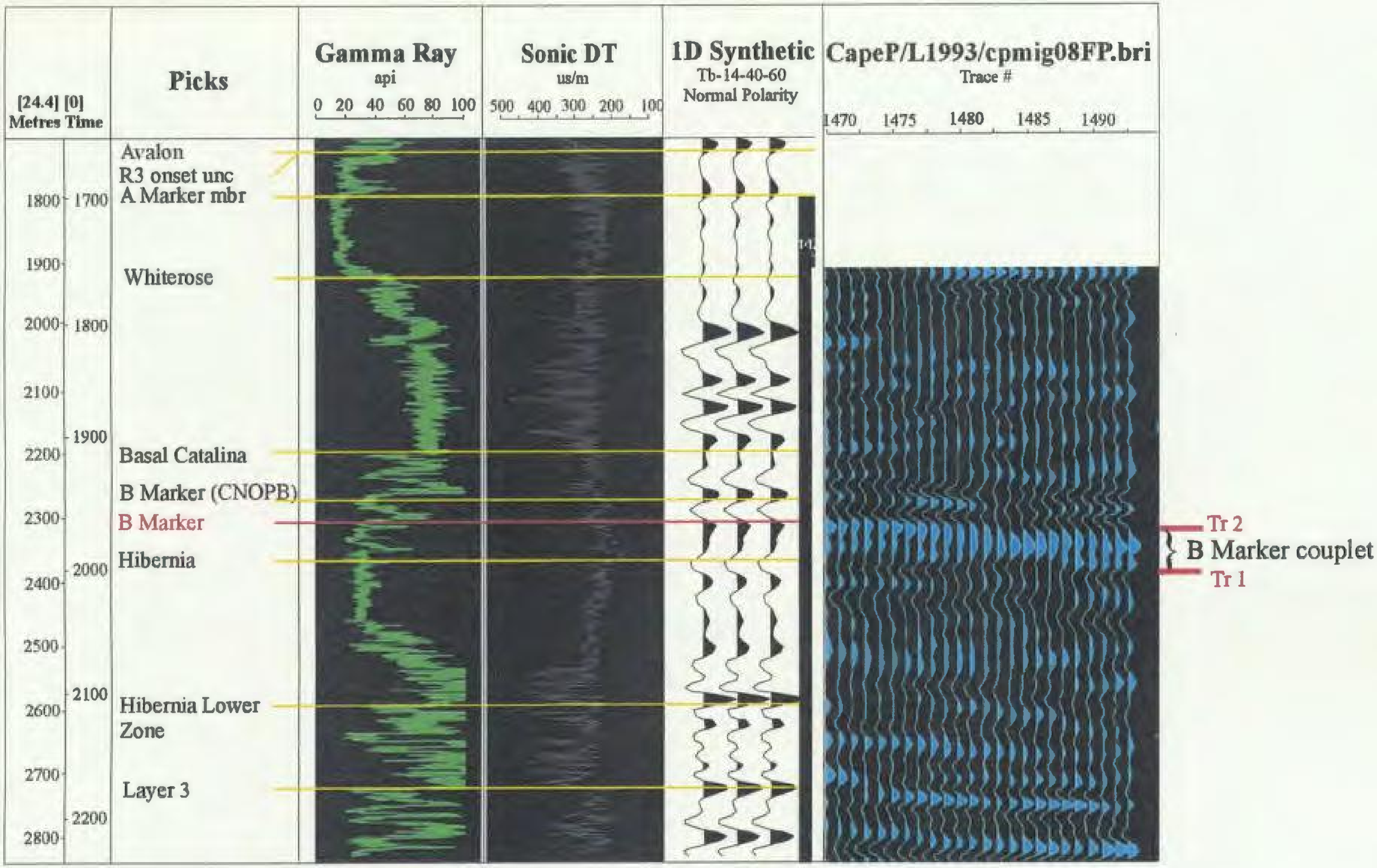

Figure 3.24. Synthetic seismogram generated for the Terra Nova K-18 well. The B Marker extended from the Hibernia C-96 well is highlighted in red. The B Marker geologic pick defined by the CNOPB (2001) occurs above the B Marker event extended from the Hibernia C-96 well. The B Marker event occurs as a couplet on the synthetic seismogram and is defined by an upper positive, moderate amplitude event (Tr 2) and a lower positive, high amplitude event (Tr 1). The B Marker couplet is present in all Terra Nova wells and the Mara M-54 well.

3.6 Lithological Character and Biostratigraphy of the B Marker

The B Marker has been treated in Previous work as a laterally continuous, and typically oolitic limestone (McAlpine, 1990; Tankard and Welsink, 1987). As demonstrated in sections 3.4 and 3.5, the B Marker is defined as an internally variable seismic stratigraphic unit with top and bottom marker surfaces (Tr 4 and Tr 1, respectively). By integrating well data for lithologies (Table 3.2), thickness and biostratigraphic data (Table 3.3 - 3.5), this section attempts to characterize the internal lithological and stratigraphic character of the seismic unit corresponding to the B Marker.

As indicated in Table 3.2, in wells located in the south of the basin (Gambo N-70, Port au Port J-97, King's Cove A-26 and Beothuk M-05, Terra Nova K-18) the limestone is classified as a wackstone/ packstone, is typically white in color, and ranges between 87 - 96 m (true vertical thickness; TVT). In the central region of the basin (Hebron I-13, Ben Nevis I-45), it is oolitc and pelletic, is buff-tan to light brown in color, and ranges between 85 - 92 m (TVT). Further north, most notably in the Hibernia oilfield, oolitic content within the limestone is absent, it is typically grey in color and between 14 - 45 m (TVT) thickness.

Well	**B Marker** (TVT)	**Lithology**
Hibernia P-15	21 m	Limestone: buff-tan, medium-coarse crystalline. Large molluscs and crinoids. 30%Limestone interbedded with medium grey siltstone.

Hibernia C-96	31 m	70% Limestone: tan-grey, fine-coarse crystalline, sparite, silty, pyrite. 30% Limestone: white-buff, chalky, argillaceous.
Hibernia B-16-18	45 m	Limestone: grey white-cream-orange brown. Minor siltstone and sandstone.
Mara M-54	92 m	Limestone: light tan-light grey, becoming oolitic and pelletoid with depth. Calcitic matrix, massive pyrite. Limestone interbedded with sandy siltstone.
Ben Nevis I-45	85 m	Limestone: light brown, oolitic-pelletoid with depth, coral, stromatoporoid, mollusc, echinoid fragments. Minor sandstone, siltstone and shale at base.
Hebron I-13	92 m	Limestone: buff-tan, oolitic grainstone, pelloids.
Terra Nova K-18	96 m	Limestone: white- buff-grey, oolitic wackestone/ packstone, shell fragments. Minor sandstone interbeds.
Beothuk M-05	96 m	Limestone: oolitic wackestone, chalky matrix
King's Cove A-26	87 m	Limestone: white, wackestone/packstone, oolitic, bioclast fragments, foraminifera.

Port au Port J-97	88 m	Limestone: oolitic and bioclastic (crinoid and coral fragments). Sandstone and siltstone interbeds.
Gambo N-70	93 m	Limestone: medium-coarse grained oolitic lime wackstone/packstone with minor siltstone and shale interbeds.

Table 3.2. Lithology and thickness of the B Marker limestone for wells used in this thesis (CNOPB, 2001).

Most published literature on the biostratigraphy of the units of the Grand Banks basins has accumulated during the last thirty years. Work by McNutty (1979; foraminifers), Roth et al. (1983; nannofossils), Habib and Drugg (1983; dinoflagellates, spores and acritarchs), Baumgartner (1983; radiolarians), Remane (1983; capionellids) and Gradstein 1986) reveal the dominant variety of microfossils found in the marine Mesozoic strata offshore, include: nannofossils (largely coccoliths), radiolarians, planktonic and benthic foraminifera, ostracods, spores and dinoflagellates.

The upper boundary of the B Marker Member occurs at approximately 3403 m true vertical depth sub-sea (TVDSS), 3437 m measured depth (MD) in the Hibernia C-96 well which designates it as an early Cretaceous, Valanginian aged limestone (Coughlon, et al., 1984) (Table 3.3). According to paleontological analysis the Valanginian is dominated by a foraminifera assemblage which includes *Buccicrenata Italica, Epistomina* and *Multirecticulata.* In the C-96 well, this assemblage occurs between 2650 - 3920 m TVDSS (Coughlon, etal., 1984). The benthic formanifera *Epistomina hecti* dominates the younger Hauterivian interval, while the older Berriasian-Tithonian stage is dominated by the nannofossil *Polycostella senaria.*

In the Hebron I -13 well the B Marker Member lithologic top and seismic event occur at ~2803 TVDSS (Huston and Ward, 1982) (Table 3.4). Paleontological analyses reveal the dinoflagellates *Phoberocysta neocomica* and *Canningia hirtella* are dominant in the I-13 well from ~2600- 3771 m TVDSS (Huston and Ward, 1982). This dates the B Marker Member as a Valanginian aged limestone.

In the Mara M-54 well the B Marker Member lithologic top occurs at 3645 m MD (CNOPB, 2001), while the seismic pick occurs at approximately 3780 m MD (Noseworthy, 2001) (Table 3.5). Paleontological analyses performed by Mobil Oil reveal the dinoflagellate *Phoberocysta neocomica* is dominant in M-54 from 3065 - 4000 m MD (Coughlon, et al., 1984). This dates the B Marker Member as a Valinginian aged limestone. From 2640 - 3065 m MD the dinoflagellate assemblage *Ctenidodinum elegantulum* is dominant. *Cantulodinium sp.* dominates the Berriasian stage, from 4000 - 4372 m MD.

The main problem with biostratigraphic analysis is sample contamination. When based on rotary-drilled rock-chip cuttings, contamination occurs through mixing of chips with younger cavings already penetrated by the drill bit, resulting in biostratigraphic analysis which is limited to last occurrences in time. In the M-54 well cutting samples were collected every 5-10 m. Besides discrepancies associated with sample quality, lack of documentation on detailed paleontological data for both the M-54 and C-96 wells, including species counts and occurrences, eliminated the possibility of constructing precise chronological curves and hence a more accurate biostratigraphic framework. However, it is unequivocal that in the C-96, M-54, and I-13 wells the B Marker Member falls within the Valanginian. Palynological studies have predominantly dated the B Marker Member as Valanginian (J.P. Bujak, pers. comm., 1981; Bujak Davies Group, 1988c), but the unit has also been dated as late Berrassian (i.e. in the Hibernia P-15 well; McAlpine, 1990).

HIBERNIA C-96 STRATIGRAPHIC COLUMN

ERA	SYSTEM/ SERIES	STAGE	PALEONTOLOGICAL ANALYSIS		LOG DEPTH SUBSEA (TVDSS)	FORMATION	LITHOLOGY
MESOZOIC	CRETACEOUS			2150	2072	PETREL LS.	Silty grey limestone
		CENOMANIAN	Radiolithus sp.	2181			
		ALBIAN	Oligosphaeridium asterigerum	2220			Calcareous siltstone, limestone and shale
		APTIAN	Cerbia tabulata	2324	2333	AVALON	very fine grained partially oil stained sandstone interbedded with siltstone and shale
		BARREMIAN	Gonyaulacysta perforobtusa	2410			
		HAUTERIVIAN	Epistomina hecti	2650	3194	'B' SAND	fine- medium grained oil stained sandstone. Limestone, claystone
		VALINGINIAN	Buccicrenata italica Epistomina Minutireticulata	3403	3784	HIBERNIA	very fine to coarse grained oil stained sandstone
				3950			
		BERRIASIAN-TITHONIAN	Polycostella senaria	4210	4191		

Table 3.3. Stratigraphic column for the Hibernia C-96 well, modified after Coughlon (1984). The B Marker seismic pick as interpreted in this thesis is highlighted in yellow.

HEBRON I-13 STRATIGRAPHIC COLUMN

ERA	SYSTEM/ SERIES	STAGE	PALEONTOLOGICAL ANALYSIS	LOG DEPTH SUBSEA (TVDSS)	FORMATION	LITHOLOGY
				1481		
MESOZOIC	CRETACEOUS	UPPER CRETACEOUS	Numerous Diagnostic Microfossils	1658	PETREL LS.	Siltstone and shales
				1774	Mid Cret. Unconformity	
		ALBIAN	Spinidinium cf. S.Vestitum/ Eckommiidites minor assemblage	1963	'A' Marker	Sandstones with minor limestone on claystone
		APTIAN	Choffatella Decipiens			
		BARREMIAN to HAUTERIVIAN	Epistomina hecti Cribroperidinium sepimentum			Sandstones with siltstones, limestone and minor claystones
		VALINGINIAN	Phoberocysta neocomica Canningia hirtella	2621	'B' SAND	
				2803	'B' Marker	Limestone
						Sandstone, v.fine-fine grained
				3010	UPPER HIBERNIA	Sandstone, fine-coarsse grained, poor-good porosity, live oil shows with minor interbeds of shale
				3232	LOWER HIBERNIA	
				3771	'J'	Shale, siltstone and sandstone
	JURASSIC	TRANSITION Zn.	Biorbifera iohnewingii Pareodinia kondratjevii			

Table 3.4. Stratigraphic column for the Hebron I-13 well, modified after Huston and Ward (1982). The B Marker seismic pick as interpreted in this thesis, is highlighted in yellow.

MARA M-54 STRATIGRAPHIC COLUMN

ERA	SYSTEM/ SERIES	STAGE	PALEONTOLOGICAL ANALYSIS		LOG DEPTH (MD)	FORMATION	LITHOLOGY
MESOZOIC	CRETACEOUS			2350			
		CENOMANIAN	Radiolithus sp1		2382.5	PETREL	Limestone
				2410			
		ALBIAN	Epistomina spinulifera		2526	AVALON	Sandstone, siltstone and shale
				2505			
		EARLY APTIAN BARREMIAN	Cerbia tabulata		2817	'A' MKR L.S.	Sandstone, siltstone and shale Limestone
				2640			
		EARLY BARREMIAN HAUTERIVIAN	Ctenidodinum elegantulum				Shale Sandstone and siltstone
				3065			
		VALINGINIAN	Phoberocysts neocomica	3780	3645	'B' L.S.	Limestone Claystone and siltstone
				4000			
		BERRIASIAN	Cantulodinium sp		4151 4366	MAIN HIBERNIA BASE HIBERNIA	Sandstone
				4372			
		TITHONIAN BERRIASIAN	Polycostella senaria	4446 T.D.			Sandstone

Table 3.5. Stratigraphic column for the Mara M-54 well, modified from Dawson (1986). The B Marker seismic pick as Interpreted in this thesis is highlighted in yellow, and the lithologic pick in red (CNOPB, 2001).

3.7 Correlation of Seismic, Synthetic and lithologic well data for the B Marker Limestone

The B Marker has been traditionally deemed to be both a regional lithostratigraphic marker and seismic event throughout the Jeanne d'Arc Basin. However, when the seismic event corresponding to the marker's geologic pick in the Hibernia C-96 well is carried eastward, it clearly falls below the B Marker geologic pick in the Mara M-54 well (i.e. between the Hibernia Formation and Hebron Well Members; Figures 3.25 and 3.26). This discrepancy is also identified in the central and southern regions of the Jeanne d'Arc Basin. When the seismic event corresponding to the B Marker geologic pick is extended from the Hibernia C-96 well and carried southeast towards Terra Nova oilfield, the event lies lower in the well section than the lithologic well pick (Figure 3.18). Similarly, when the B Marker lithologic pick is extended north and correlated with Hibernia wells, it is located higher along the well section, within the sandstones of the Catalina Member (Figure 3.26). In addition, ambiguities associated with continuity and amplitude data between the C-96 and M-54 wells (Figure 3.21), further demonstrate a miscorrelation associated with the B Marker seismic event. This clearly shows that there is a fundamental discontinuity in the seismic tracing and that there are significant changes in the seismic attributes associated with the B Marker limestone.

Seismic data and syntheic seismograms generated for wells throughout the Jeanne d'Arc Basin illustrate that the B Marker seismic event is defined as a couplet, but frequently splits/forks into two events, which are both seen as couplets (see Figures 3.22 - 3.26). Recognition of the couplets, which have been traced in detail through the basin indicate that the B Marker can be sub-divided into more than one seismic event. Detailed examination of the seismic reflection profiles together with synthetic seismograms show that there are up to four seismic traces (Tr 1 to Tr 4) within this interval, observed in numerous wells across the Jeanne d'Arc Basin (Figures 3.23-3.26).

Changes in the seismic attributes associated with the B Marker limestone are substantiated by lithologic variation observed in well log profiles across the basin (Figures 3.27- 3.29). In the Hibernia C-96 well, the top of the limestone unit occurs at 3400 m (TVDSS), and corresponds with the B Marker seismic event as presented herein (Figure 3.27). In the Hibernia B-16-18 well, the B Marker lithologic top occurs at 3545 m (TVDSS), while the B Marker seismic event occurs near the base of a limestone unit at 3585 m (TVDSS) (Figure 3.27). Further southeast, in the Mara M-54 well, the lithologic top of the B Marker occurs at 3625 m (TVDSS), and, as seen in the B-16-18 well, the B Marker seismic event is located lower in the well at 3750 m (TVDSS) (Figure 3.27). The miscorrelation between lithologic and seismic picks is also observed in the southern region of the Jeanne d'Arc Basin. In all wells located in the Terra Nova oilfield region, the B Marker seismic event occurs lower in the well section than the lithologic pick (Figures 3.24 and 3.28).

Lithological characterizations of Tr 1 to Tr 4 can only be made locally through correlations with well data (Figures 3.27, 3.28). These lithological control points provide the basis for paleogeographiv reconstruction of the B Marker provided in the following Chapter 4. In seismic reflection profiles, Tr 1 corresponds to the base of the B

Marker seismic unit and lithologic (limestone) unit defined in this thesis as the B Marker limestone (see Figure 3.29 at the Hibernia C-96 well). Throughout the basin the B Marker seismic event changes from a single event into a couplet. In places where there is a couplet, Tr 1 corresponds to the positive, moderate amplitude event at the base of the couplet. The second seismic trace identified within the B Marker stratigraphic unit (Tr 2) is also associated with the B Marker couplet. Tr 2 corresponds with the positive, moderate-high amplitude event at the top of the couplet. The lithologic correlation of Tr 1 in the Hibernia C-96 well differs from the Mara M-54 well. In the Mara M-54 well both Tr 1 and Tr 2 correlate with the sandstones Hibernia Formation, suggesting a lateral change of lithology. The seismic trace Tr 3, corresponds to the basal surface of the B Marker lithologic pick in the Mara M-54 well. Tr 4 defines the upper surface of the B Marker lithologic pick in Mara M-54. This correlation is evident in the synthetic seismogram generated for the Mara M-54 well shown in Figure 3.23. Similarly, in Figure 3.29, the upper surface of the B Marker lithostratigraphic pick correlates with the top of the limestone unit. In Terra Nova wells, seismic traces T1 and T2 are recognized, and are located near the upper surface of the Hibernia Formation (Figure 3.23). This suggests the B Marker couplet juxtapose the sandstones of the Hibernia Formation (Figure 3.29). Although up to four seismic traces are clearly evident wells section (ie. Mara M-54; Figure3.23), this is not true for all wells in the basin (ie. Hibernia C-96; Figure 3.22 and Terra Nova K-18; Figure 3.24). Lack of continuity between seismic traces (Tr 1 - Tr 4) across the basin, suggests that B Marker exhibits seismic stratigraphic and lithofacies variation across the Jeanne d'Arc Basin.

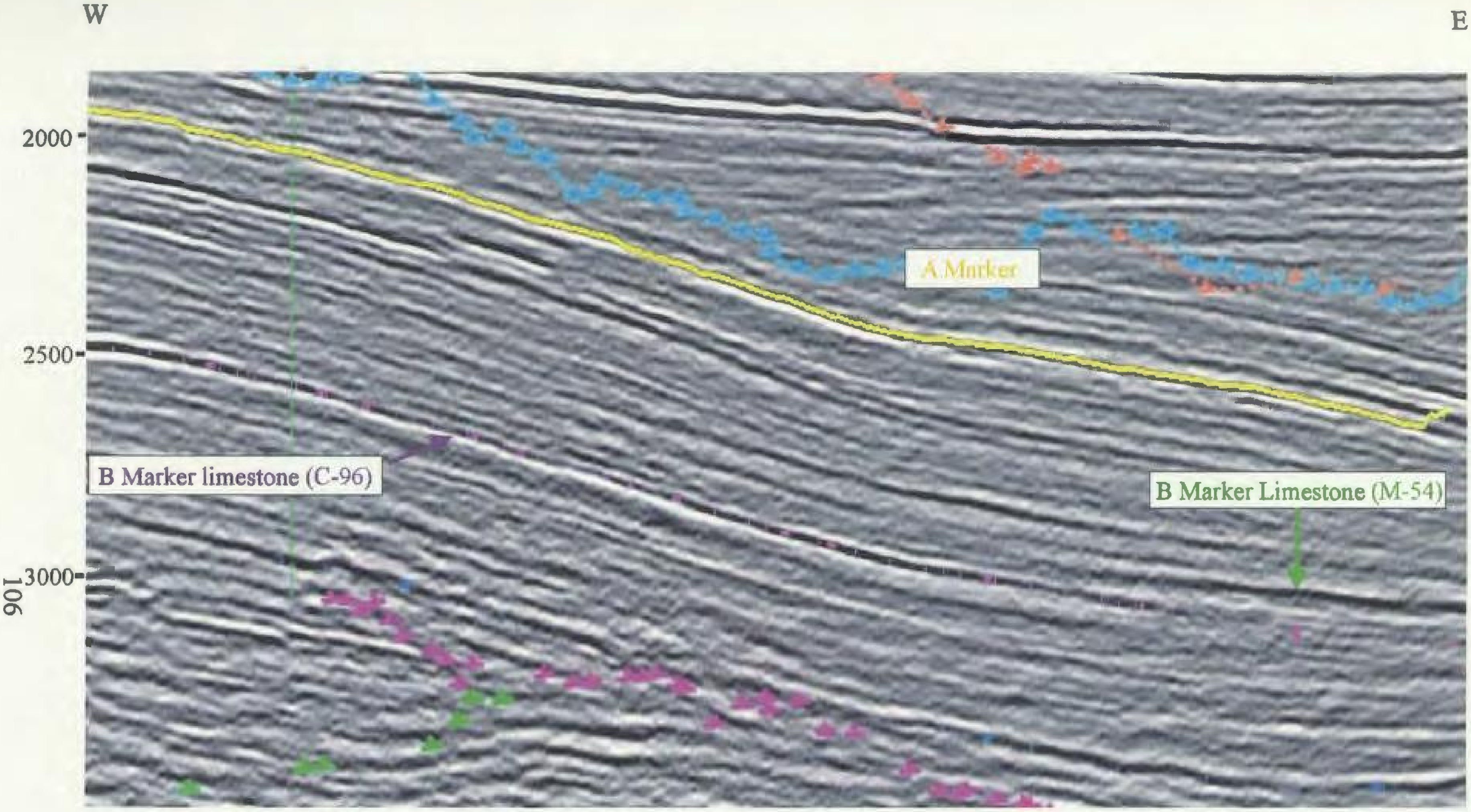

Figure 3.25. This seismic section shows the B Marker seismic trace (in purple) extended from the Hibernia C-96 well. The B Marker corresponds with a continuous, very high amplitude seismic event in the northwest, and becomes a discontinuous, low amplitude event near the Mara M-54 well toward the southeast. In this region, a high amplitude event occurs above the discontinuous, low amplitude B Marker event interpreted from the C-96 well This upper high amplitude event corresponds with the B Marker seismic event extended from the Mara M-54 well. When this event is extended back into the Hibernia C-96 well, it falls within the Catalina Mbr. This clearly demonstrates seismic ambiguity and miscorrelation with lithologic data associated with the B Marker. See Figure 3.2 for line location.

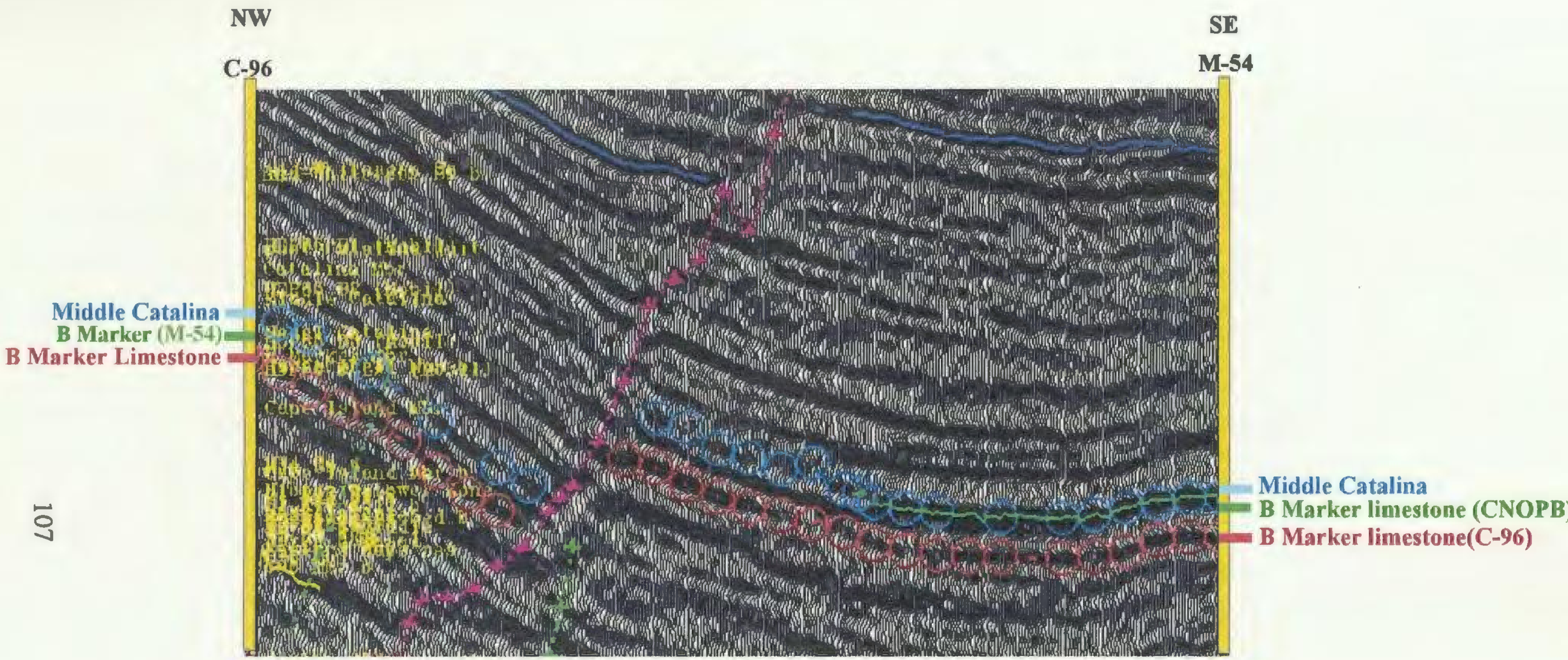

Figure 3.26. This seismic section shows the location of the seismic event associated with the B Marker, between the Hibernia C-96 well and the Mara M-54 well. When the B Marker seismic event, interpreted from the Hibernia C-96 well, is extended into the Mara M-54 well, it lies lower in the well than the B Marker limestone lithologic pick defined by the CNOPB (1990). When the seismic event corresponding to the B Marker lithologic pick in the Mara M-54 well is extended into the Hibernia C-96 well, it is located higher in the well, above the B Marker lithologic pick defined by CNOPB (1990). See Figure 3.2 for line location.

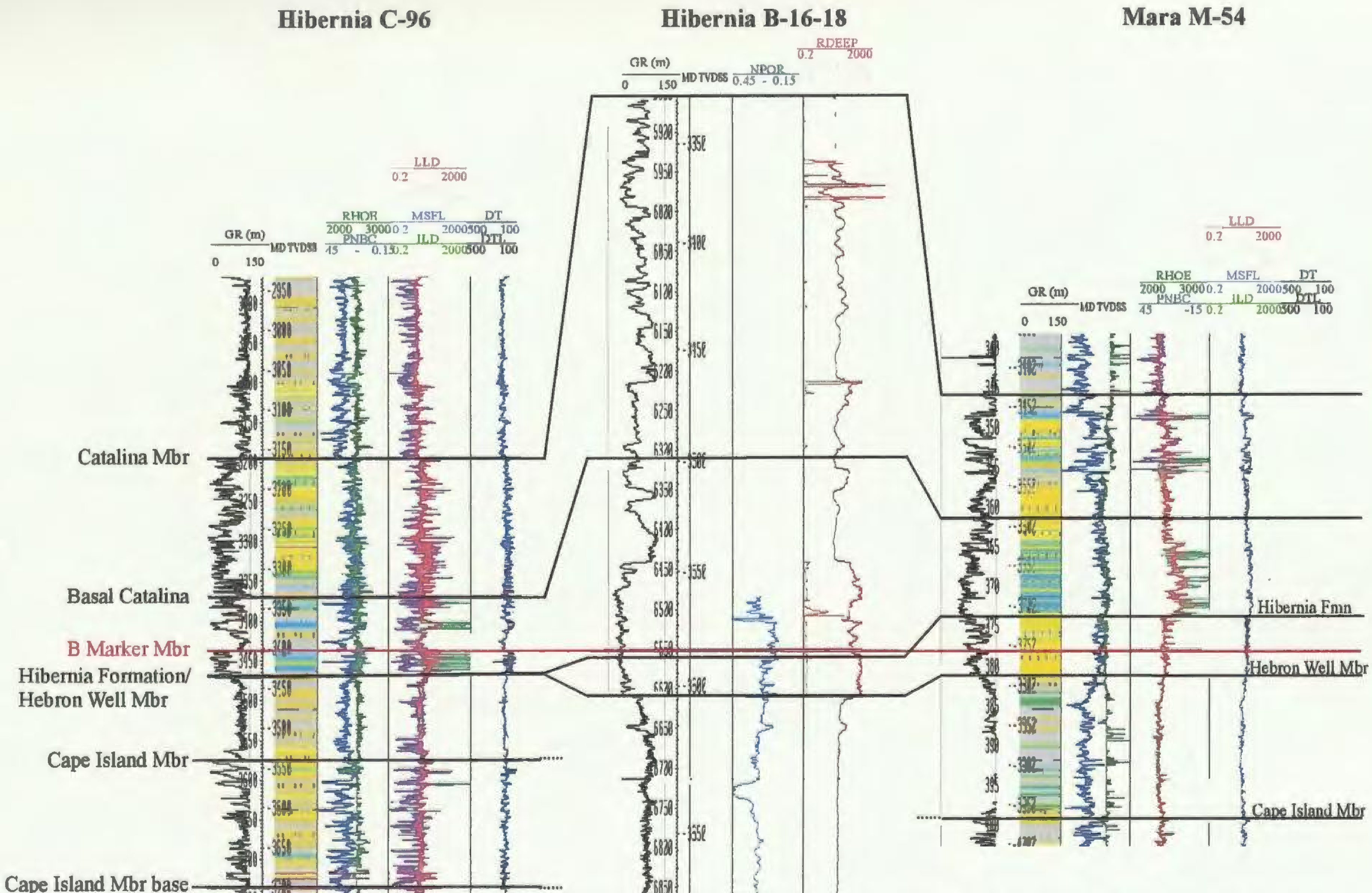

Figure 3.27. NW-SE trending well cross section from Hibernia C-96 to Hibernia B-16-18 to Mara M-54, showing gamma ray (GR), density (RHOE, PNBC, NPOR), resistivity (LLD, LLS, MSFL, IDL, RDEEP, RSHALLOW) and sonic (DT, DTL) logs. The seismic B Marker event interpreted from C-96 is shown in red. The B Marker displays low gamma ray and high acoustic velocities.

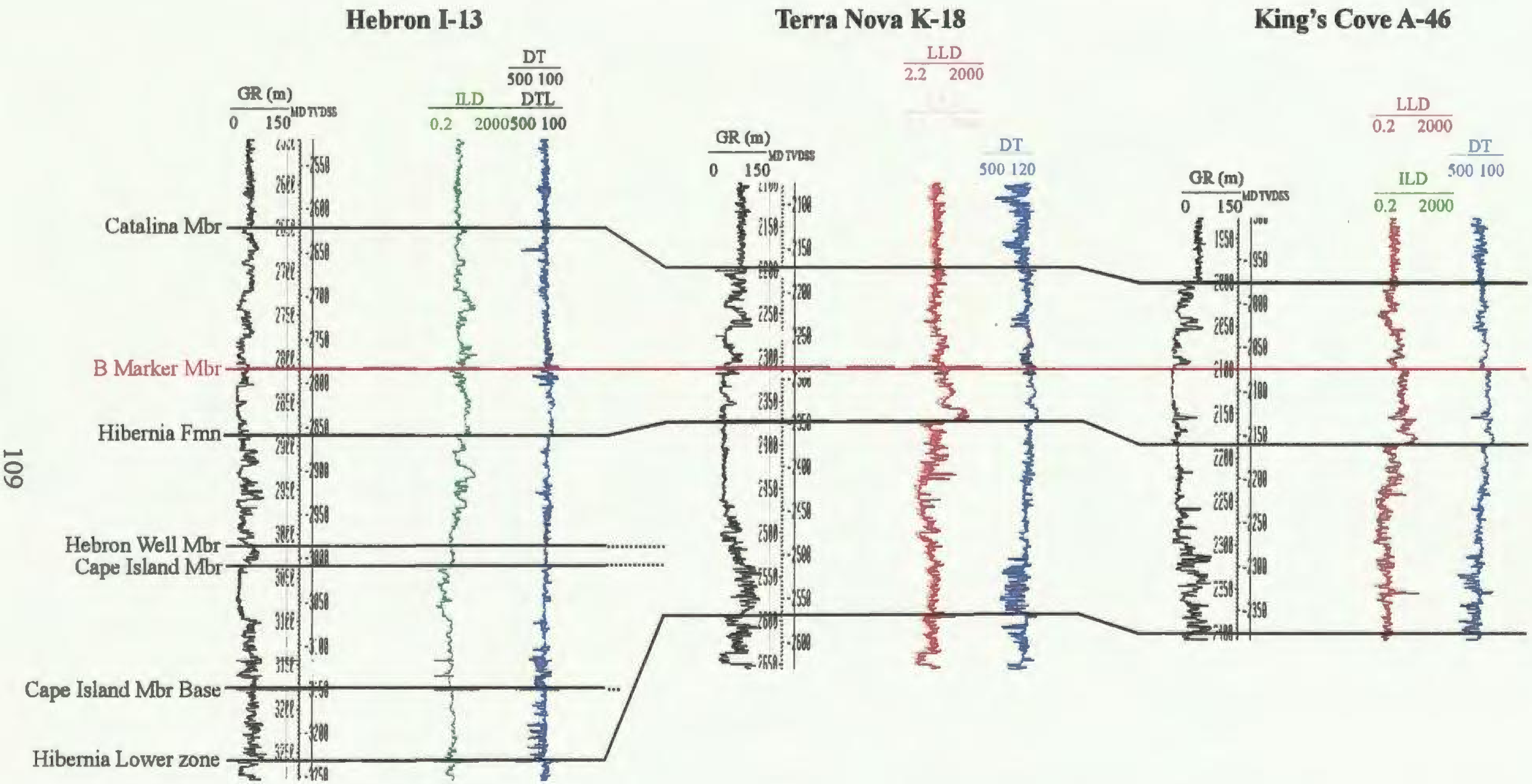

Figure 3.28. N-S trending well cross section of Hebron I-13, Terra Nova K-18 and King's Cove A-46, showing gamma ray (GR), resistivity (ILD, LLD, LLS) and sonic logs (DT, DLT). The B Marker seismic event is interpreted from Hibernia C-96. It typically shows low gamma ray and high acoustic velocities in well logs. The position of the B Marker Mbr appears higher in well than in Figure 3.29, this is due to scaling differences between the two images.

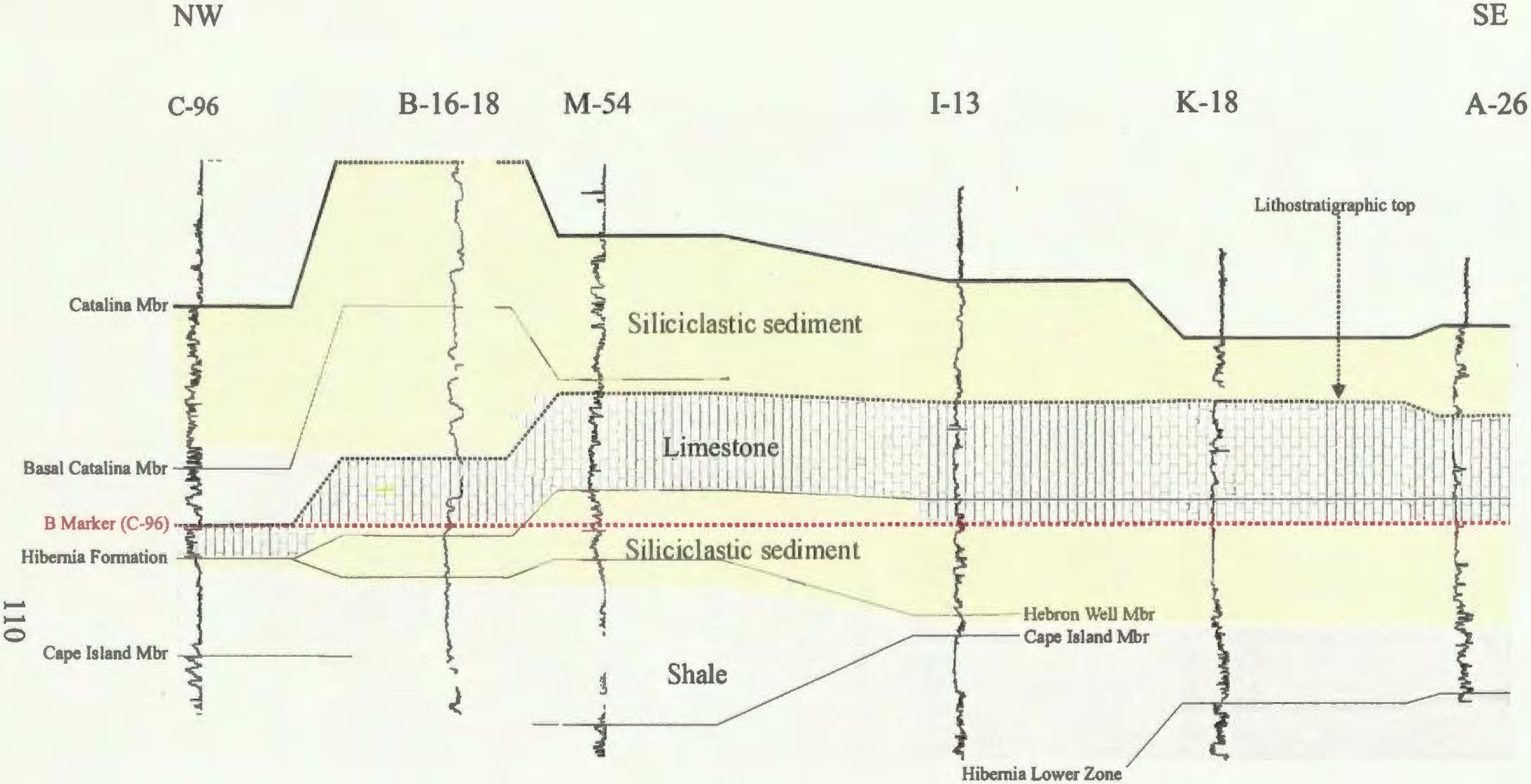

Figure 3.29. NW-SE oriented well cross section, which uses the C-96 seismic B Marker event as datum. The section shows the gamma ray log for the Hibernia C-96, Hibernia B-16-18, Mara M-54, Hebron I-13, Terra Nova K-18 and King's Cove A-26 wells, from NW-SE respectively, overlain by dominant lithologies. For more detailed well logs see Figures 3.27 and 3.28. The horizontal spacing of well locations in not absolute, but distances between wells are approximately comparable to spacing of wells on the line of section.

CHAPTER 4: A NEW B MARKER MODEL

Previously published models for the origins of the B Marker have suggested that it represents a regionally persistent transgressive limestone unit, deposited above deltaic sandstones of the Hibernia Formation, during a time of relative basin stability in a warm, shallow, high-energy marine environment (McAlpine, 1990). The marker also constitutes a prominent seismic reflector across the Jeanne d'Arc Basin (Mackay and Tankard, 1990). This thesis partially supports these interpretations but also concludes that B Marker is better described in the context of a Carbonate Ramp Model, to account for the inconsistencies associated with both the variable seismic expression and lithological character of the B Marker across the Jeanne d'Arc Basin.

This chapter presents an integrated model for the deposition of the B Marker limestone in the context of the tectonic evolution of the Jeanne d'Arc Basin. Details of the different models proposed by previous workers for the stratigraphic and structural evolution of the Hibernia and Whiterose formations during the Early Cretaceous are presented first. This is followed by a new synthesis of the stratigraphic architecture of the B Marker Member of the Whiterose Formation. A new depositional model for the B Marker Member is then proposed. The final section of this chapter presents a discussion of the relationships between sedimentation and tectonism in the basin during the Early Cretaceous in the light of the new model and previous models.

4.1 Previous Models for Tectonism and Sedimentation in the Early Cretaceous.

From the Triassic to Cretaceous, the Jeanne d'Arc Basin was situated along the eastern fringes of the North American continent, immediately west of the (North Atlantic) rift zone. The proto-Atlantic Ocean formed an epicontinental seaway, penetrating northward as the final phases of rifting continued in the Cretaceous. The basin developed over the stretched and attenuated continental crust following the initiation of rifting in the late Triassic. Since this time, the basin experienced up to three major episodes of rifting: in the Triassic-Early Jurassic, Tithonian - Early Valanginian, and Aptian-Albian (Sinclair, 1988; Tankard et al., 1989). Each of these phases of extension is associated with periods of subsidence and deposition, followed by periods of tectonic quiescence in the basin.

Models for the stratigraphic and structural evolution of the Jeanne d'Arc Basin have been proposed by Tankard et al. (1989) and Sinclair (1988). The following discussion will focus on those aspects of these models, which are intrinsically related to the deposition of the B Marker limestone, spanning the Valanginian-Hauterivian periods.

Tankard et al. (1989) proposed two major periods of rifting in the Jeanne d'Arc Basin, during the Late Triassic and Late Jurassic-Early Cretaceous, respectively. The later, more prominent rift phase spanned from Late Callovian to Aptian times. This phase was punctuated by three episodes of syn-rift extensional faulting, characterized by varying degrees of subsidence. The initial stage of subsidence occurred during the Late Callovian-Middle Kimmeridgian, and is characterized by minor structural relief and argillaceous-calcareous marine and terrestrial sedimentation (Tankard et al., 1989).

The second phase of subsidence spanned from Late Kimmeridgian-Early Valanginian times. It marks the most intense phase of rifting in the Jeanne d'Arc Basin. During this time, fluvial-deltaic clastics (i.e. Jeanne d'Arc and Hibernia formations) were deposited in shallow basins, in restricted marine and terrestrial environments. No conglomerate facies were deposited during this period, because of subdued topographic gradients in the basin. In the Late Kimmeridgian especially, an intense phase of normal faulting, accelerated subsidence within the basin. Tankard et al. (1987, 1989) noted evidence for rapid subsidence, including: 1) deposition of the westward thickening clastic wedge of the Jeanne d'Arc Formation; 2) rollover of this unit in the hanging wall of the listric Murre Fault along the western margin of the basin (Hibernia oil field), and 3) variations in thickness and facies patterns of the Jeanne d'Arc Formation observed across normal faults along the western flank of the Central Ridge complex (Terra Nova oil field).

The second phase of subsidence culminated in the Valanginian, with the widespread deposition of the B Marker limestone above the Hibernia Formation (Tankard et al., 1989). The B Marker forms the upper boundary of the Hibernia sequence, separating underlying sediments, which were deposited in a closed system under restricted marine to terrestrial conditions, from overlying sediments of the Whiterose Formation deposited in an open marine environment. This change in depositional environments was relatively rapid, and occurred with little interruption of the sedimentary record. However, Tankard et al. (1989) note the development of an unconformity at the base of the B Marker in the southern Jeanne d'Arc Basin (Port au Port J-97) well.

The final phase of subsidence proposed by Tankard et al. (1989) spanned from latest Valanginian-Early Aptian times, and is associated with the deposition of the Avalon, Ben Nevis, and Nautilus formations. This phase was presumed to be slower,being associated with less syn-depositional faulting than the second phase. Marine sedimentation prevailed in the basin and along its margins, where units display onlap onto the flanks of the bounding culminations. Tankard et al. (1989) noted sedimentation under increased water depths and normal marine circulation during this time in the basin.

Sinclair (1988) defined three phases of rifting in the Jeanne d'Arc Basin, spanning the Triassic-early Jurassic, Tithonian-Early Valanginian, and Aptian-Albian times. Each phase of rifting was preceded by a stage of broad regional arching, and followed by thermal subsidence and associated post-rift sedimentation (see also Sinclair and Riley, 1995). The first phase of rifting established the N-NE trending, basin-bounding faults of the Jeanne d'Arc Basin (e.g., the Murre and Voyager faults). Continental red beds and evaporites were deposited in the fault-bounded basin during the Triassic-Early Jurassic. In Early-Late Jurassic (i.e. Pliensbachian-Oxfordian), clastic sediments sourced from basement structures to the southeast (e.g., Morgiana Uplift), were deposited in the broadly sagging Jeanne d'Arc Basin, marking the end of the first rift cycle (Sinclair and Riley, 1995).

The second phase of rifting started with domal uplift of the region to the south of the basin (i.e. the Avalon Uplift), leading to erosion of the Rankin Formation (Sinclair and Riley, 1995). The Jeanne d'Arc, Fortune Bay and Hibernia formations record the deposition during the ensuing syn-rift phase. Re-activation of the N-NE trending fault system, which was established during the first rift phase, is associated with growth in the Jeanne d'Arc, Fortune Bay and Hibernia formations. The Hibernia Formation represents two cycles of deltaic sedimentation in the basin, with the upper zone of lower Valanginian age concluding syn-rift deposition. It is overlain by the Late Valanginian B Marker Member of the Whiterose Formation. The marker rests with marked unconformity on the Hibernia Formation in the southern region of the basin, but the unconformity disappears basin-ward. B Marker deposition was followed by progradation of calcareous sandstones of the Catalina Member, which graded basin-ward into shales of the Whiterose Formation. Faults cutting the B Marker and terminating in the Whiterose Formation were thought to be contemporaneous with a rapid thermal sag phase affecting the basin (Sinclair and Riley, 1995). This caused flooding of the basin margins, retreat of terrestrial clastic sediments (i.e. Hibernia Formation), and development of holomarine conditions commencing with the deposition of the B Marker Member and continuing with deposition of the remainder of the Whiterose Formation (Sinclair, 1988). The architecture of these Tithonian-lower Valanginian "drift" strata is interpreted by Sinclair (1988) as a partially preserved "Steer's Head" geometry (McKenzie, 1978; Dewey, 1982). He suggested that this, combined with the absence of igneous activity during the Late

Valanginian-Hauterivian, is consistent with a phase of post-rift thermal sag in the basin (Sinclair 1988; Sinclair and Riley, 1995).

The final stage of rifting proposed by Sinclair (1988) commenced in the Aptian after a period of domal uplift, followed by erosion (i.e. of the Avalon Formation) and deposition of the Ben Nevis and Nautilus formations.

In summary, Tankard et al. (1989) proposed that the B Marker was deposited at the end of an intense phase of fault-controlled subsidence during the Valanginian. The change between depositional environments at this time was relatively rapid, and occurred with little interruption to sedimentation preceeding and following the deposition of the B Marker (Tankard et al.,1989). Sinclair (1988), on the other hand, proposed full rift cycles to explain basin evolution. He postulated punctuated phases of post-rift subsidence following the main phases of syn-rift sedimentation in the basin, and attributed the deposition of the B Marker limestone to a period of rapid, basin-wide thermally driven subsidence following the second phase of rifting. This established a partially preserved "Steer's Head" architecture in the Jeanne d'Arc Basin (Sinclair, 1988).

4.2 Depositional Model of the B Marker Limestone

A new depositional model for the B Marker is described within the context of the immediately preceding (Unit A) and subsequent phases (Unit B and higher successions) of deposition with in the Jeanne d'Arc Basin. The well data, structural interpretations and seismic stratigraphic analyses previously presented indicate that at the time of B Marker deposition the following conditions existed.

The Early Cretaceous marked the end of a period of regional subsidence, and the deposition of the large deltaic complex (i.e. the Hibernia Formation; Arthur et al., 1982; Tankard et al., 1989; McAlpine, 1990). The paleogeography of the Jeanne d'Arc Basin during the Early Cretaceous is well understood (Tankard et al., 1989; McAlpine, 1990; Shannon et al., 1995; Sinclair, 1995, 1994, 1992, 1988). The regional tectonic uplift during the Early Cretaceous (i.e. Avalon Uplift) and the fall in global sea-level during the Berriasian to Valanginian (Harland et al., 1982) caused exposure and sub-aerial erosion of most of the southern portion of the Grand Banks, as well as the isolated structural highs, such as the Central Ridge Complex. During this period the Jeanne d'Arc Basin was an elongate depression, closed toward the south. The basin acted as a spacious, very shallow depocentre for large fluvial systems draining mostly from the Avalon uplift in the south, from the Bonavista Platform in the west and from the Central Ridge Complex in the east (Arthur, 1982; McAlpine, 1990). Large deltas which developed in the Jeanne d'Arc Basin during this period include: 1) the complex in the south between the Voyager Fault and the Egret Ridge, with a fluvial system draining the Avalon Uplift; and 2) the fluvial system draining the eastern portion of the Bonavista Platform in the area north of the Nautilus Fault and east of the Mercury Fault (Figures 4.2-4.5). The interpretation of the lithologies encountered in exploration wells in southern Jeanne d'Arc Basin suggests that the basin gradually deepened toward the north.

The following discussion of the depositional evolution of the B Marker limestone will focus on the stratigraphic interval between the Hibernia Formation and Catalina Member of the Whiterose Formation.

4.2.1 The Hibernia Formation: Regressive deltaic sandstone facies

The Hibernia Formation extends from the top of the Fortune Bay Formation to the base of the B Marker limestone, in the Whiterose Formation. It consists of a sandstone-dominated unit with shale interbeds. On the basis of lithological characteristics and mode of deposition, the Hibernia Formation is further subdivided into upper and lower subunits (McAlpine, 1990; Sinclair, 1998, 1999, CNOPB, 2001). The upper subunit includes two depositional cycles: the Cape Island Member and the Hebron Well Member (Sinclair, 1999).

The Hibernia Formation thickens northward within the Jeanne d'Arc Basin. The formation is absent on the Bonavista Platform, south of the Egret Fault, on the Central Ridge Complex, and in the northern most regions of the basin where the sandstones of the Hibernia Formation grade laterally into the shale of the Whiterose Formation (McAlpine, 1990). The Hibernia Formation is thinnest along the southern margins of the basin, in regions associated with sediment bypass and erosional truncation (Sinclair and Riley,1995).

Thick coarse sandstones of the Hibernia Formation were deposited by fluvial systems in deltaic distributary channels into the Jeanne d'Arc Basin. The lower subunit is composed of fine-grained sandstones and shales, believed to be deposited by high-bed load fluvial channel processes with flow from south to north (Sinclair, 1999). The upper subunit is characterized by thickly- and thinly-bedded sandstones along the eastern and southeastern margin of the basin, which grade laterally into siltstones and silty shales in the west. According to Sinclair (1999), the sandstones and shales in the upper subunit were deposited on broad, wave-dominated deltas in contrast with the river-dominated systems of the lower subunit of the Hibernia Formation. Thin sandstones near the base of the Cape Island Member are interpreted to represent deposition in fluvial distributary channels. Sandstones at the top of the Cape Island Member are interpreted to represent a series of progradational delta front sandstones. Coarsening-upward sandstones of the Hebron Well Member were deposited beneath the B Marker limestone (in the Mara M-54 well; Sinclair, 1998).

4.2.2 B Marker Member, Whiterose Formation: Carbonate Ramp Facies Model

Lithostratigraphically, the B Marker is the limestone unit immediately above the Hebron Well Member of the Hibernia Formation, and below the base of the Catalina Member of the Whiterose Formation (Sinclair, 1988; Tankard et al., 1989; McAlpine, 1990; Mackay and Tankard, 1990). It has been traditionally deemed a regional lithostratigraphic marker and coincident seismic event throughout the Jeanne d'Arc Basin.

Although biostratigraphic data designate the B Marker limestone as Valanginian in age (see section 3.6), there are no detailed biostratigrahic well data in the study area to further restrict the age range of the marker. Therefore, precise chronostratigraphic correlations between the lithologies of the wells along each seismic trace cannot be made.

Current thinking argues that the B Marker limestone represents a single carbonate marker which is a time-correlative event across the Jeanne d'Arc Basin. Thorough examination of the seismic reflection profiles and well history reports allows the development of a carbonate ramp model (focusing on the stratigraphic interval between Hibernia and Whiterose formations), which overcomes this discrepancy, and better describes the depositional evolution of the B Marker limestone in the Jeanne d'Arc Basin.

Detailed examination of the seismic reflection profiles shows that there are up to four seismic traces within the interval represented by the seismic B Marker unit. These traces can be mapped across the Jeanne d'Arc Basin, but their presence and attributes varies laterally. These seismic traces are labeled as Tr 1, Tr 2, Tr 3 and Tr 4. Lithological characterizations of Tr 1 to Tr 4 were made through correlations with well data (Figures 3.27 - 3.29). Careful seismic tracing has demonstrated that laterally the Tr 1 - Tr 4 traces are each associated with varied lithologies, including transition from siliclastic to carbonate facies. Although biostratigraphic data designate the B Marker limestone as

Valanginian in age, there are no detailed biostratigrahic well data in the study area to further restrict the age range of the marker. Therefore, precise chronostratigraphic correlations between the lithologies of the wells along each seismic trace cannot be made. Thus, Tr 1 - Tr 4 may not represent time-lines (sensu stricto); however, it is believed that each trace represents broadly synchronous depositional environments.

Four paleogeographic maps were constructed, representing the interpreted distribution of inferred depositional environments for four hypothetical timeslices, labeled S1 through S4 (Figures 4.1 - 4.5). The lithofacies represent the dominant rock type and were chosen to best depict the various lithological successions of the B Marker limestone throughout the Jeanne d'Arc Basin. The NW-SE schematic geological cross section (Figure 4.1) shows the temporal and spatial variations in depositional environments across the Jeanne d'Arc Basin, from the Hibernia oilfield to the Terra Nova oilfield. The section is based primarily on the lithofacies data synthesized in Figure 3.29.

During S1, the sedimentation within the southern Jeanne d'Arc Basin was dominated by the fluvial systems draining the Avalon uplift in the south and the Bonavista Platform in the west (Figures 4.1 and 4.2). The coarse sandstones encountered in the Ben Nevis I-13, Terra Nova K-18 and King's Cove A-26 wells, grade northward into the finer sandstones and shales encountered in Mara M-54 well, and these in turn grade northward into the limestones penetrated in Hibernia C-96 and B-16-18 wells. Limestone deposition was confined to a narrow E-W trending belt (Figure 4.2). S1 marks the end of a phase of

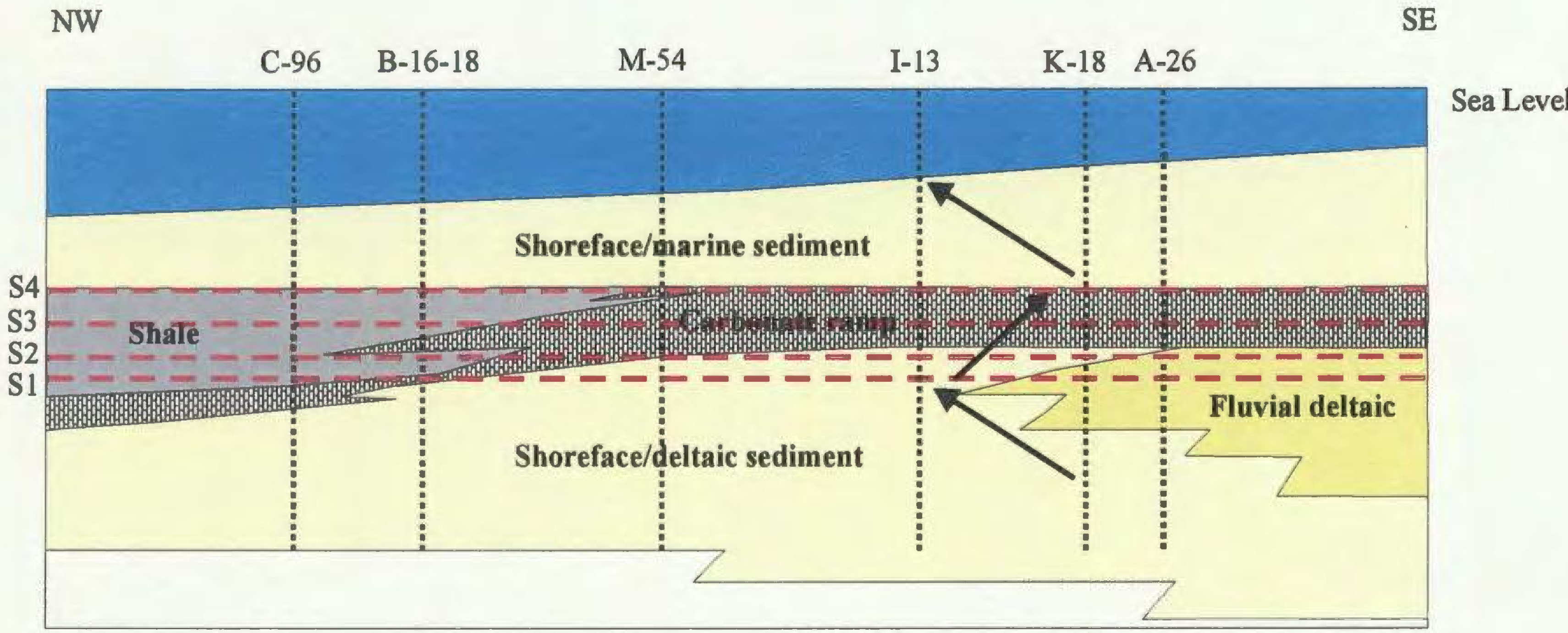

Figure 4.1. Schematic cross section showing the B Marker Carbonate Ramp Model lithofacies, and their location in wells shown in Figures 3.27-3.29. S1-S4 events are shown as dashed red lines, and arrows indicate periods of transgression (toward the SE), and regression (toward the NW).

regression, associated with the progradation of the Hibernia delta within the Jeanne d'Arc Basin. Limestone deposited in the northern portion of the basin indicates the start of transgressive phase of marine deposition across the existing shoreface/delta environment.

During S2, landward migration of the shoreline caused the deposition of deeper water shales over the limestones in the north, as seen in wells C-96 and B-16-18 (Figures 4.1 and 4.3). These shales are interbedded with thin bedded, tan to grey colored limestone in the both wells. A wider E-W trending zone of limestone deposition, therefore, prevailed during S2 (Figure 4.3). Sandstone is present on the shallow shelf (in I-13, K-18 and A-26 wells). Detailed examination of seismic sections in this region, revealed toplap of the upper successions of sandstone against the base of the B Marker limestone in the shallow shelf environment (Figure 3.7).

During S3 a very broad E-W trending belt of light brown to white colored oolitic limestone blanketed the southern shallow shelf in the Jeanne d'Arc Basin, including Whiterose, southern Hibernia, Ben Nevis, Hebron and Terra Nova oilfields. This limestone is flanked by the Egret Fault and Ridge to the south and west, respectively, and by the Voyager Fault and Central Ridge Complex to the southeast and northeast, respectively (Figures 4.1 and 4.4). The thin-bedded limestones in the C-96 and B-16-18 wells (Table 3.2) seen in S1 and S2 are inter-fingered with the thicker bedded oolitic limestones encountered in the M-54 and I-13 wells further to the south (Figure 4.4 and Table 3.2). The inter-fingering and lateral change in lithology are inferred to account for the discontinuous and fragmented appearance of the seismic signature of the B Marker in these areas (Figures of 3.4). The depositional architecture suggests that the thin-bedded portion of the limestone succession is probably shingled beneath the thicker-bedded limestone blanket. This geometry is interpreted to reflect the southward migration of the subtle depositional hinge zone on the evolving shallow basin floor during the ensuing transgression from S1 to S3.

During S3, the transition from shallow to the deeper shelf occurs near the B-16-18 well, where limestones and shales are inter-bedded. The location of this transition is similar to the shelf break associated with S2, suggesting the boundary was relatively stationary from S2 to S3. The shelf break extended northeast of the Bonavista Platform, across the southern region of the Hibernia oilfield, and toward the Whiterose oilfield and the Central Ridge Complex (Figure 4.4). This places the C-96 well, as well as most of the Hibernia wells in the deeper shelf, the B-16-18 well on the shelf break and the M-54, I-13, K-18 and A-26 wells on the shallow shelf environments. In the M-54, I-13, K-18 and A-26 wells the B Marker is mainly composed of oolitic and lesser pelitic limestone (Table 3.2).

Up until S4, carbonate deposition was outbuilding toward the southeast, but, during S4 it maintained its position with minor southeast shift over the partially erosive Hibernia Formation. S4 marks the peak of transgression within the Jeanne d'Arc Basin. During this time the shoreline migrated south, thus resulting in the widest coverage of the deeper shelf across basin. Sedimentation above the S4 event is marked by a prominent lithological change from limestone of the B Marker Member to sandstone of the Catalina Member in the shallower shelf (i.e. M-54, I-13, K-18 and A-26 wells in the southeast), and from shale to sandstone in deeper water (i.e. C-96 and B-16-18 wells in the northwest). Fluvial/deltaic and delta front sandstones were thus deposited over the carbonate ramp, and over the deeper shelf in the B-16-18 and C-96 wells (Figures 4.1 and 4.5).

The shape and trend of the shorelines depicted in Figures 4.2-4.5 is largely based on the northerly plunge of the basin, and the location of the regional highs which were active at the time of B Marker deposition, (i.e. the Bonavista Platform, Central Ridge Complex and Avalon Uplift). It is noted that the location of the shallow carbonate shelf is not thoroughly constrained by well control.

The stratigraphic architecture of the B Marker limestone shown in Figure 3.29 and 4.1 and the supporting palinspastic maps (Figures 4.2-4.5) is interpreted to result from the development of a carbonate ramp in response to a transgression over an uplifted and eroded structural high in the east. Carbonate ramps are defined as large carbonate bodies built along gentle regional slopes with no distinct break in the slope gradient. In such environments a wide-range of facies form irregular belts, with the highest energy zone located relatively close to the shore (Wilson, 1975). Similarly, carbonate platforms are defined as huge carbonate bodies, but are exclusively developed on shelves; therefore, they have a horizontal top and display an abrupt shelf break where the high-energy

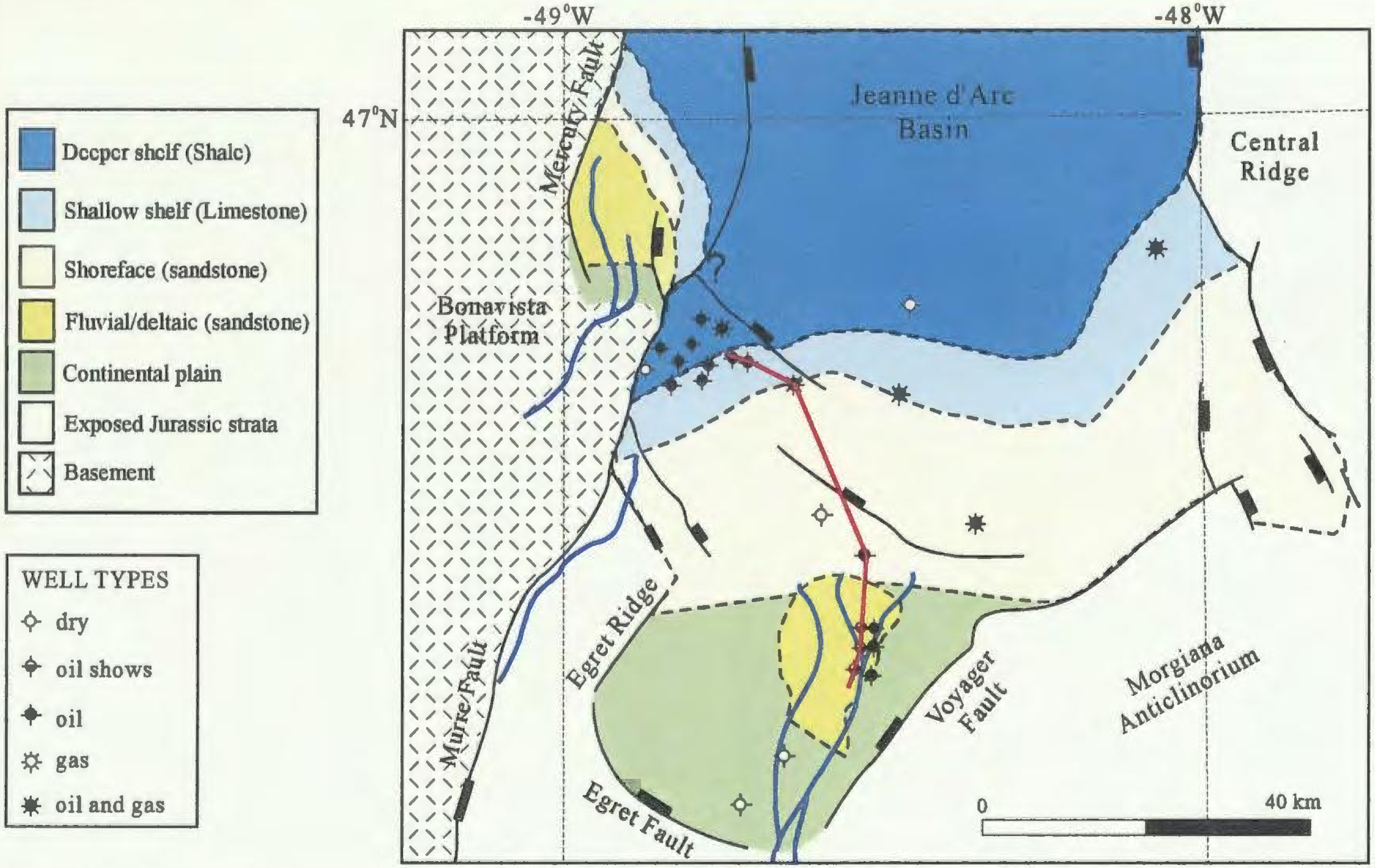

Figure 4.2. Paleogeographic map during the S1 event. This map shows fluvial systems draining the Avalon uplift in the south and the Bonavista Platform in the west. These areas provided the coarse sandstones in the Ben Nevis I-13, Terra Nova K-18 and King's Cove A-26 wells, which grade northward into the finer sandstones and shales in the Mara M-54 well, and these in turn grade northward into the limestones penetrated in the Hibernia C-96 and B-16-18 wells. Limestone deposition was confined to a narrow E-W trending belt. S1 marks the end of a phase of regression, associated with the progradation of the Hibernia delta within the Jeanne d'Arc Basin. The red line corresponds with wells and schematic sections as shown in Figure 3.27-3.29.

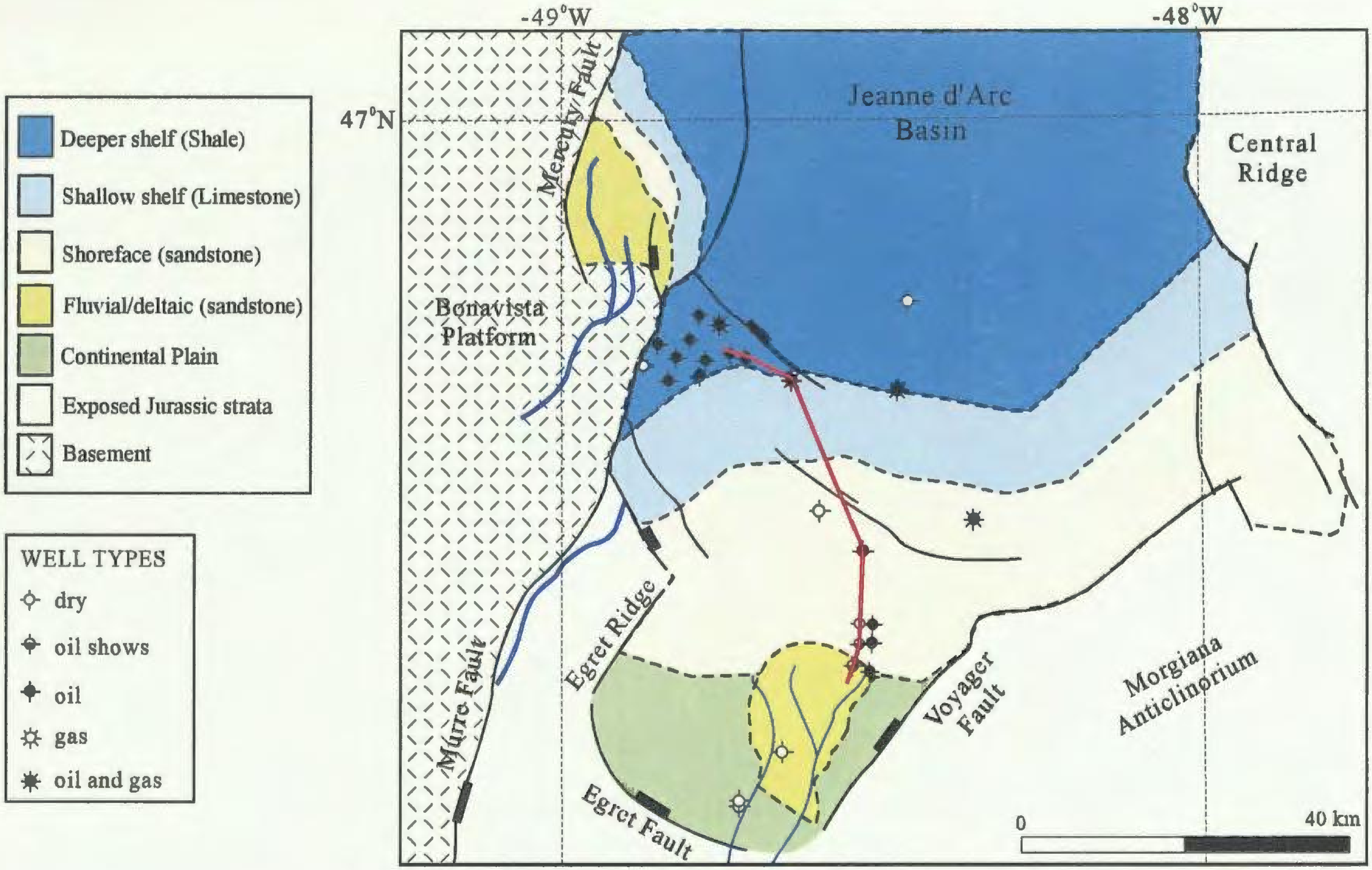

Figure 4.3. Paleogeographic map during S2, showing the deposition of deeper water shales over the limestones in the north, (in wells C-96 and B-16-18). These shales are interbedded with thin bedded, tan to grey colored limestone in the both wells. A wider E-W trending zone of limestone deposition prevailed during S2. Sandstone is present on the shallow shelf (in I-13, K-18 and A-26 wells).

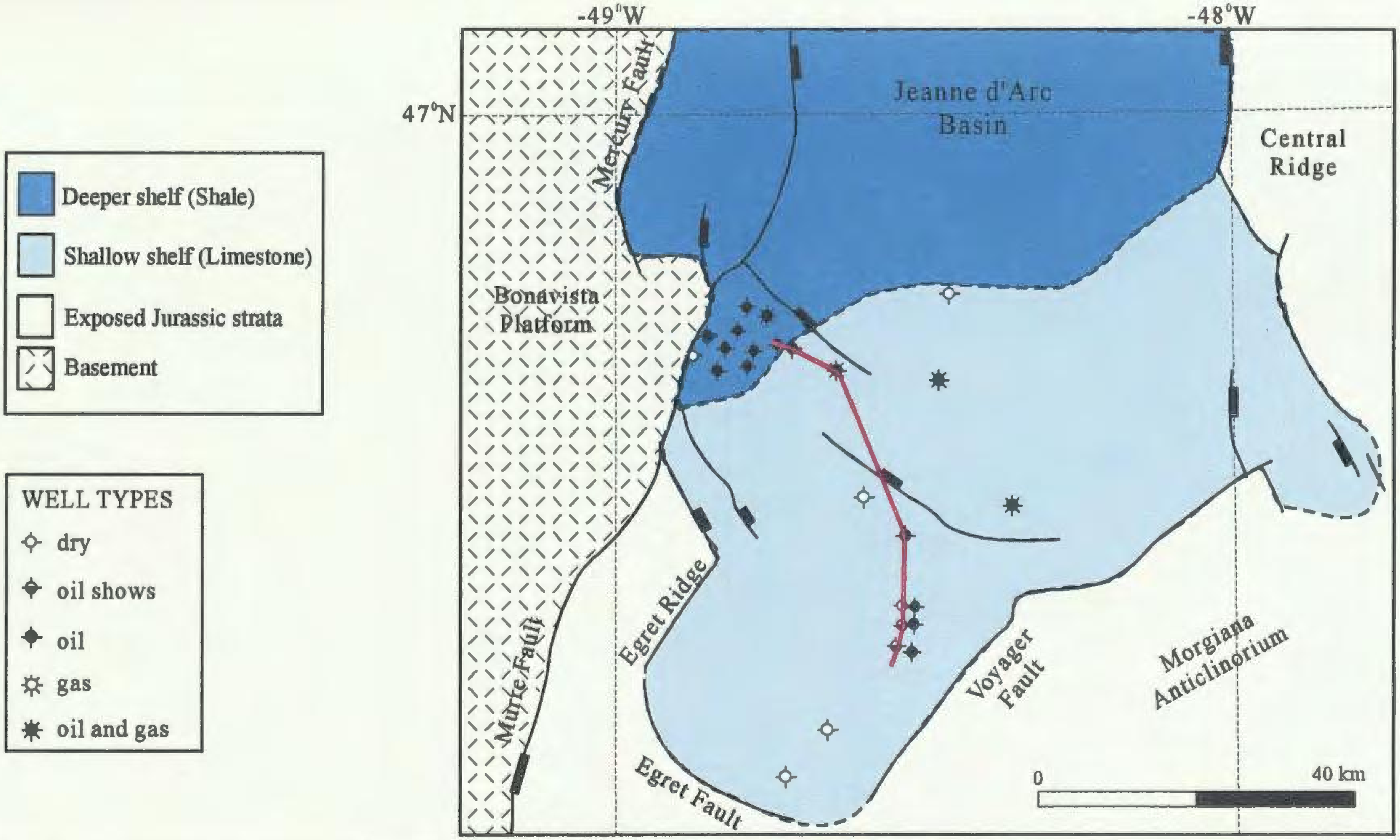

Figure 4.4. Paleogeographic map of the S3 event, showing a very broad E-W trending belt oolitic limestone in the southern shallow shelf. The thin-bedded limestones in the C-96 and B-16-18 wells seen in S1 and S2 are inter-fingered with the thicker bedded oolitic limestones encountered in the M-54 and I-13 wells further to the south. The depositional architecture suggests that the thin-bedded portion of the limestone succession is probably shingled beneath the thicker-bedded limestone. This geometry is interpreted to reflect the southward migration of the subtle depositional hinge zone on the evolving shallow basin floor during the ensuing transgression from S1 to S3.

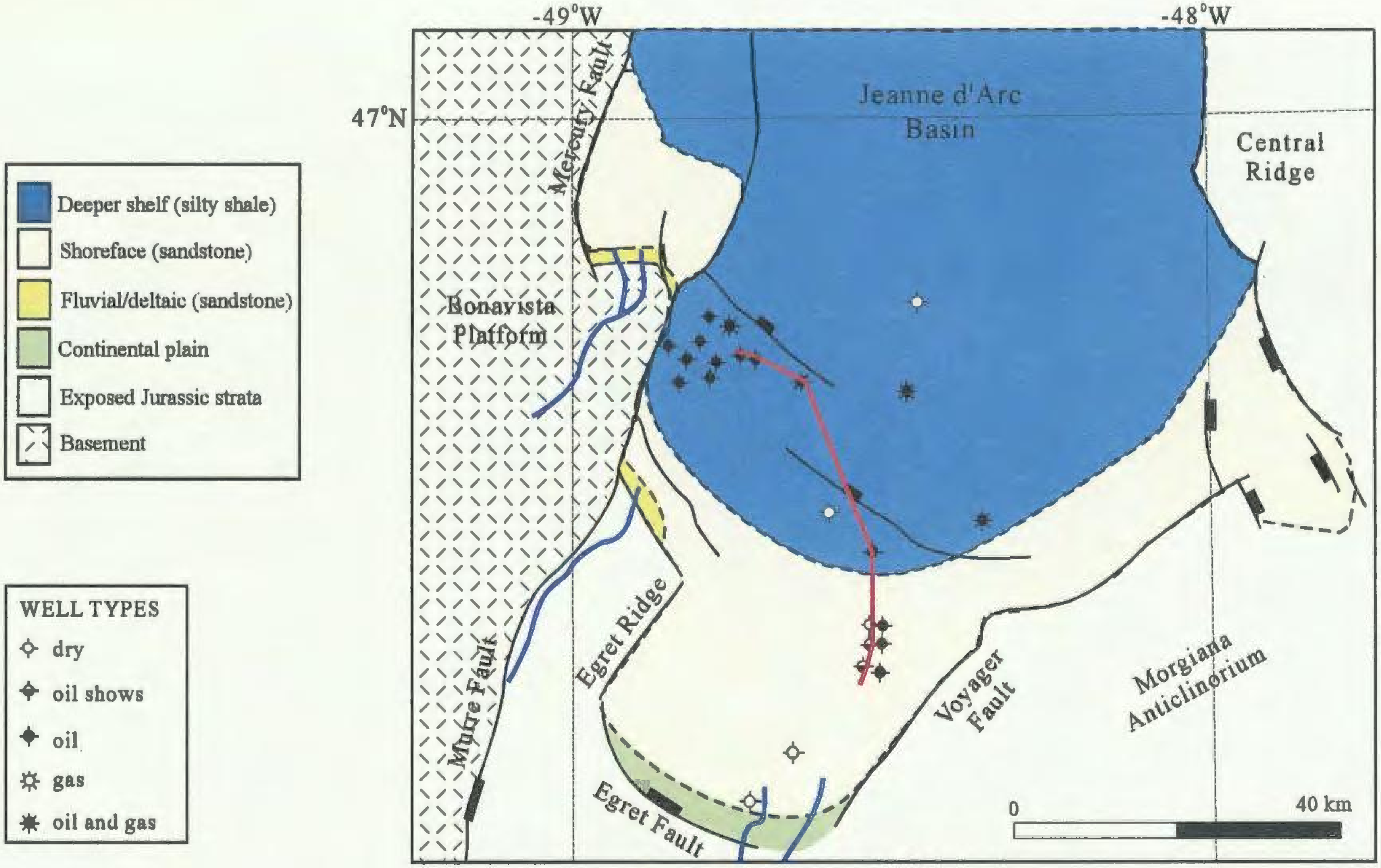

Figure 4.5. Paleogeographic map of the S4 event. S4 marks the peak of transgression within the Jeanne d'Arc Basin, and widest coverage of the deeper shelf across basin. Sedimentation above the S4 event is marked by a prominent lithological change from limestone of the B Marker Member to sandstone of the Catalina Member in the shallower shelf (i.e. M-54, I-13, K-18 and A-26 wells), and from shale to sandstone in deeper water (i.e. C-96 and B-16-18 wells). During S4 the depositional hinge zone demonstrated minor southeast shift, over the partially erosive Hibernia Formation.

sedimentary environment is located. The normal process of carbonate sedimentation can turn ramps into platforms and create narrow, steep shelf margin ridges. When ramp slopes are gentle enough to make them indistinguishable from platforms, the terms are often used interchangeably (Wilson, 1975).

Facies changes were observed within the B Marker limestone across the carbonate ramp shown in Figure 4.4. The presence of ooids in the southern region of the Jeanne d'Arc Basin suggest this facies formed in a unique depositional environment. An oolitic limestone is an even-textured rock which is composed almost entirely of calcareous ooliths with essentially no matrix (Parker, 1994). The oolite grains are small (0.25 - 2.0 mm) rounded accretionary bodies generally of calcium carbonate formed by inorganic precipitation, or by replacement, and typically exhibit concentric or radial internal structure (Parker, 1994). Particles can be oolitically coated with one or two concentric laminae, retaining the original grain shape (Wilson, 1975). In modern carbonate sediments, ooids are found in chlorozoan assemblages[2], which are dominated by hermatypic corals and calcareous green algae. They develop in warm waters where temperature is above 18°C and salinity ranges between 32 and 40‰ (Jones et al., 1992). Well-formed ooids are the products of tidal action (Wilson, 1975). The presence of ooids in a limestone suggests it was deposited in a shallow marine environment where there

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2 Modern carbonate sediments are largely controlled by temperature and salinity and can be divided into formal and chlorozoan assemblages (Jones and Desrochers, 1992).

was enough wave or tidal energy to provide an adequate environment for ooid formation. Pelletoids are also a carbonate grain, composed of microcrystalline carbonate, generally agglutinated or cemented feces or diagenetically altered grains (James and Kendall, 1992). The presence of ooids and pelletoids in M-54, I-13, K-18 and A-26 wells substantiates the deposition of the B Marker limestone on a broad shallow shelf. In deeper shelf environments (i.e. in C-96 and B-16-18 wells) no ooids are present. The presence of ooids on the shallow shelf and their absence on the deeper shelf, further supports the establishment of a subtle depositional hinge zone by the S2 event. The placement of the hinge zone remained relatively stationary during S2, migrated southward through the S3 event and became stationary again by the S4 event (Figures 4.3-4.5).

4.2.3 Catalina Member, Whiterose Formation: Regressive oolitic sandstone and oolitic limestone facies

The late Valanginian transgression was followed by the onset of regression, and a new phase of progradation and associated deposition of the Catalina Member across the Jeanne d'Arc Basin. Sandstones of the Catalina Member were deposited above the B Marker limestone, which led to the drowning of the carbonate ramp.

The Catalina Member of the Whiterose Formation is present across much of the Jeanne d'Arc Basin but grades laterally to silty shales to the north and east. The member ranges from 71 m at Terra Nova K-18, to 147 m in Hebron I-13, and 273 m at Hibernia

C-96 wells. In the Hibernia oilfield, silty shales of the lower Catalina subunit commonly lie above the B Marker limestone, with a gradual change to silty sandstone interbeds occurring higher within the section. Further south, in the Terra Nova oilfield, sandstone and siltstone beds of the Catalina Member are often in direct contact with the underlying limestones of the B Marker Member.

The Catalina Member is composed of oolitic sandstones and oolitic sandy limestones with no terrestrial lithofacies. Fossils typically include bivalves, echinoderms, gastropods, calcareous worm tubes, and coralline algae, representing a fully marine macrofauna (.McAlpine, 1990). The depositional environment is interpreted as a gently sloping shoreface characterized by marine shelf storm deposits and probable minor oolitic shoals. Northeastward the Catalina Member shows a gradational change from lower shoreface muddy sandstones into offshore silty shales (McAlpine, 1990).

4.2.4 Changes in marine circulation during the Valanginian

The B Marker limestone unequivocally marks a change in depositional environments from restricted marine (i.e. Hibernia Formation) to open marine (Catalina Member) conditions in the Jeanne d'Arc Basin (Sinclair, 1988; Tankard et al., 1989). Tankard et al. (1989) believe that this transition is substantiated through paleontological evidence, specifically data suggesting changes in paleogeography and marine circulation in the basin. Sediments occurring below the B Marker contain impoverished assemblages of dinoflagellates and other marine organic matter. Sediments containing organic matter are terrigeneous, and sorted by currents and/or oxidation in a high-energy environment, such that resistant minerals and robust spores have been preserved rather than delicate leaf tissue and pollen (Tankard et al., 1989). Therefore, sediments deposited below the B Marker during the Berriasian and Early Valanginian were deposited in restricted marine and non-marine environments with inferred sub-normal salinities (Tankard et al., 1989). In contrast, sediments deposited above the B Marker contain abundant and diverse dinoflagellate assemblages, and other marine organic materials. Organic matter found above the marker shows little evidence of current activity sorting and/or oxidation, indicating a low energy sedimentation regime. Thus, after B Marker deposition, salinities returned to normal and deposition commenced in open marine conditions during Late Valanginian, Hauterivian, and Early Barremian (Tankard et al., 1989).

4.3 Tectonics and Sedimentation in the Early Cretaceous

The seismic section shown in Figure 3.7 highlights the four seismic events, which correlate with stratigraphic well picks in the Terra Nova K-18 well. Thorough examination of the Cape Pine survey shows that an older phase of rapid growth has occurred between the Tithonian and Jeanne d'Arc markers, which terminated at the onset of deposition of the Jeanne d'Arc Formation. In this package there is substantial onlap and thinning, which is most evident in the south, and more specifically in the SW region of the Cape Pine survey. This package thins significantly from ~ 700 ms TWT in the NW to ~150 ms TWT in the south.

Onlap and associated overstep with thinning over the crests of the flanking culminations is evident in Unit A, and is most prominent toward the SW, where thicknesses range between 580 ms in the syncline, and ~300 ms TWT on the SW flank of the syncline. Changes in Unit A thickness are, however, less pronounced than seen below the top of the Jeanne d'Arc Formation, indicating a slower phase of growth before the time of B Marker deposition. The westward and eastward onlap of Unit A on the flanks of the syncline suggests deposition during rise of the bounding ridges, following deposition of the Jeanne d'Arc sandstone, and associated activity on E-W transfer faults. The patterns clearly indicate a phase of sediment growth during deposition of Unit A. Unit B also shows overstep and thinning over the crests of the culminations that is mostly concentrated in the southern regions; the thickness of the unit excludes the variations in thickness of the A Marker limestone. The degree of toplap and amount of package thinning seen below the A Marker suggests growth was accentuated during the later part of deposition of Unit B. In areas of most significant erosion within Unit B, thicknesses decline from ~ 650 ms near the synclinal axis, to ~350 ms TWT along the southern periphery of the syncline.

In summary, the regional thickness contrast in Unit B is more pronounced than in Unit A. This suggests there was a period of relatively slow growth from Jeanne d'Arc

Formation to the base of the B Marker deposition (Unit A). This cycle of deposition was terminated at the base of the B Marker limestone. This was followed by a period of relatively rapid growth (Unit B) following deposition of the B Marker. Similarly, this cycle of sedimentation ended with the rise and erosion of strata beneath the A Marker limestone.

4.3.1 Structural Synthesis

In this section, the two tectonic models presented in Section 4.1 are discussed in the light of the B Marker Carbonate Ramp Model proposed in this study.

The Jeanne d'Arc Formation is overlain by the Fortune Bay Formation (Unit A) and by notable onlap (Figure 3.6). This onlapping relationship can only be explained by either a regional doming of the Jeanne d'Arc Formation, or by a significant rise of base level within the Jeanne d'Arc Basin. The Fortune Bay Formation is overlain by the progradational deltaic sandstones of the Hibernia Formation, which in turn are overlain by the B Marker limestone. In the southern region of the Jeanne d'Arc Basin the contact between the Hibernia Formation and the base of B Marker limestone is defined by a mild toplap, indicating sediment bypass and minor erosion, as also suggested by Sinclair (1988). The toplap observed on the crests of the southern culminations and depositional hinges indicates that the base level (i.e. sea-level) was too low to allow deposition of strata updip. However, Sinclair (1988) suggested that the deposition of the upper portion of the Hibernia Formation as well as the B Marker took place during a interval of basinal subsidence associated with the post-rift thermal sag following the second rift phase. Although toplap can develop in subsiding basins with falling base level, where rates of subsidence = rates of sea-level fall, this interval is marked in the geological record as a period of global sea-level rise (Harland et al., 1982). The B Marker oversteps the Terra Nova culmination. In the east toward the Egret Ridge, the marker is onlapped by sandstone of the overlying Catalina Member, suggesting a rise in eustatic sea level. Thus, sedimentation continued through deposition of Unit B during sea-level rise. This cycle of sedimentation ended with the rise and erosion of strata beneath the A Marker limestone in Barremian. Therefore, the observed toplap cannot be reconciled with the regional subsidence proposed by Sinclair (1988), but was probably caused by stick slip on the master fault during a period of regional transgression. Stick slip on the master Voyager Fault led to the uplift of the southern culminations, followed by erosion and subsequent regional leveling of the paleo-topography in southern regions of the Jeanne d'Arc Basin. This provided a level surface to deposit a limestone of relatively even thickness across the basin. The stick phase occurred during the evolution of the fault system, and coincides with an ensuing sea-level rise which punctuating two (Unit A and Unit B) modest growth phases (slip and relative uplift of basin flanks) during the latest stages of the second rift phase. The deposition of the B Marker marked the transition between these two growth phases.

Tankard et al. (1989) suggested that the widespread deposition of the B Marker (limestone) Member above the Hibernia Formation followed the second phase of subsidence in the Valanginian. They noted that the B Marker indicates the transition between a closed system under restricted marine to terrestrial conditions, to an open marine environment, and suggested that the change in depositional environments was relatively rapid, and occurred with little interruption of the sedimentary record. The results of the present study support these earlier findings. However, the development of a notable unconformity at the base of the B Marker in the southern Jeanne d'Arc Basin in the Port au Port J-97 well, is noted by Sinclair (1988) and Tankard et al. (1989). This strongly suggest that there was a significant interruption in the deposition at the base of the B Marker limestone. On the other hand, the B Marker Carbonate Ramp Model supports the development of toplap at the base of the B Marker on the shallow shelf.

The final episode of tectonism resulted in the southward shift of the depositional hinge zone of the carbonate ramp, between the Hibernia B-16-18 and the Hebron I-13 wells. Shifting of the hinge zone began at the S2 event and ended just before the S4 event. Stick slip on the master fault is associated with the lateral gradation of the carbonate ramp on the shallow shelf into sandstones further north, and thus accounts for the diachroniety of the B Marker limestone. Stick slip on the master fault during transgression led to uplift of the southern culminations at the end of the syn-rift depositional cycle. In summary, the B Marker limestone was deposited as a carbonate ramp during a period of relative tectonic quiescence and relative rise of base level and ensuing transgression in the Jeanne d'Arc Basin, which was coincident with a rise of global sea level.

CHAPTER 5: CONCLUSIONS

Detailed interpretation of 3D seismic reflection profiles and various well log data revealed the following salient conclusions:

1. There are several notable discrepanies in the correlation of the B Marker and the sedimentary successions above and below this event in the well data and seismic reflection profiles across the Jeanne d'Arc Basin. Synthetic seismograms generated for the wells in the southern region of the basin consistently revealed a couplet corresponding to the B Marker seismic event, which occurred below the B Marker lithological pick in the wells.
2. Continuity and amplitude maps generated for the B Marker seismic event, revealed zones of seismic discontinuity which corresponded with zones of low amplitude reflectivity. These zones clearly illustrate that the sediments associated with the B Marker are not regionally laterally homogeneous and continuous, supporting the presence of discrepancies between seismic reflection and well data.
3. A Carbonate Ramp Model was proposed to explain the inconsistencies associated with the B Marker across the Jeanne d'Arc Basin. In this model, the B Marker (limestone) was deposited as a carbonate ramp along the shallow shelf in the Jeanne d'Arc Basin during the Valanginian. In deeper water environments, the B Marker limestone graded into sandstone of the Catalina Member. Here, the thin-bedded limestone unit is shingled beneath the thicker, oolitic ramp portion of the

carbonate. This shingling is interpreted to define a depositional hinge zone, which is also identified in continuity and amplitude maps. The B Marker was largely deposited in a time of tectonic quiescence and relative rise of base level, during the ensuing transgression in the Jeanne d'Arc Basin, which was coincident with a rise of global sea level. However, there was a final episode of tectonism during the Valanginian, which resulted in the southward shift of the depositional hinge zone of the carbonate ramp (between Hibernia B-16-18 and the Hebron I-13 wells). Stick slip on the master fault is associated with the lateral gradation of the carbonate ramps into sandstones further north, and thus accounts for the diachroniety of the B Marker limestone, as observed between seismic and well data across the basin.

Appendix 1.

Programs Used

All programs used during interpretation and analysis in this thesis are **Landmark** products. Landmark Graphics Corporation established a new standard in the energy industry when it helped launch an era of computer-aided exploration that focused on 3-D seismic interpretation in 1982. Landmark is run from an **OpenWorks** project database which stores all aspects of well-related data, log acquisition data, surface and fault interpretations, seismic acquisition and navigation data, computed map data, production and drilling data.

SeisWorks was the most extensively used interpretive tool employed in this thesis. SeisWorks is a 3-D seismic interpretation and analysis program which supports seismic interpretation in either time or depth, and simplifies SeisWorks depth interpretation. SeisWorks allows you to merge 2-D with 3-D seismic data projects, and combine multiple 3-D projects without data reformatting or reloading. This function was beneficial when merging Cape Pine and Hibernia 3-D surveys.

Seismic data can be displayed in a number of ways using the display option in SeisWorks wiggle trace and variable density displays were used the most. Wiggle traces can bias your eye toward the solid color filled peak, while variable fills show both wave form and color amplitude variation.

Faults can be interpreted and edited on vertical seismic sections and time slices in SeisWorks, and are stored in the OpenWorks database, so information can be accessed and instantly updated by others. Faults can be mapped in SeisWorks in a variety of ways. In this thesis, faults were mapped manually, trace by trace, rather than extrapolated and autotracked. Eliminating data manipulation yields the most accurate fault trace maps and throw displays.

Maps generated in SeisWorks include time-structure, isochore, isopach, amplitude and continuity maps. Time-structure displays are instantly generated in the MapView window of SeisWorks during seismic interpretation. With some manipulation exceptionally detailed time-structure maps were created. Data manipulation can be employed in a number of ways. For example, **ZAP!** is a 3-D Automatic Horizon Tracking tool used in this thesis to eliminate detailed picking and editing seismic horizons within a large 3-D volume. ZAP! allows autotracking within triangulated, fault-bounded blocks to aid in structurally complex areas. A coarse grid of manual interpretation is used as a framework to guide autotrack interpolation and extraction. The "zapped" interpretation was typically used for coarse resolution mapping, and always examined thoroughly for erroneous data points ("busts"). Isochore maps (commonly referred to as "isochron") and isopach maps are generated in SeisWorks using standard horizon subtraction computations, to yield vertical stratigraphic thickness measured in either time (milliseconds) or depth (metres). Amplitude maps generated in SeisWorks accentuate similar amplitude trends, and when displayed in multi-colored gradation maps, show sharp lateral variations in amplitudes for detailed stratigraphic analysis. The seismic file used at Hibernia Management and Development Company Ltd. to extract seismic amplitudes is *mg16_ph1* in the Hibernia survey and *cpmig08FP* in Cape Pine survey. Continuity maps are generated in SeisWorks. They are displayed in this thesis using two-color gradation to enhance faults and stratigraphic shapes and changes. Seismic files used by Hibernia Management and Development Company Ltd. to extract coherency is *edph16p2* in Hibernia survey and *CP-edge_8b_40_4avg_dip* in the Cape Pine survey.

SynTool allows you to tie well correlations, formation tops and lithologies with seismic data. SynTool was used to generate synthetic seismograms from either sonic logs, density logs or both. Using SynTool, seismic wavelets can be calculated, displayed and used to derive synthetics. Generation of synthetics for wells in the Cape Pine survey was a vital tool because the well data was loaded without a datum. Synthetics throughout the study area were correlated and imported into SeisWorks to tie the well data to the seismic data.

StratWorks is designed for 2-D geologic interpretation and well log correlation. StratWorks is also built upon the OpenWorks project data management system. It was used in this thesis for well log correlation, cross section construction, depth to seismic-time ties through integration with SeisWorks, and map creation.

EarthCube is a three-dimensional, real-time seismic interpretation system. EarthCube was primarily used in this thesis to view the geometry of interpreted horizons and fault plane intersections. Data can be manipulated using volume rendering, zooming and rotation, chair displays and animation planes. EarthCube seismic slice plane animation allows you to create arbitrary seismic slice planes in any orientation then drive the slice planes throughout the seismic volume for interpretation. Similar to SeisWorks, EarthCube includes autotracking, fault and horizon picking, and voxel tracking tools.

Z-MAP Plus is a surface mapping and modeling component fully integrated with the OpenWorks data management environment. This integration enables creation of reservoir models by incorporating data and interpretations from seismic, geologic, petrophysical and 3D geocellular models.

TDQ is an Openworks application which allows the construction of three-dimensional velocity models for performing time-to-depth or depth-to-time conversions. TDQ provides the link between geologic and geophysical interpretations. For any surface location and time, the corresponding depth can be extracted from the TDQ velocity model. All geophysical horizon and fault surfaces mapped in Seisworks were converted into depth using velocity models specifically designed for Hibernia and Cape Pine surveys.

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