STRUCTURAL AND STRATGRAPHIC STUDY OF THE LAURENTIAN BASIN, OFFSHORE EASTERN CANADA

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By

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ABSTRACT

The Laurentian Basin is a large Mesozoic rift basin located off the south coast of the island of Newfoundland and directly east of the Scotian Shelf. In spite of being adjacent to hydrocarbon discoveries of the Scotian Shelf the basin has remained essentially unexplored because of a moratorium that has only recently been lifted. Only one exploration well has been drilled in the central part of the basin and has been reported as a dry hole in a press release from the operator. Detailed results of this well are still proprietary and therefore unavailable for this study. However, several wells located near the eastern and western margins of the basin and further along strike in adjacent basins with a similar structural and depositional history were suitable for seismic stratigraphic correlation to the study area.

The basin was previously studied by MacLean and Wade (1992), of the Geological Survey of Canada (GSC), whose primary dataset consisted of 3072 km of 2D reflection seismic data acquired for the GSC in 1984 and 1987. The current study used the same core dataset but with the benefit of modern re-processing by Arcis of Calgary. This reprocessing, which was carried out in 2005, resulted in significant improvements to the data, largely because of better multiple suppression and pre-stack time migration. The GSC seismic dataset was supplemented by approximately 14,000 km of 2D reflection seismic data provided by geophysical contractors GSI, GX Technology and Western Geco. The seismic data were integrated with well data, the GSC's regional gravity and magnetic data, and a recent high resolution magnetic survey donated to this project by Fugro. The study area covered approximately 87,000 km^2 of which 51,000 km^2 was located off-shelf on the continental slope and rise.

The Laurentian Basin has also been subjected to recent tectonism. In 1929 a magnitude 7.2 earthquake with an epicentre close to the geographic centre of the basin triggered an immense turbidite flow known as the Grand Banks Slide. The mass transport event caused a tsunami which resulted in significant damage and loss of life on the south coast of Newfoundland. The regional geological framework includes two major fault systems converging in the study area, namely: the Cobequid – Chedabucto (CC) system running east-west along the northern boundary of the basin; and the Newfoundland Fracture Zone (NFZ) which projects into the basin from a southeast direction. The CC fault system also corresponds to a hinge line that divides the basin in two. North of the hinge the pre-Mesozoic basement is overlain by a thin Mesozoic section. Crossing the hinge line to the south we enter a deep complexly structured Mesozoic basin that has been formed by extensional tectonics during the rifting of the Scotian – Grand Banks margin. The Mesozoic sequences are overlain by a Cenozoic section that reaches thicknesses of up to 3000 m and thins landward to a zero edge. To varying degrees during its development the Mesozoic – Cenozoic section in this area has been deformed by localized compressional strike slip movement, oblique extension and salt tectonism. One of the goals of the study was to investigate the role of the CC and NFZ fault systems in the basin's evolution since the start of rifting in the Late Triassic.

The major effort in defining the tectono-structural setting of the basin went into mapping the Pre-Rift horizon (basement), which presented significant challenges due to: (a) thick sedimentary cover resulting in poor energy penetration; and (b) the presence of complex salt features in the overburden. The resulting Pre-Rift basement map is tenuous in some areas, but reveals a southeast trending en echelon ridge and fault system in the northern part of the basin. Further south, near the modern shelf edge, a large ridge or perhaps series of coalescing smaller ridges trends in a roughly east – west direction. The Pre-Rift section drops off to much greater depths under the continental slope, and ultimately falls below the seven second recording time for much of the seismic data. Certain regional seismic lines running further seaward and recorded to thirteen seconds show the Pre-Rift horizon fading below complex salt structures and re-emerging seaward in approximate continuation with a strong rough textured reflector interpreted to be transitional crust.

Time and depth maps were also constructed for the Break-up Unconformity (Pleinsbachian), the Avalon Unconformity (approximate base Cretaceous to Albian), the Base Tertiary Unconformity, Late Oligocene(?) Unconformity and the Mid Miocene(?) Unconformity. Structural mapping shows two largely independent fault systems: (1) older rift related faults which have been re-activated from time to time by recurring tectonic events; and (2) younger gravitationally driven faults affecting the Tertiary, Cretaceous and Late Jurassic sediments. The rift related faults seldom penetrate the shallower sedimentary section. However, in the northwestern corner of the basin, extensional faults propagate upwards and show inversion caused by transtension and convergence of the NFZ and CC faults. Compressional folds are also observed in this area. Additionally, a series of shallow seated faults penetrating the seabed are observed to correlate to short wavelength magnetic lineaments running parallel and sub-parallel to the NFZ, which are an indication of recent movement on the NFZ and its imbricates.

Dip seismic lines indicate that the basin experienced periods of significant seaward tilting during the Jurassic and Tertiary. Jurassic tilting was caused by differential thermal subsidence that followed the start of seafloor spreading in the Pleinsbachian. A thickened Jurassic section is observed in the Laurentian Basin as compared to the Scotian Shelf. One explanation as to why Jurassic subsidence was greater in the Laurentian Basin than in the Scotian Shelf basins to the west, is that continued activity along the NFZ at this time may have introduced additional heating and cooling episodes to the Laurentian Basin. Basinward tilting during the Tertiary is the result of gradual cooling / subsidence as the spreading centre moved further away. Similar basinward tilting during the Tertiary is observed in all of the Atlantic Canada Mesozoic – Cenozoic basins.

The Laurentian basin is expected to have a similar petroleum system to the Scotian Shelf basins, because of its proximity and similar Mesozoic - Cenozoic geological evolution. Seismic lines show numerous direct hydrocarbon indicators such as gas chimneys and amplitude anomalies, which are often coincident with potential stratigraphic and structural traps.

Dramatic erosional features associated with eustatic sea level changes, the arrival of the paleo St. Lawrence River / Estuary(?), and numerous canyons related to recent de-glaciation periods are observed throughout the Tertiary section.

ACKNOWLEDGEMENTS

First and foremost I would like to thank my supervisor Dr. Michael Enachescu who suggested it would be a good idea for me to go back to school and do a Masters program to become more current in the latest geoscientific ideas and methods and learn more about offshore Atlantic Canada. He was right, as is often the case, and it can truly be said that without his encouragement and good natured arm twisting I would never have braved this path into uncertainty. Michael has also been very generous in sharing his knowledge and expertise in this project and others that I have been involved with, and for this I am also very grateful.

I would like to thank the Geological Survey of Canada, whose seismic data formed the core of this study and whose publications on the geology of Atlantic Canada are the bedrock upon which this study was built. I also want to thank Chris Jauer, Don McAlpine and Phil Moir (and their colleagues at the GSC) for their efforts to re-process and make data available for broader use by the geoscience community. I am very grateful to the private companies that made their very expensive geophysical data available for this study including: Geophysical Service Incorporated, GX Technology, Western Geco and Fugro. Thanks are also extended to Arcis, who reprocessed the GSC seismic data for this project. Additionally I am very grateful to IHS Inc. for providing digital logs to tie the well data to the seismic data. Sincere thanks are extended to ConocoPhillips who allowed the author to spend a week viewing their recently acquired Laurentian Basin seismic grid at their office in Calgary, even as they were planning an exploration well in the area. In particular I would like to acknowledge the assistance of Hans Speelman and Leah O'Shea during the week I was there; and for follow-up discussions and assistance. ConocoPhillips also provided an industry grant to my supervisor, Dr. Michael Enachescu. I believe that it is this kind of cooperation between the public and private sector that can result in a benefit to all parties involved, and it is a credit to the wisdom of the individuals at these corporations that they recognize this and through their generosity, embrace it.

I would like to thank NSERC, PRAC and PPSC and the Department of Earth Sciences at Memorial University for funding my participation in two conferences abroad to present my results, as well as part of my trip to Calgary to view the ConocoPhillips data. I would also like to thank Vulcan Minerals Inc. who sponsored my presence at a conference where I presented a paper on the Laurentian Basin. I am grateful to Halliburton for their donation of the Landmark workstation software to Memorial, which makes this kind of project possible for students.

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Last and by no means least, a huge debt of gratitude is owed to Peter Bruce who was a constant source of technical support throughout this project and also prepared some of the key graphics.

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Acronyms Used in This Document

AU	Avalon Unconformity (except in Figure 2.1 where it means "Avalon Uplift)
BA	Bandol Anomaly
BIO	Bedford Institute of Oceanography
BT	Base Tertiary
BTU	Base Tertiary Unconformity
BU	Break-up Unconformity
CA	Collector Anomaly
CB	Carson Bonnition Basin
CC	Cobequid – Chedabucto Fault Zone
C-NLOPB	Canada Newfoundland and Labrador Offshore Petroleum Board
C-NSOPB	Canada Nova Scotia Offshore Petroleum Board
COGR	Canada Oil and Gas Regulations
DCF	Dawson Canyon Formation
DHI	Direct Hydrocarbon Indicator
EA	Egret Anomaly
ECMA	East Coast Magnetic Anomaly
EOB	East Orphan Basin
ESE	East Southeast
FB	Fundy Basin
GSC	Geological Survey of Canada
GSI	Geophysical Services Incorporated
IODP	Integrated Ocean Drilling Program
JDB	Jeanne d'Arc Basin
KA	1000 years
KT	Cretaceous Tertiary boundary
LAS	Log ASCII Standard
LOU	Late Oligocene Unconformity
MB	Magdalen Basin
MMU	Mid Miocene Unconformity
My	Million years
NE	Northeast
NS	Newfoundland Seamounts
NW	Northwest
OG	Orpheus Graben
SB	Sydney Basin
SE	Southeast
SPM	St. Pierre and Miquelon
SSB	Sable Subbasin
SWB	South Whale Basin
Tcf	Trillion Cubic Feet
TMI	Total Magnetic Intensity
USGS	United States Geological Survey
WNW	West Northwest
WOB	West Orphan Basin

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Terminology

The Laurentian "Basin" is formally a sub-basin of the Scotian Basin. However, in many publications, and in the common parlance in the province of Newfoundland & Labrador, it is more regularly referred to as the "Laurentian Basin". The convention of referring to it as the "Laurentian Basin" is followed in this text, and the same can be said for the Whale and South Whale "Basins" which are also formally considered to be sub-basins of the Scotian Basin.

An additional convention followed in this text, is that where information (such as a formation top in a well) has been reported as questionable by the source of that information, it will be quoted followed by a bracketed question mark. For example: Iroquois(?).

Dedication

This work is dedicated to the memory of my mother, Mildred Fagan, who passed away on May 13, 2008. Her belief in the intrinsic and essential value of education as a source of well being for the individual and the community continues to exert a powerful influence on the lives of her children.

Chapter 1
Introduction

1.1 An Unexplored Basin

The Laurentian Basin lies on the continental shelf and slope directly south of the island of Newfoundland (Figure 1.1), in water depths ranging from about 100 m on the shelf to 450 m in the Laurentian Channel and to about 3000 m on the lower continental slope. Although the basin boundaries are not clearly defined by geographical or geological features, it can generally be described as being located at an "elbow" of the Atlantic rifted margin, where the continental shelf switches from a northeasterly to a southeasterly strike direction. The basin is contained within a broader depocentre known as the Scotian Basin that extends from the Yarmouth Arch to the southwest to the Avalon Uplift to the east. (Figures 1.4, 2.1 and 2.7). Although the area is judged to have significant oil and gas potential (Maclean and Wade 1992), Laurentian Basin is perhaps best differentiated from the adjacent basins along the Scotian Shelf and Southern Grand Banks by its lack of exploratory drilling and published geoscience papers. As seen in Figure 1.1, only four wells have been drilled in or near the approximately 87,000 km^2 study area, despite the fact that large oil and gas reserves have been discovered in similar age rocks on the Grand Banks to the east and the Scotian Shelf to the west. The conspicuous gap in the drilling pattern seen in Figure 1.1 is best explained by politics rather than geology, as this area has been subject to a drilling moratorium that has only recently been lifted. The moratorium arose from a dispute between the nations of Canada and

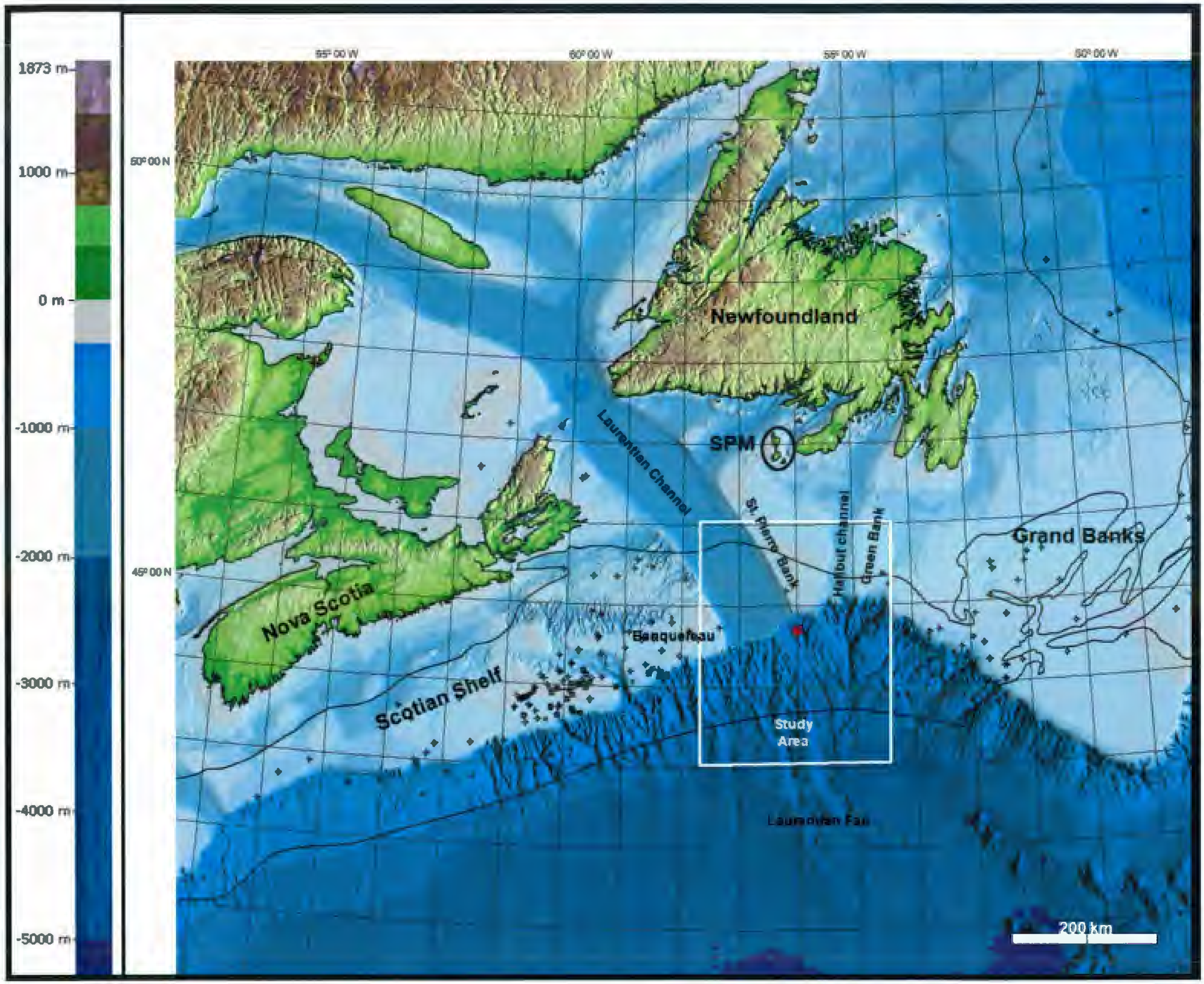


Figure 1.1

Bathymetry map showing the study area (white box) with bathymetric features and well locations. Outlines of sedimentary basins are shown by black lines. The epicentre of the 1929 earthquake is indicated by a red star. The French islands of St. Pierre and Miquelon (SPM) are circled. Modified after the Geological Survey of Canada and the Canadian Hydrographic Service.

France regarding the marine territorial boundary of the French islands of St. Pierre and Miquelon located just to the north of the study area (Figure 1.1).

The Territorial Collectivity of St. Pierre and Miquelon is an archipelago of eight small Islands lying about 25 km south of the island of Newfoundland that are the only North American remnant of the former colonial territory of France (Wikipedia: http://en.wikipedia.org/wiki/St._Pierre_and_Miquelon). The islands were awarded to France by the 1763 Treaty of Paris at the close of the Seven Years War, and are today home to about 6000 French citizens who make their living mostly from fishing and tourism. Although harmonious relations with the islands have generally prevailed in modern times, a point of contention arose with the development of new rules around the exploitation of resources on and below the seabed. When the 1958 *Geneva Convention on the Law of the Sea* recognized the exclusive right of coastal nations to "exploit the seabed and subsoil to a water depth of 200 m" or "limit of exploitability" (effectively the outer edge of the continental margin), countries around the world including Canada and France began to position themselves for maximum benefit from the new arrangement. Given that offshore petroleum drilling "outside the sight of land" had been ongoing in the Gulf of Mexico since 1947 (National Ocean Industries Association website: http://jobfunctions.bnet.com/abstract.aspx?docid=103577), an obvious first step into this new jurisdictional domain was to issue exploratory rights for oil and gas beneath the seabed. The newly proclaimed Canada Oil and Gas Regulations (COGR) provided the legal instrument for the issuance of offshore "exploratory permits" which included the exclusive right to drill for petroleum and the non-exclusive right to conduct geophysical operations (Allen, 1992). Under the original version of the COGR the federal Ministry of Energy, Mines and Resources permitted large tracts of land throughout offshore Atlantic Canada in the mid 1960s, on a "first come first served" basis. Of particular importance in regard to the study area were the permits issued to companies in adjacent basins to the east and west, leading to aggressive seismic and drilling programs in the 1960s and 70s by which the regional geology of the area came to be defined. Mobil and Shell led the way on the Scotian Shelf and a consortium headed by Amoco Canada (called Pan American Petroleum at the time) were the key players on the southern Grand Banks.

Notwithstanding questions surrounding the boundary, France asserted its jurisdictional ambitions in 1966 by issuing "Prospecting Permits" to Petropar in the Laurentian Basin, which were later transferred to Elf-Aquitaine (now TOTAL). Canada revised its regulations the following year to a public tendering permitting system and invited bids for permit blocks in the area. Gulf Canada (called the British American Petroleum Company at the time) was the winning bidder, and Mobil Canada also acquired rights in the basin by filing under the old permitting system one day after the closing of the 1967 public tender. The final permit issued in the basin by Canada during this period of unresolved boundaries was a relatively small block directly south of the French permits that went to Texaco Exploration Canada in 1971 (Allen, 1992).

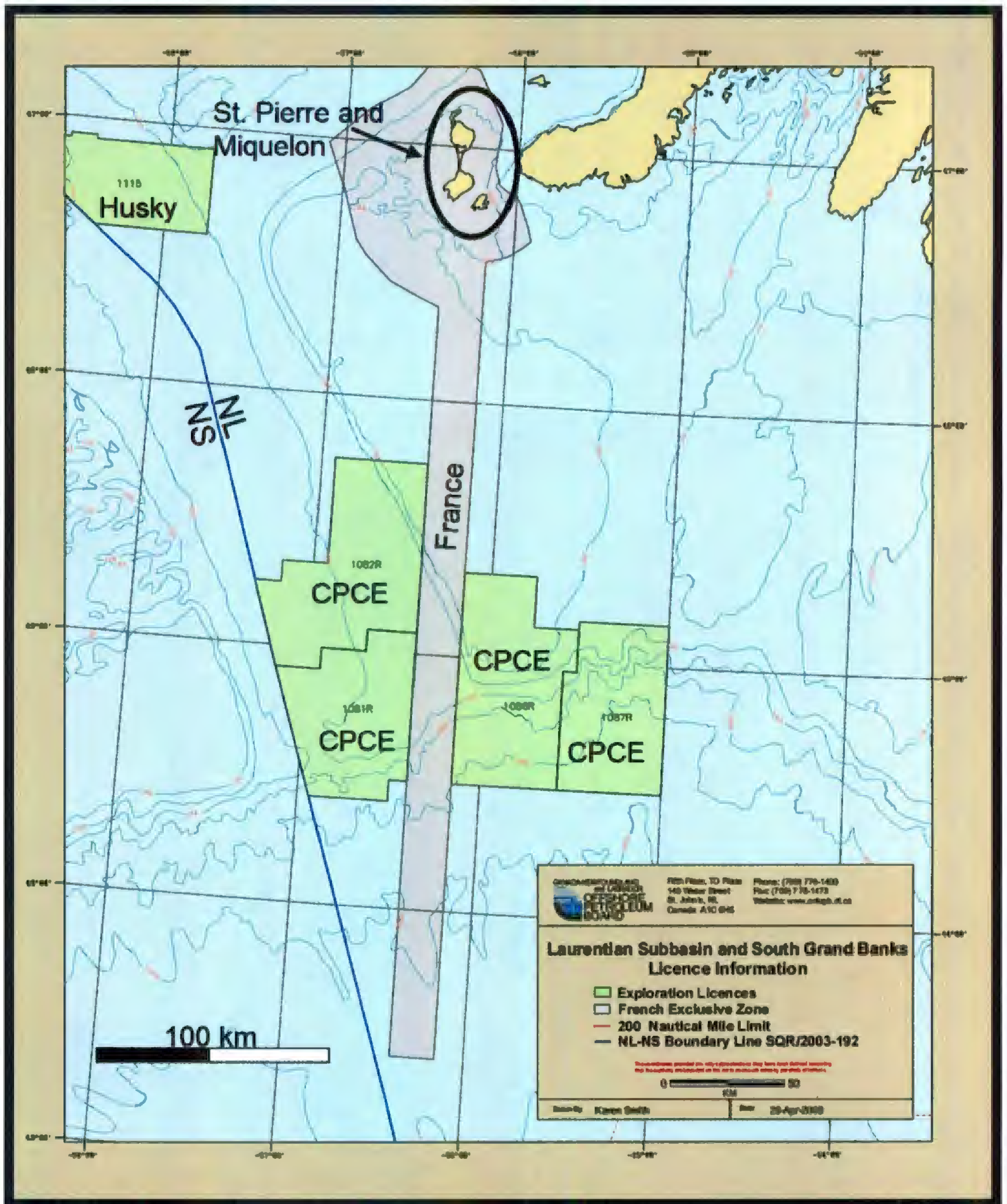


Figure 1.2

Bathymetry and Exploration Licences (2009) of the Laurentian Basin and environs. The French territory is shown in grey and the inter-provincial boundary is shown as a blue line. The Husky Oil Operations licence in the nearby Sydney Basin is also shown. Acronyms: NL (Newfoundland and Labrador), NS (Nova Scotia), CPCE (ConocoPhillips Canada East). Murphy Oil Canada Ltd. and BHP are partners in the CPCE licences. Modified from Canada-Newfoundland and Labrador Offshore Petroleum Board website: http://www.cnlopb.nl.ca/maps/sgb_2009.pdf.

Having tried to establish sovereignty in the area by unilateral issuance of petroleum permits the two countries agreed to curtail exploration in the disputed area until a boundary could be established. After several unsuccessful attempts to resolve the issue by negotiation the said boundary was ultimately decided by the International Court of Arbitration in 1992. By this time the government of Canada had signed individual agreements ("Accords") with the provinces of Nova Scotia and Newfoundland & Labrador that allowed for joint management of offshore oil and gas activities on their adjacent offshore areas, as well as for the collection of production royalties by the provinces. The resolution of the Canada-France dispute opened the door for the definition of an interprovincial boundary, between the neighbouring provinces, which was resolved by arbitration in 2002. This was followed by a renegotiation of the long dormant Canadian "exploratory permits" to convert them to Exploration Licences under the current legislation, which was concluded in May 2004. After farmins, company buyouts and mergers that have occurred over the years the current licences in Canadian territory are held by ConocoPhillips with partners Murphy Oil Canada Ltd and BHP (Figure 1.2).

1.2 1929 Earthquake and Tsunami

Laurentian Basin is of interest for geological reasons that go beyond its significant oil and gas potential. In 1929, a magnitude 7.2 earthquake off the south coast of Newfoundland triggered a massive sediment slide / turbidity current with a resultant tsunami that did severe damage to communities on the Burin Peninsula, and claimed 28 lives (Ruffman, 2005). The hypocentre of the quake lies at a depth of 20 km (Dewey and Gordon, 1984; Piper et al., 1985; and GSC website: http://earthquakescanada.nrcan.gc.ca/histor/20th-eme/1929/1929-eng.php), at a location close to the geographic centre of the study area (44.69°N, 56.00°W; See Figure1.1). One of the goals in reviewing the seismic data in this study is to look for evidence of recent faulting and to recognize areas of mass transport on the continental slope. Piper et al. (1985) used sidescan sonar and drill cores to measure the size of the slump. They estimated that some 185 km^3 of sediment were displaced in this event - enough to cover the entire island of Newfoundland to a depth of 1.7 m! This material was mostly sand, and is postulated to have accumulated pro-glacially during the Wisconsinian glaciation, and to have failed through liquefaction in response to the earthquake (Piper and Aksu, 1987). The earthquake hypocentre lies near the point of convergence of two major fault systems (Newfoundland Fracture Zone and Cobequid – Chedabucto Fault: see Figure 1.4). Its 20 km depth would place it near the base of the sedimentary section as indicated by the Geological Survey of Canada's Depth to Basement Map (Grant, 1988) - likely within but near the top of basement.

One of the significant events associated with the turbidite (Figure 1.3) is that as it advanced down the continental slope it ruptured some 12 trans-Atlantic

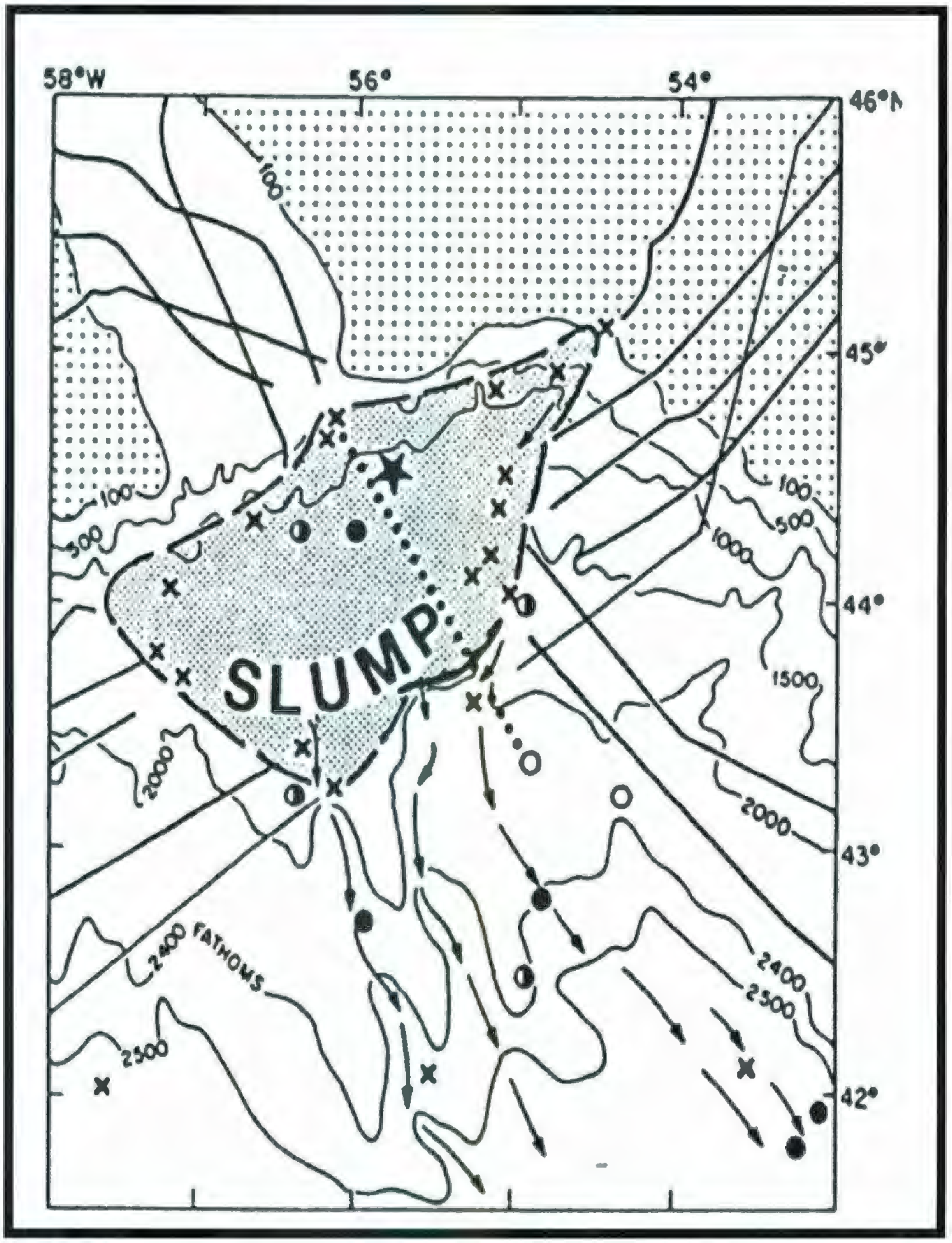


Figure 1.3

Map showing the location of the 1929 "slump" as estimated by Doxsee (1948) along with the locations of several transatlantic cables. The epicentre of the 1929 Grand Banks earthquake is indicated by a star, the circles represent coring locations and the arrows represent the direction of turbidity currents. The locations of cable breakages are shown by "x"s. Four additional cables were broken outside the map area. Map from Hasegawa and Kanamori (1987) in Ruffman (1996). Originally published in Heezen and Drake (1964).

communications cables (Doxsee, 1948; Ruffman, 1996) over a period of thirteen hours, with the distance between the first and last being some 885 km! (Louisiana State University Website: www.geol.lsu.edu/Faculty/Juan/PhysicalGeology_F2004/images/liquefaction). This series of unfortunate events for the cable owners provided critical data on the dynamics of underwater "landslides" which allowed the "Grand Banks slide" to be both the very first identified and first defined "turbidity current" (Ruffman, 2005). Ruffman (1996) prepared a study of the tsunami for Emergency Preparedness Canada, which is available online at:

http://dsp-psd.pwgsc.gc.ca/Collection/D82-41-1-1996E.pdf

Some of Ruffman's observations and conclusions, along with selected quotes from witnesses are repeated below.

The earthquake occurred at 17:02 Newfoundland Standard Time and tremors were felt throughout the island of Newfoundland, as far west as Ottawa and as far south as Delaware (Doxsee, 1948 quoted in Ruffman, 1996). At about 19:30 residents of several communities on Newfoundland's Burin Peninsula noticed the sea retreating to levels never before witnessed. Ruffman reports of several witnesses indicating that the harbours "went dry", and one Douglas Hillier at Point au Gaul is quoted as follows:

"When it was finally over the water (tide) in the cove went out around 5,000 feet, the lowest it had ever gone. . ."

The initial retreat was followed by three main pulses spread over a time of about one half an hour. In an interview published in the November 25, 1929 issue of the St. John's newspaper "The Telegram", Mr. Adolph Giovannini, described the event as he witnessed it in the community of St. Lawrence:

". . . it was a clear moonlight night when the disaster occurred. The tidal waves could be seen very clearly, and on receding out the harbour to meet an oncoming one, the water would rise thirty to forty feet in height, and with the roar of the water and the cracking of timber, the spectacle was terrifying."

These waves travelled the 343 km to the southern margin of the Burin Peninsula in 2 hours 23 minutes – an average speed of 144 km/hr. The same waves on the open ocean covered the 1444 km to Bermuda in 2 hours 58 minutes – an average speed of 488 km/hr. Ruffman estimates that the tsunami waves that crossed the continental shelf and struck the south coast of Newfoundland had a wavelength of 20 km and a period of about ten minutes. Water levels rose from 2 to 7 m and as high as 27 m at the heads of long narrow bays. Judging from Mr. Giovanni's description it would appear that each run-up was followed by a significant retreat as the next wave approached. Another witness, Mr. Lou Etchegary, who was eight years old at the time recalls: *"a wall of foaming water lit up by the moon"*. From this and the testimony of other witnesses, Ruffman concludes that at least one of the three main waves broke and advanced onto the land as a "foaming white wall of water".

These were indeed momentous and unusual events in the normally peaceful coves of Newfoundland, and there are many alive on the island today that remember exactly what they were doing on the evening of November 18, 1929. But the cause of these events was not entirely clear at the time. Ruffman (1996) notes that although there were a few scientific articles published immediately after, it wasn't until the publication of Doxsee's paper in 1948 that the broader geoscience community took serious interest in the event. Doxsee's publication was followed by a series of papers from Columbia University researchers (Ericson et al., 1952; Heezen and Ewing, 1952; Kuenen, 1952; Heezen et al., 1954; Kullenberg, 1954; Shepard, 1954; Heezen and Drake, 1964; Sen Gupta, 1964; Fruth, 1965) that had come to understand the significance of the cable breaks and from there developed the model that defined the origin and characteristics of "turbidity currents". The event was revisited by Murty and Wigen (1976), Dewey (1977), Dewey and Gordon (1984), Hasegawa and Kanamori (1987), Hasegawa and Herrmann (1989), and by researchers at the Geological Survey of Canada, including Piper et al (1985), Piper and Aksu (1987), and Bent (1994, 1995).

Bent (1994, 1995) used archival seismograms as input to a waveform model to show that the 1929 Laurentian Basin event was a tectonic earthquake, and was not caused by the landslide, as had been previously suggested by Hasegawa and Kanamori (1987). She further concludes that the recorded seismograms indicate that there was in fact more than one event, and that:

"... *the first and largest subevent was a strike-slip double-couple event occurring on a northwest-striking plane. Two later subevents were probably strike-slip double couples on northeast-striking planes, but other mechanisms cannot be completely ruled out.*"

Therefore, it would appear that what happened that day in the Laurentian Basin was an earthquake caused by strike slip movement on a northwest trending fault which then triggered two subevents on a northeast striking fault. This, in turn triggered a massive slump and turbidity current with associated tsunami. My seismic interpretation in this study attempts to map some of these strike-slip faults and explain their role in the evolution of the Laurentian Basin.

1.3 Major Strike Slip Faults

The events described in section 1.2 are not only interesting in terms of their historical significance to the people of Newfoundland, but also provide important clues to the area's structural geology. Regional geological studies and potential field data indicate that two major strike slip faults merge in the north central area of the Laurentian Basin (Figure 1.4). The Cobequid-Chedabucto Fault which represents the Paleozoic suture between the Avalon and Meguma Terranes (Williams, 1995) runs westward some 600 km from the study area to the Bay of Fundy. Its eastward extension (or a major imbricate?) can also be traced as the gravity/mag "Collector Anomaly" for 400 km across the southern Grand Banks (Haworth, 1975; Williams, 1995). Moving further eastward onto the abyssal plain

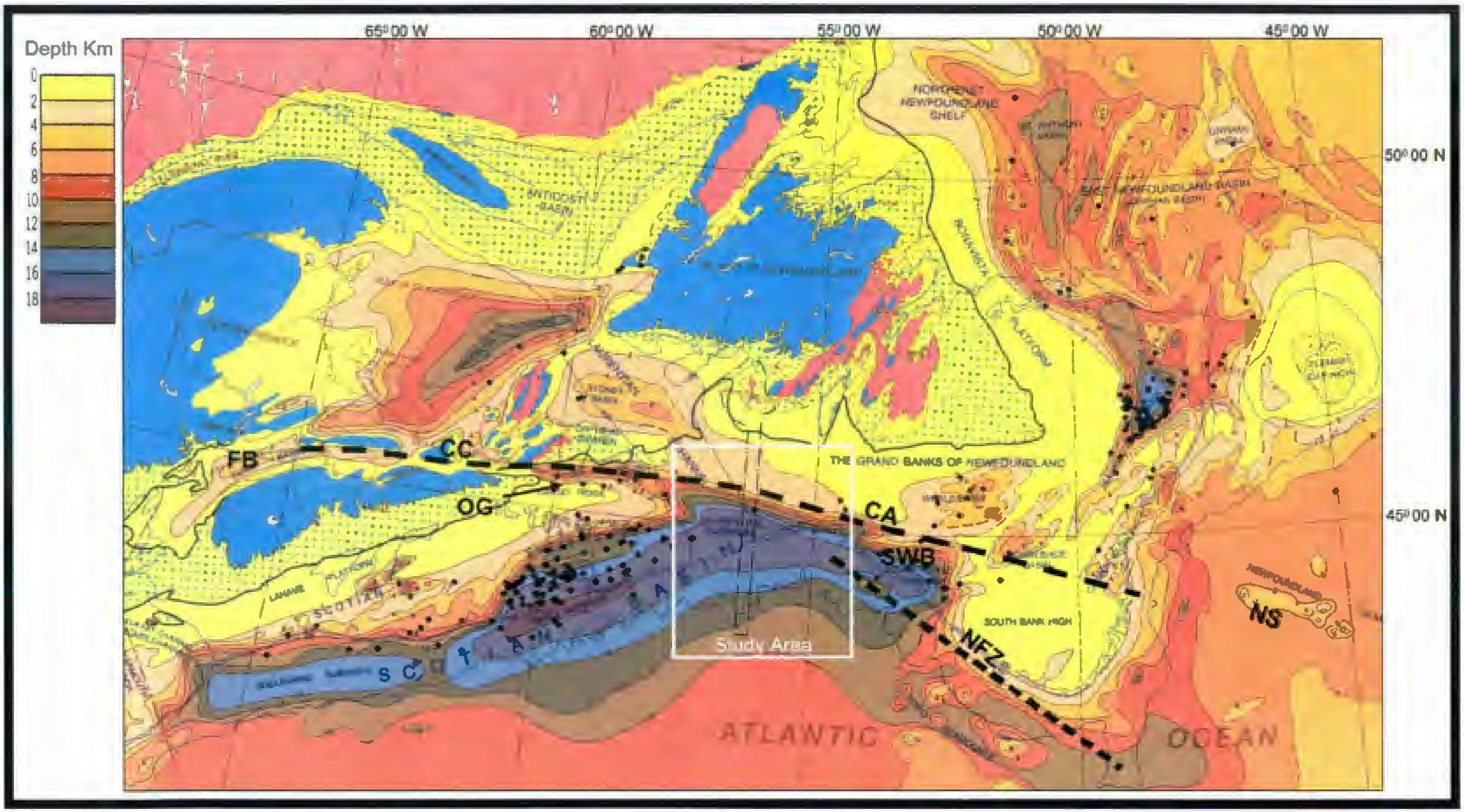


Figure 1.4

Depth to Basement Map with well locations and selected tectonic and structural elements and exploration wells. Major strike slip faults that are recognized to have affected the Laurentian Basin include the Cobequid – Chedabucto Fault and the Newfoundland Fracture Zone. Acronyms: FB (Fundy Basin), CC (Cobequid-Chedabucto), OG (Orpheus Graben), SWB (South Whale Basin), NFZ (Newfoundland Fracture Zone) and NS (Newfoundland Seamounts). Modified after the Geological Survey of Canada's Depth to Basement Map downloaded from Natural Resources Canada website: http://apps1.gdr.nrcan.gc.ca/mirage/db_results_e.php. Reference: Grant (1988).

the trend is continued through the Newfoundland Seamounts indicating possible reactivations along this zone of weakness after the start of seafloor spreading to the east of the Grand Banks. A second strike slip fault, the Newfoundland Fracture Zone, runs roughly southeast from the Laurentian Basin along the shelf edge and corresponds to the southern transform margin of the Grand Banks. Right lateral movement along this fault (Auzende et al., 1970; Grant and McAlpine, 1990) is postulated to have accommodated a delay of roughly 55 million years between the time when seafloor spreading began off Nova Scotia (Pleinsbachian) to when it stepped to the east of the failed rifts on the Grand Banks (Valanginian) (Sinclair 1988, Gradstein et al, 2004). It follows from this reasoning that the failed rift basins of the Grand Banks which are now offset from the Scotian Shelf by 200 to 250 km were once laying directly on trend at the start of rifting in the Late Triassic. One of the goals of this study is to look for the effects of the strike slip movement on these faults in various stages of the basin's evolution, and in this regard to investigate the relationship between the Mesozoic extensional rifting and the structural fabric of the underlying Paleozoic terranes. More detail on the regional structure and stratigraphy is provided in Chapter Two.

1.4 Previous Work

The marine geology of eastern Canada was first studied in the seventeenth century when seamen measured water depths and collected bottom samples to aid in locating suitable anchorage and harbour sites. Serious geographic mapping was pursued in the eighteenth century, with the most notable among

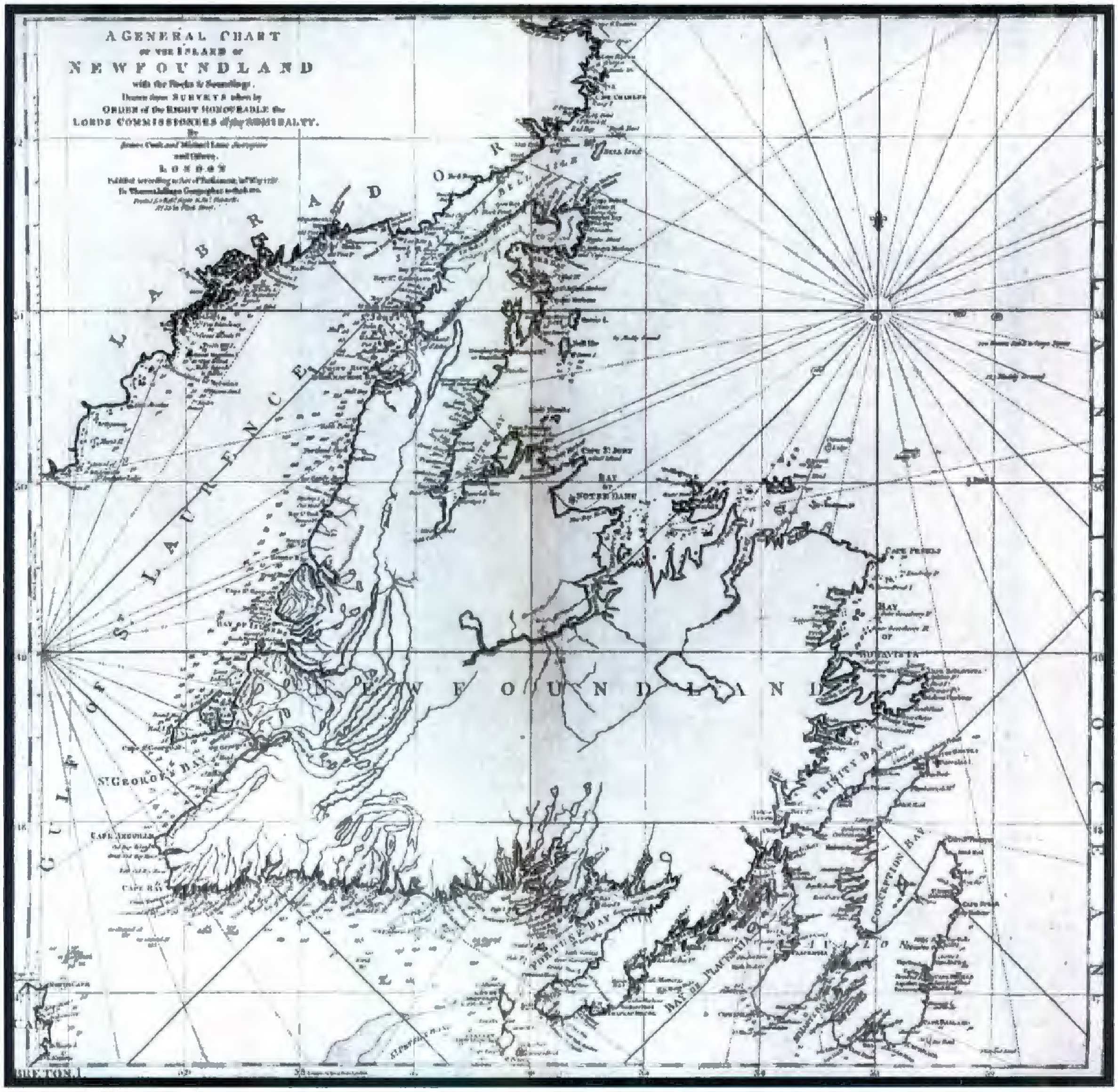


Figure 1.5

Newfoundland Map by Captain James Cook. The title reads: "A General Chart of the Island of Newfoundland with Rocks and Soundings. Drawn From Surveys Taken. Published May 10, 1775. (Wikipedia: http://en.wikipedia.org/wiki/Captain_James_Cook) these explorer scientists being Captain James Cook, who produced the first reasonably accurate map of the island of Newfoundland in 1775 (Figure 1.5; source Wikipedia: http://en.wikipedia.org/wiki/Captain_James_Cook). Sherwin's 1973 paper, which integrated the available well and seismic data to present a regional picture of the Grand Banks – Scotian Shelf geology, also provided a detailed summary of the offshore geoscientific research that had occurred in the area up to that time. He indicates that the first true geological research in the Atlantic Canada offshore area occurred in 1878 when the US Fish Commission at Gloucester Massachusetts asked fishermen to collect samples of rocks brought up with their trawls. Even at this early stage geologists were able to identify microfossils from samples collected from the Grand Banks and Georges Bank as being of Tertiary age, and from this to conclude that extensive areas along the submerged Atlantic coastal plain had Tertiary bedrock.

More directed dredge hauls and samplings of ledge outcroppings were carried out by the Woods Hole Oceanographic Institute in the 1930s in Georges Bank canyons, confirming the presence of both Cretaceous and Tertiary sediments. The first geophysical work was a refraction seismic survey across the Georges Bank, Scotian Basin and Grand Banks, carried out in 1948 under the direction of Maurice Ewing of the Lamont Geological Observatory. Additionally, regional refraction surveys, aeromagnetic surveys and gravity surveys were carried out by both Canadian and American research institutions, throughout the 1950s and 60s. American contributions were provided by workers from the Lamont

Geological Observatory, the U.S. Geological Survey, the U.S. Navy Hydrographic Service and the Woods Hole Oceanographic Institute. Canada's efforts to map the margin began in 1955 when the Ottawa based Dominion Observatory joined forces with the Nova Scotia Research Foundation to acquire aeromagnetic and refraction surveys. In 1958 the Geological Survey of Canada (GSC) began collecting refraction and magnetometer data. In 1962 the Bedford Institute of Oceanography (BIO) was established in Dartmouth, Nova Scotia, and within a short time evolved to take the lead in carrying out Canada's earth science research in the region. The earth science group at the BIO (which was rolled back into the GSC as the "Atlantic Geoscience Centre" in 1971) carried out detailed bathymetric studies, dredge and coring programs, gravity and magnetic surveys, shallow seismic (echo sounder) and seismic refraction surveys on the Scotian Shelf and Grand Banks throughout the 1960s, and thereby significantly increased the knowledge of the area's geology. Other contributions at this time came from Dalhousie University (with the Nova Scotia Research Foundation) which carried out refraction surveys on the Scotian Shelf, slope and rise, and from aqualung divers at Memorial University who collected outcrop samples from shoals on the Grand Banks.

By the late 1950s it was abundantly clear from the work by the various government agencies that a thick sequence of Mesozoic – Cenozoic sedimentary rocks was present across the Atlantic Canada shelf – a fact that did not go unnoticed by the petroleum industry. The first industry marine seismic reflection surveys began in the early 1960s with Amoco and partner Imperial as key players on the Grand Banks, and Shell and Mobil exploring the Scotian Shelf. A computer search by the C-NLOPB for geological / geophysical surveys carried out in the latitude longitude limits of the study area indicated 53 industry reports had been filed between 1964 and 2003 that "touched" or overlapped the area. A visit to C-NLOPB data library revealed that most of these reports involved reflection seismic surveys (often supplemented by gravity and magnetic data) carried out in adjacent areas (particularly the South Whale Basin), including both detailed prospect level grids and regional reconnaissance work using widely spaced lines. Older programs that included significant amounts of data reaching into the study area included: Elf's 1970 and 1971 "Green Bank" reports; Petro-Canada's 1981 "Laurentian Cone" survey and the 1982 "Emerillon - Grand Banks" reports. Key reports relating to the Southern Grand Banks basins to the east of the study area included: Amoco's 1973 "North and South Grand Banks" report; Northcor's 1983 and 1984 South Whale Basin Reports (filed in 1985); and Petro-Canada's 1981 and 1983 South Whale Basin Reports. A similar search carried out by the Canada-Nova Scotia Offshore Petroleum Board (C-NSOPB) indicated 24 industry reports that had some overlap with the Banquereau Bank on the western margin of the study area. A visit to the C-NSOPB data library proved that, as expected, most of this work involved reflection seismic supplemented by gravity and magnetic data, which was integrated with well information. Some of the key reports included those submitted for Petro-Canada's 1982 Banquereau and East Banquereau surveys and Soquip's 1983 and 1985 Banquereau reports. A complete listing of the search results from the two boards is provided in Appendix A.

The GSC acquired 3072 km of reflection seismic data over two field seasons (1984 and 1987) which provided the first continuous reflection seismic grid between the southern Grand Banks and the Scotian Shelf (Maclean and Wade, 1992). These data were collected to allow a geological assessment of what might be at stake in the still unresolved boundary dispute. France too is reputed to have sent a geophysical vessel into the area in the mid 1980s, to carry out its own assessment (David Hawkins, pers comm.) After the resolution of the boundary in 1992, MacLean and Wade published their interpretation of the data acquired in 1984 and 1987. Their 1992 paper provided a detailed discussion of the basin's structure, stratigraphy and petroleum potential, and is at present the only comprehensive study of the Laurentian Basin that exists in the public domain – and as such it is also a key reference for this study. A reprocessed version of the 3072 km of 2D reflection seismic data used by MacLean and Wade (1992) is also the core dataset for this study. The most recent industry work in the Laurentian Basin proper includes 2D and 3D seismic carried out by past and current licence holders. Gulf Canada (now ConocoPhillips) acquired 3495 km of 2D seismic on the eastern side of the basin in 2001. These data are now released by the C-NLOPB, but being available only in hardcopy were not employed in this study, which was carried out on a digital dataset using a Landmark workstation. ConocoPhillips acquired an additional 3314 km of 2D seismic in 2004 along with 90,319 cmp km of 3D seismic in 2005 on its Laurentian Basin licences. None of these recently acquired data have been used directly in this study, but ConocoPhillips was kind enough to allow the author to spend a week viewing their 2D seismic data at their office in Calgary. More detail will be provided on the dataset utilized in this study in Chapter Three. The regional geology of the Grand Banks and Scotian Shelf, covering portions of the Laurentian Basin, has been presented in several key papers originating from the Geological Survey of Canada, academia and the petroleum industry, and will be discussed at length in Chapter Two.

1.5 Objectives

The paucity of exploration drilling and very limited published research means that the Laurentian Basin presents a knowledge gap between the more explored areas of the Scotian Shelf and Southern Grand Banks. The shortage of well data, also means that we will have to rely primarily on geophysical data to correlate the geology to the adjacent basins. The primary objective of this study is to investigate the structure and gross stratigraphy of the Laurentian Basin and thereby improve our understanding of how this area fits into the geomorphology and the geodynamic evolution of the region. The fact that the GSC's seismic dataset has been improved by reprocessing and that additional seismic data and high resolution magnetic data have been made accessible by the private sector companies, allows the author to build upon the work of previous researchers. Structural maps will be constructed on key seismic horizons which will shed light on geomorphology of the basin at various points in its history. Seismic cross-sections will be prepared to provide an understanding of the stratigraphic and tectonic framework. The combination of maps and cross-sections will allow comments to be made and conclusions to be drawn about the evolution of the basin and how this evolution has been influenced by the pre-existing basement fabric in general, and the Cobequid-Chedabucto and Newfoundland Fracture Zone fault systems in particular.

Although it is not the intent of this study to map petroleum prospects or to do a resource assessment, the detailed interpretation of the seismic data will inherently allow for observations concerning the possible presence of commercial hydrocarbons. In this regard, features of interest relating to the basin's general petroleum system will be noted and discussed.

Given that a major earthquake has occurred in the basin within modern times, an additional objective will be to look for geophysical evidence of recent tectonic activity.

Chapter 2
Regional Geology

2.1 Structural Regime

Laurentian Basin is one subdivision of a large Mesozoic sedimentary depocentre known as the Scotian Basin that extends from the Yarmouth Arch on the southwest margin of the Scotian shelf to the Avalon Uplift on the southwest margin of the Grand Banks of Newfoundland (Figures 1.4, 2.1 and 2.7).

The basin can essentially be divided into two distinct zones separated by the Cobequid – Chedabucto Fault (CC Fault). The CC Fault was a critical element in the development of the basin, and marks the location of a hinge line separating a thin Mesozoic section to the north from a dramatically thickened section to the south (MacLean and Wade, 1992). This fault / hinge line which evolved along a pre-existing Paleozoic suture between the Meguma and Avalon Terranes (Williams, 1978 and 1995; Bell and Howie, 1990), in effect represents the northern boundary of the Mesozoic Laurentian Basin (MacLean and Wade, 1992). Movement along this and related mega-shears during the Frasnian to Westphalian led to the creation of a series of Carboniferous aged basins that are preserved throughout Atlantic Canada today (Bell and Howie, 1990, Langdon and Hall 1994), including the Sydney and Magdalen basins (Figure 2.1). The southeast extension of the Carboniferous Sydney Basin forms part of the pre-rift "basement" of the Laurentian Basin. The pre-rift sequences were overlain by

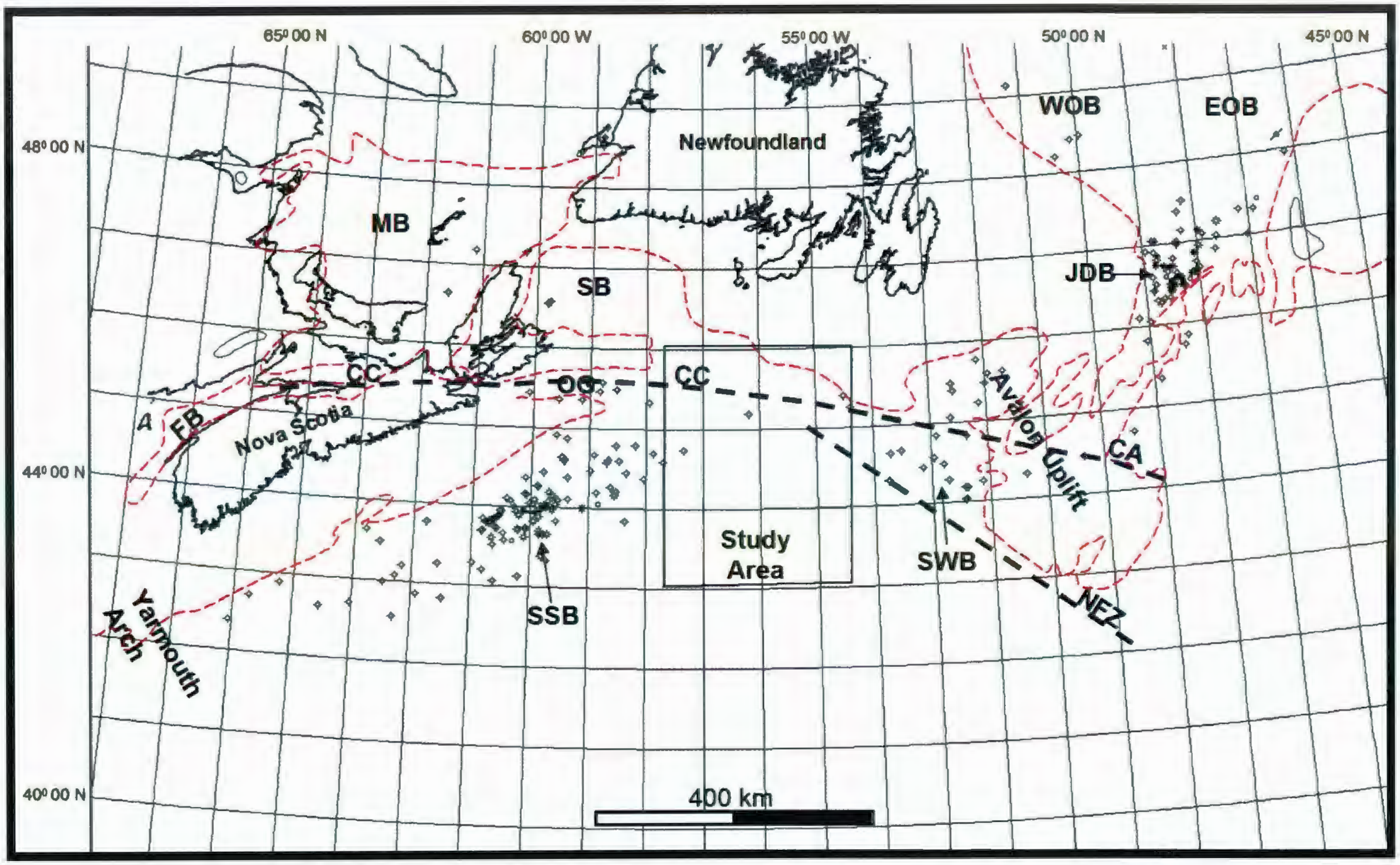


Figure 2.1

Regional map indicating basin outlines (red dashed lines) as defined by the 4000 m depth to basement contour, relevant tectonic elements and well locations. Acronyms include: FB (Fundy Basin); CC (Cobequid-Chedabucto Fault); MB (Magdalen Basin); OG (Orpheus Graben); SB (Sydney Basin) SSB (Sable Sub-Basin); SWB (South Whale Basin); NFZ (Newfoundland Fracture Zone); CA (Collector Anomaly); JDB (Jeanne d'Arc Basin); WOB (West Orphan Basin); EOB (East Orphan Basin); and CB (Carson - Bonnition Basin). Modified after Geological Survey of Canada's Depth to Basement Map (Grant, 1988).

Mesozoic-Cenozoic sedimentary fill during the subsequent break-up of Pangea and opening of the Atlantic Ocean.

During the late Paleozoic, right lateral strike slip movement occurred along the CC fault as the Meguma terrane arrived from the southeast and collided with the already docked Avalon terrane. Its direction of movement was reversed at the start of Scotian Shelf rifting in the Late Triassic (Keppie, 1982; Tankard and Welsink, 1989). The ensuing left lateral movement along the fault opened up the Fundy Basin and created the Orpheus Graben which extends into the northwest corner of the Laurentian Basin. On pure geometry alone it appears that the large Scotian Shelf block lying south of the CC Fault can be restored to the west and fit neatly against the far side of the Fundy Basin. On this basis one can anticipate that there would have been significant compressional and shear stresses projected into the western side of the study area during the Late Triassic – Early Jurassic synrift phase, as this large block pressed into the basin from the west.

Although the original (Tethys) rift can be traced from the Scotian Shelf to the East Orphan Basin (Enachescu, 1987; Enachescu et al., 2005) the start of seafloor spreading did not begin "simultaneously" along the entire rift, but proceeded in a series of pulses advancing generally from the south to the north. Recognizing that rifts are likely to advance through many smaller less noticeable and disparate tectonic events, there are four major tectonic episodes noted in the literature regarding the development of the Atlantic Canada Mesozoic basins.

The first of these major episodes relates to the break-up and separation of Nova Scotia from Morocco, the next two to the separation of the Grand Banks from Southern and then Northern Europe, and the fourth marks the separation of Labrador from Greenland (Enachescu, 1987; Tankard and Welsink, 1989). These major episodes are observed to be associated with "break-up" unconformities. Therefore the said break-up unconformity, by definition, marks the boundary between synrift and postrift sedimentary sequences. In the research carried out for this study the author was unable to find a definitive explanation for the break-up unconformity. Withjack et al. (1998) proposes incipient ridge push combined with an initial continental resistance to plate motion as one possibility. An alternative hypothesis is presented here based on the results of ODP drilling results on the Iberian abyssal plain (site 1070) and the Newfoundland Basin (site 1277). Sibuet et al. (2007) indicate that both these drill holes encountered transitional crust that is interpreted to be exhumed mantle. Accepting that the mantle is exhumed prior to break-up and comes in contact with water, it would undergo rapid cooling and subsidence landward of the rising spreading centre. Subsidence would occur along a line running parallel to rift axis causing an upward flexural bulge on either side. The seaward bulge undergoes constructive interference with the rising spreading centre, accentuating the crustal flexure. The landward flexure results in uplift and erosion of the adjacent continental crust, recorded in the sedimentary sequence as a "break-up unconformity". When basalt comes in contact with water at the start of sea floor spreading, rapid cooling begins anew and the basin tilts seaward. Seismic data used in this study do indeed show evidence of seaward tilting of the basin following the start of seafloor spreading. Seaward tilting at this stage may result in a second flexural bulge that migrates landward across the shelf with resultant erosion. This hypothesis could also explain why the "Avalon Uplift" (Figure 2.1) on the southeastern Grand Banks experienced additional uplift in comparison to the surrounding areas. Being located on a "corner" where the spreading vector changed direction from southeast to northeast, it would have been affected by two partially overlapping crustal flexures. Other considerations as to whether the transition from rifting to spreading is accompanied by uplift would relate to the specifics of the particular rift including: whether it is actively or passively driven; local stresses associated with plate geometry; and relative motion between mircoplates.

Using the break-up unconformities, and where possible age dating of oceanic crust and of volcanics believed to have been triggered by the "break-up" process as time markers, it is reasoned that seafloor spreading off Nova Scotia began in the Pleinsbachian about 190 million years ago, but did not begin on the Grand Banks until the Valanginian about 55 million years later (Jansa and Wade, 1975b; McWhae, 1981, Enachescu, 1987; Sinclair, 1988; Wade and MacLean, 1990). This means that the Moroccan and Scotian Shelves would have been steadily moving apart for 55 million years with new oceanic crust filling the in-between space, while the Grand Banks remained attached to Europe. Even with

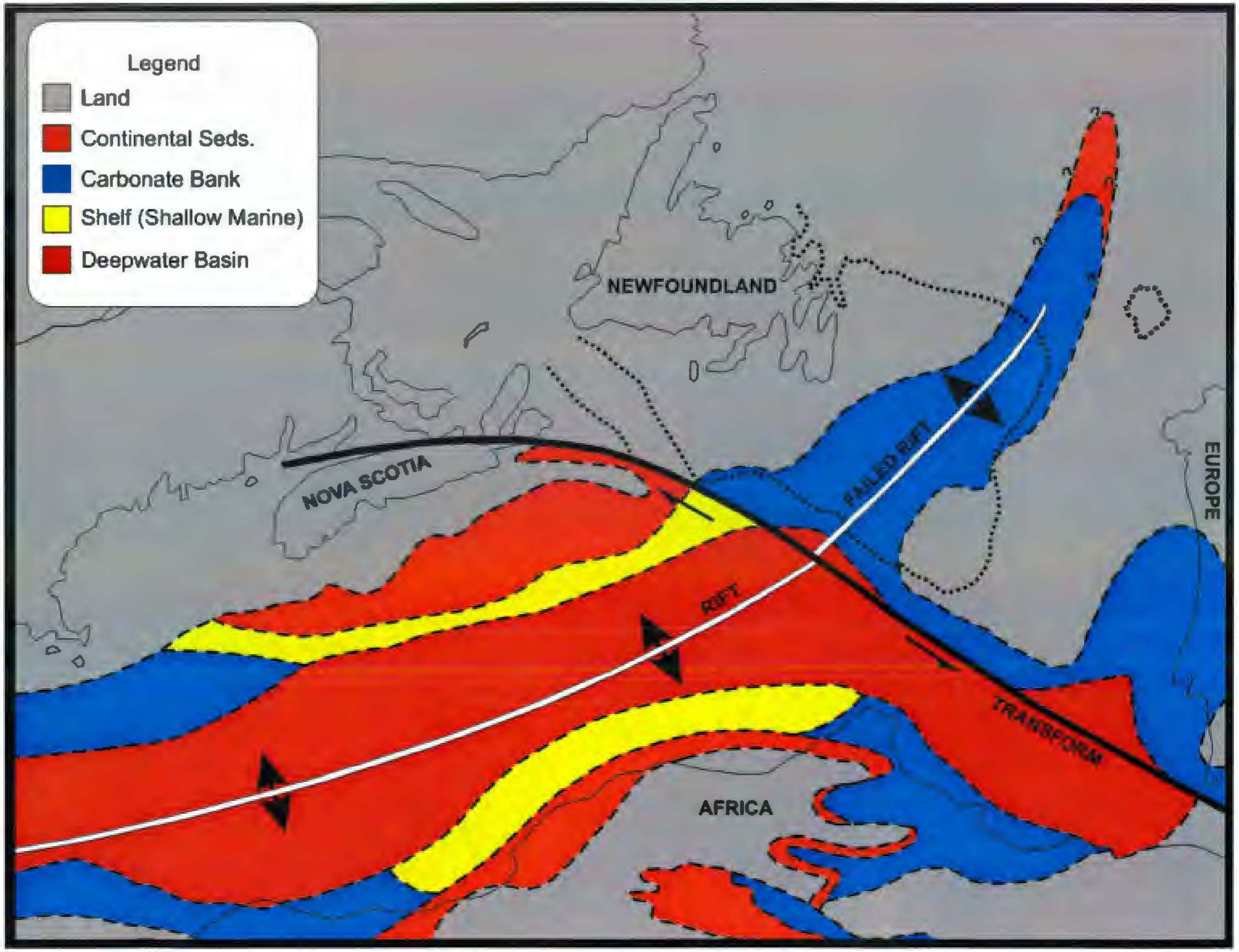


Figure 2.2

Schematic of Mid-Jurassic tectonic / depositional environment showing a major transform fault (NFZ) running through the study area and linking to the CC fault. Modified after Jansa and Wade, 1975a and Northcor 1985.

a generous allowance for crustal extension of the Grand Banks during this period, significant strike slip accommodation is warranted along the southern margin of the Grand Banks at this time of active plate separation south of the margin. The required accommodation is reckoned to have occurred along the Newfoundland Fracture Zone and its imbricates (Figure 2.1) (Jansa and Wade, 1975a, Northcor, 1985). Figure 2.2 is a simplified conceptual drawing modified from Jansa and Wade (1975a) and Northcor (1985), showing the failed rift to the north, separated from the successful rift to the south by a major strike slip fault. This figure suggests that the right lateral movement (on the North American side) would project along the CC fault into the Orpheus Graben and likely onto the Nova Scotia mainland. Indeed Pe-Piper and Piper (2004) report evidence of Cretaceous and Tertiary strike slip motion along the CC fault onshore Nova Scotia as evidenced by syndepositional deformation of the Lower Cretaceous Chaswood Formation. Additionally, the epicentre of the 1929 Laurentian Basin earthquake (Piper et al., 1985) lies very close to this fault system, indicating that some measure of tectonic activity has continued into modern times. From the simplified picture presented in Figure 2.2 it would appear that the successfully rifted Scotian margin would move as a single unit along the transform fault with only localized compressional or extensional effects near the fault. To a large degree this may be the case, as the displacement would have been concentrated along the zone of weakness where continental crust met newly formed hot and weak oceanic crust. However this juncture was likely not a simple straight line, and may also have included transitional crust of varying strength. Combine this with the likely presence of geographical irregularities (embayments, capes) along the margin and we can more realistically expect to see a fault zone, rather than a single fault, with a complex interplay of fault splays and rotated blocks projecting well into the Laurentian and South Whale Basins.

The "Collector Anomaly" shown in Figures 2.1 and 2.3 represents the extension of the Avalon-Meguma suture across the Grand Banks (Haworth, 1975; Williams, 1995). This additional zone of weakness would also have been vulnerable to reactivation during the various rifting phases that affected this area, including during the 55 million year gap between Scotian-Moroccan and Grand Banks-Iberian seafloor spreading. The presence of the Newfoundland Seamounts within oceanic crust along this lineament (Figures 2.1 and 2.3) and the offset at the southern boundary of the Carson-Bonnition Basin (Figure 2.1) are further testament to Mesozoic activity along this segment of the CC Fault.

The East Coast Magnetic Anomaly (ECMA) is a prominent magnetic lineament that can be traced down the eastern seaboard of the United States and is believed to mark the boundary between continental and oceanic crust in that area (Rabinowitz, 1974, Dehler and Keen, 2001). The anomaly becomes disrupted on the Scotian Shelf by a transfer fault visible on seismic data, and fades as one enters the study area. Of note, an anomaly of similar strength and character is evident directly north of the Collector Anomaly and can be followed

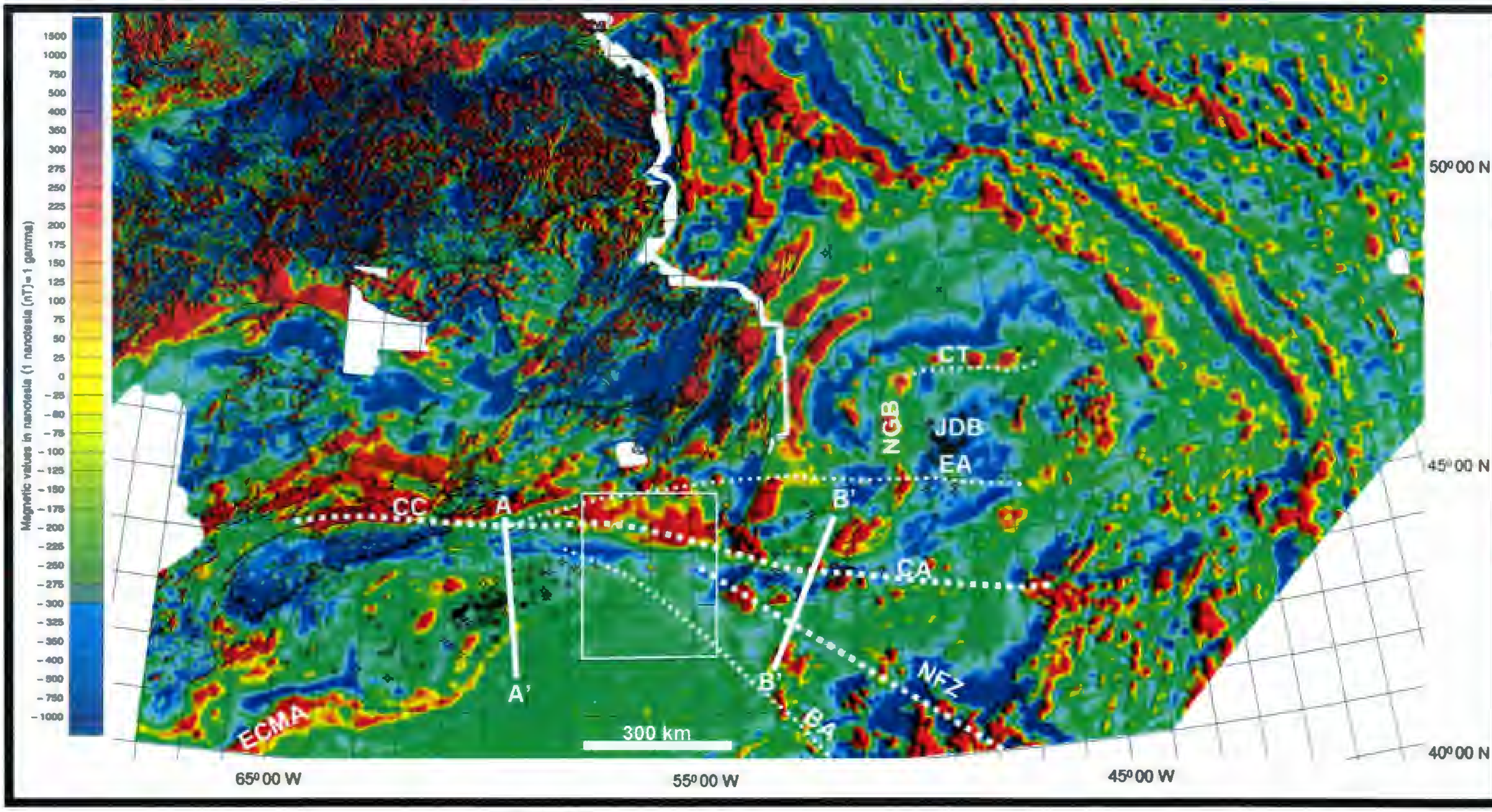
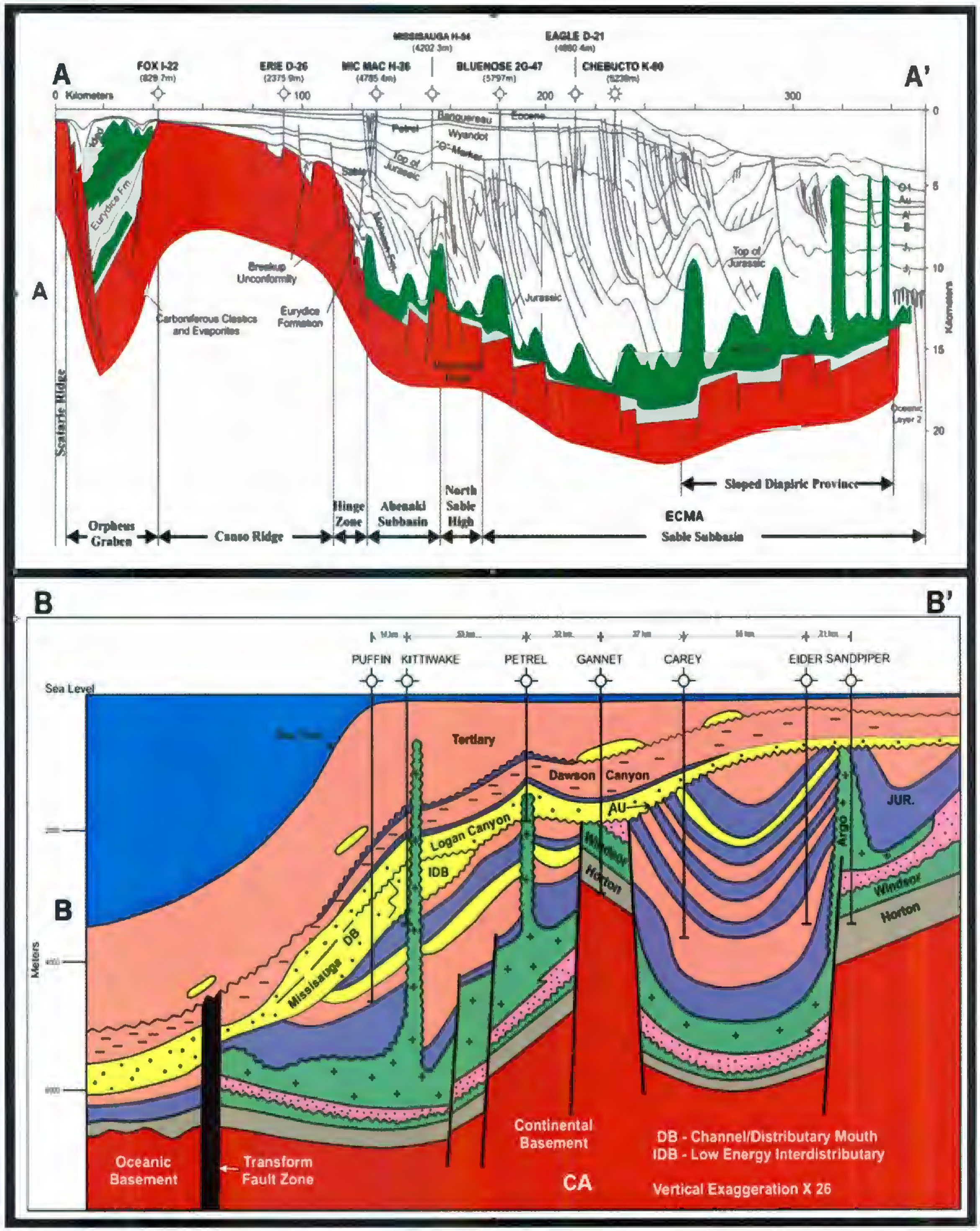


Figure 2.3

Regional magnetic data with well locations and showing the locations of cross-sections AA' and BB'. Acronyms: Cobequid-Chedabucto (CC) Fault, East Coast Magnetic Anomaly (ECMA), Collector Anomaly (CA), Jeanne d'Arc Basin (JDB) the Newfoundland Fracture Zone (NFZ), North Grand Banks Basin (NGB) and CT (Cumberland Transfer). The Egret Anomaly (EA) and Bandol Anomaly (BA) are suggested names for two other lineaments noted here. Magnetic data from the Geological Survey of Canada (1988b).

it undergoes left lateral transfer and counterclockwise rotation along lineament EA (Figure 2.3) before turning sharply eastward along the Cumberland Transfer Zone. If this anomaly does represent the continent ocean boundary (COB) where it occurs south of Nova Scotia, it must surely represent something else on the Grand Banks. Its close proximity to the west bounding fault of the Jeanne d'Arc Basin (within Enachescu's (1992) North Grand Banks Basin) might mean that this anomaly is being generated by volcanics and intrusive bodies associated with the initial Tethys rift. It is also noteworthy that other lineaments seem to converge on the CC fault, indicating a possible diffusion of extensional stress along several faults at this focal point – which may partially explain why the initial Grand Banks rift failed, and ergo, why the Grand Banks exist today as a promontory of continental crust. The fading of the ECMA anomaly within the study area is likely due to a dispersion of these initial rift volcanics by strike slip faults radiating south from the CC Fault - Laurentian Basin area. A weakly traceable lineament (BA in Figure 2.3) lying directly south and sub-parallel to the NFZ, projects into the study area at a point very close to the epicentre of the 1929 event and may represent an imbricate of the NFZ. Figure 2.3 also shows the locations of cross sections AA' (Scotian Shelf) and BB' (Southern Grand Banks). Section AA' (Figure 2.4A) runs from the Orpheus Graben across the Sable Sub-Basin into deep water and all the way to oceanic crust. On this section we can see that the magnetic anomaly associated with the CC marks the northern flank of the Orpheus Graben and that the faded remains of the ECMA



Figures 2.4 A and B

2.4A: Scotian Shelf Cross-Section. Modified after Wade and MacLean, 1990.

2.4B: Southern Grand Banks Cross Section. Locations of ECMA and CA from regional magnetic data (GSC, 1988b). Modified after Swift and Williams, 1980 and Northcor Energy Ltd. 1985. See figure 2.3 for locations.

run approximately along the continental slope of the Scotian Shelf, and over the very deepest part of the Scotian Rift. Figure 2.4B is a cross section through the Whale and South Whale Basins. Here we see a prominent ridge associated with the CA, with apparent compressional folding to the north of the ridge, within the Whale Basin. This localized compressional regime can be explained by strike slip movement, and adds support to the CA representing the extension of the CC fault across the southern Grand Banks, and that the fault remained active well into the Jurassic (at least). Figure 2.4B also shows how the Avalon Unconformity (AU), which is associated with the Late Jurassic – Early Cretaceous Avalon Uplift (Figure 2.1), resulted in intense erosion of the Jurassic sediments of the Whale Basin and the northern part of the South Whale Basin during this phase of rifting. This unconformity can be traced westward into the study area, indicating that the Late Jurassic – Early Cretaceous Laurentian Basin may have had more in common with the Whale – South Whale basin system than with the Scotian Shelf basins to the west. Section BB' provides less detail as one moves seaward of the Puffin well but the magnetic data show a roughly circular anomaly just south of the NFZ (identified as a transform fault zone in the figure). We know from the well that was drilled at this anomaly (Narwhal F-99) that this is a prominent basaltic high, which would appear to be associated with the NFZ.

Figure 2.5 shows the regional gravity map (Bouguer onshore and Free Air offshore) (GSC, 1988a) along with the major faults discussed above. The gravity map indicates the location of sedimentary depocentres quite well and suggests

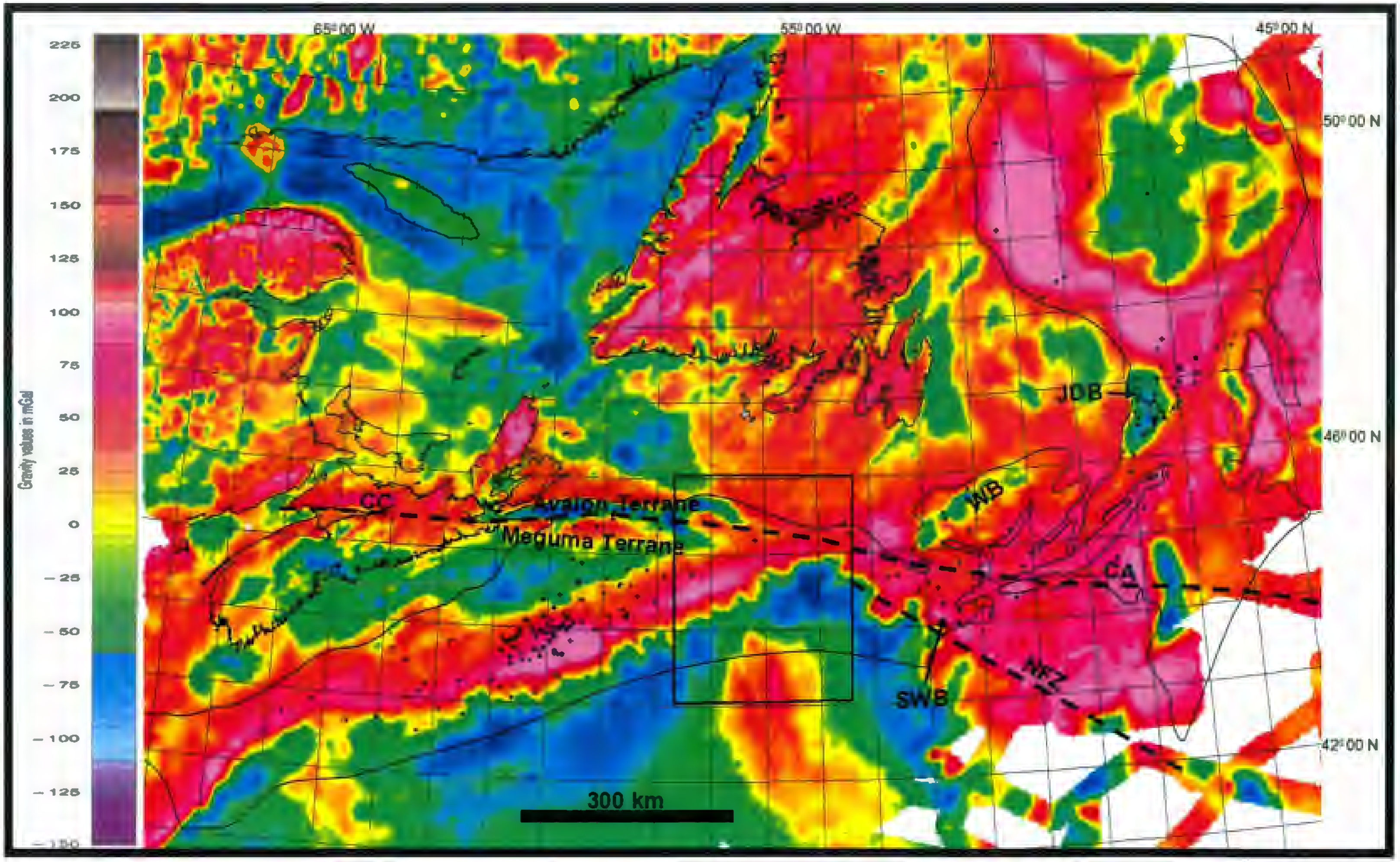


Figure 2.5

Regional gravity map (Bouguer onshore and Free Air offshore) with location of Avalon- Meguma boundary, the Cobequid-Chedabucto Fault (CC), Collector Anomaly (CA), Whale Basin (WB), South Whale Basin (SWB), Jeanne d'Arc Basin (JDB) and Newfoundland Fracture Zone (NFZ). Study area indicated by box. Gravity data from the Geological Survey of Canada (1988a).

the presence of several embayments along the NFZ. In fact the gravity high extending southwest from the SWB represents the basaltic basement mound that was drilled by Narwhal F-99. The CA is not well represented on the gravity data but we can clearly see the Whale Basin to its north and on trend with the Jeanne d'Arc Basin. The portion of the South Whale Basin lying north of the NFZ sits on a gravity high, which is likely associated with the ridges seen on section BB' between the Cary and Kittiwake wells. The gravity map is dominated by the shelf edge anomaly, which is likely related to a sharply rising Moho resulting in a transition zone where continental crust is being replaced by mantle material. Seaward of the shelf edge the Free Air gravity drops off sharply as the crustal material is replaced by water, and the remaining anomalies are more a reflection of seabed topography than crustal density variations. On the eastern side of the map, the shelf edge gravity anomaly is roughly coincident with the NFZ, suggesting that this zone of weakness is associated with an elevated Moho in this area. Also of interest is a broad anomaly near the southern boundary of the study area which correlates very well with bathymetry of the area (Figure 1.1). This anomaly may in part have been shaped by the massive turbidite deposit triggered by the 1929 earthquake, and perhaps other major slumps in the past. The water depth shallows over this sea floor fan which fades away to the southeast in a similar fashion to the gravity anomaly. A similar but smaller gravity feature can be seen off the southwest Scotian Shelf, suggesting the presence of another recent turbidite in that area.

In this study the regional GSC magnetic and gravity data were supplemented by non-exclusive high resolution magnetic data donated to this research by Fugro, which will provide a more detailed view of what happens as the NFZ and CC-CA fault systems converge in the study area. Seismic data combined with the potential field data will also help identify major ridges, similar to the one that separates the Whale and South Whale Basins (Figure 2.4B), that are present in the study area, and that can play a role in creating large hydrocarbon traps.

2.2 Stratigraphy

An in-depth discussion of the stratigraphy of the Laurentian Basin is not possible as there has been only one well drilled in the basin proper (Bandol #1 spudded in 2001) that remains on confidential status until 2011 (Enachescu, pers. comm.). Two of the other three wells within the study area (Hermine E-94 and Emerillon B-56; Figure 2.6) were drilled north of the basin hinge line, and encountered a Tertiary sequence overlying a thin Mesozoic section before entering the Carboniferous pre-rift basement. Dauntless D-35 drilled a significant Mesozoic section but, being located at the very western margin of the basin, it is likely to be more representative of the Abenaki Sub-basin of the Scotian Basin than the Laurentian Basin.

The stratigraphy of the Scotian Shelf has been described in detail by Wade and MacLean (1990) and was extended to the Laurentian Basin in a 1992 publication by the same authors. An abridged description is available on the GSC's website (http://gsc.nrcan.gc.ca/marine/scotianmargin/so_e.php). Sherwin (1973), Jansa

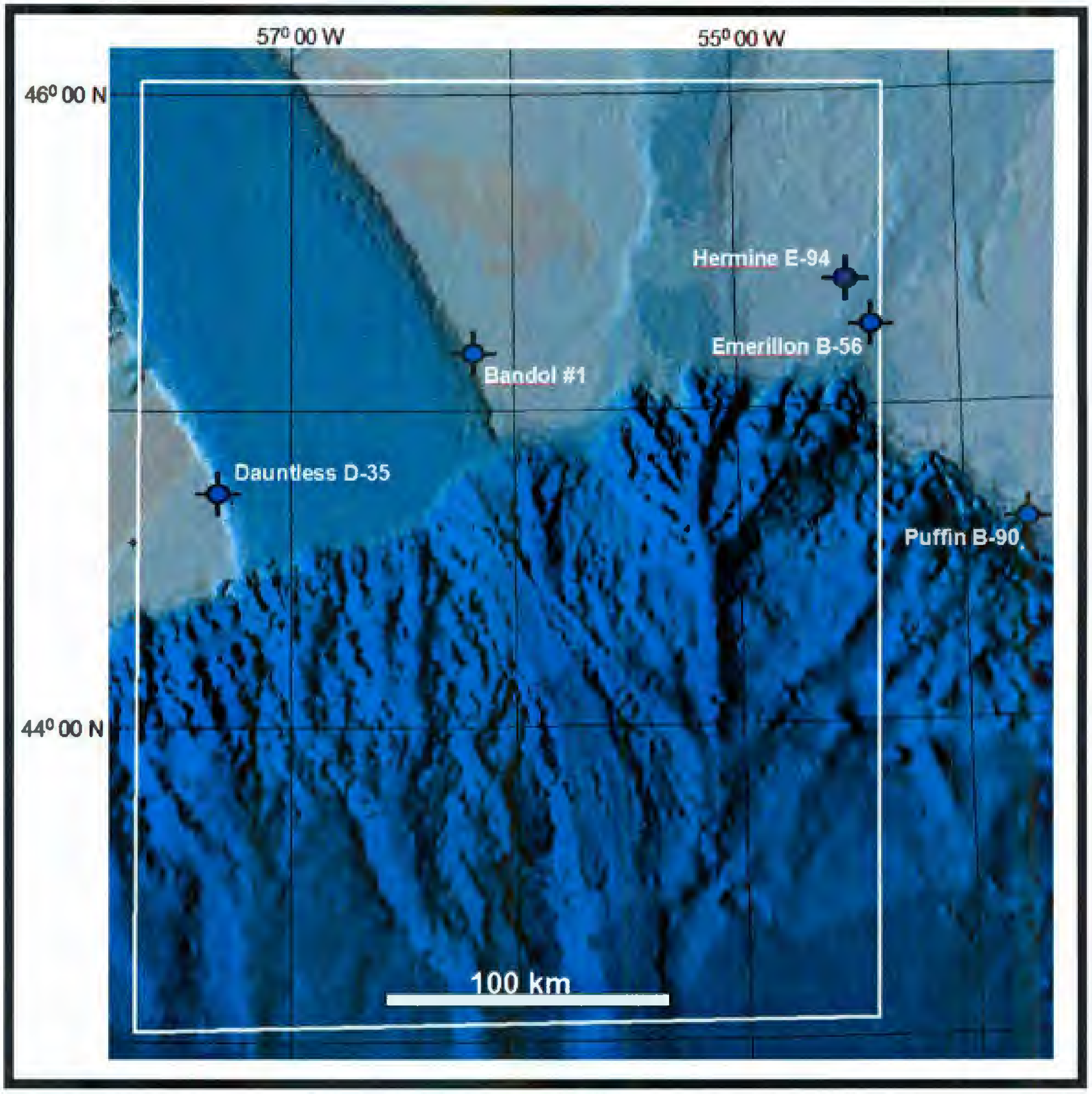


Figure 2.6

Map of study area showing wells, on the GSC / Canadian Hydrographic Institute bathymetry map. Wells within the study area are highlighted along with the Puffin B-90 well which is referenced in the biostratigraphy discussion. Modified after the Geological Survey of Canada and Canadian Hydrographic Service. See Figure 1.1 for colour legend.

and Wade (1975a,b) and McWhae (1981) outlined the major features of the Atlantic Canada Mesozoic basins and their structural evolution. The depositional environments of the Atlantic Canada basins were described by Williams et al. (1990). Additional information on the stratigraphy and depositional environments of the South Whale Basin is presented in the Northcor (1985) report to the C-NLOPB. The discussion of stratigraphy provided below draws heavily from these sources.

General Stratigraphic History

The Scotian Basin (Figure 2.7) is a Mesozoic - Cenozoic depocentre bounded to the southwest by Yarmouth Arch, and to the northeast by a Late Jurassic – Early Cretaceous uplifted region known as the Avalon Uplift (Jansa and Wade, 1975a; Enachescu, 1987; Tankard and Welsink, 1989; Wade and MacLean, 1990). The Georges Bank appears to have been a high from the very beginning of Mesozoic rifting, while the Avalon Uplift developed later. The basin evolved through a Late Triassic – Early Jurassic rift phase which involved widespread deposition of continental clastics and evaporites (Figure 2.8) within a series of NE-SW oriented rift grabens. Uplift associated with the start of seafloor spreading in the Pleinsbachian was manifested as a Break-up Unconformity that is believed to have peneplained much of the Scotian Basin and the southern Grand Banks (Maclean and Wade, 1992). With the onset of open marine conditions in the mid-Jurassic the evaporites were overlain by clastic and carbonate facies deposited in a variety of environments ranging from non-marine / marginal marine facies to

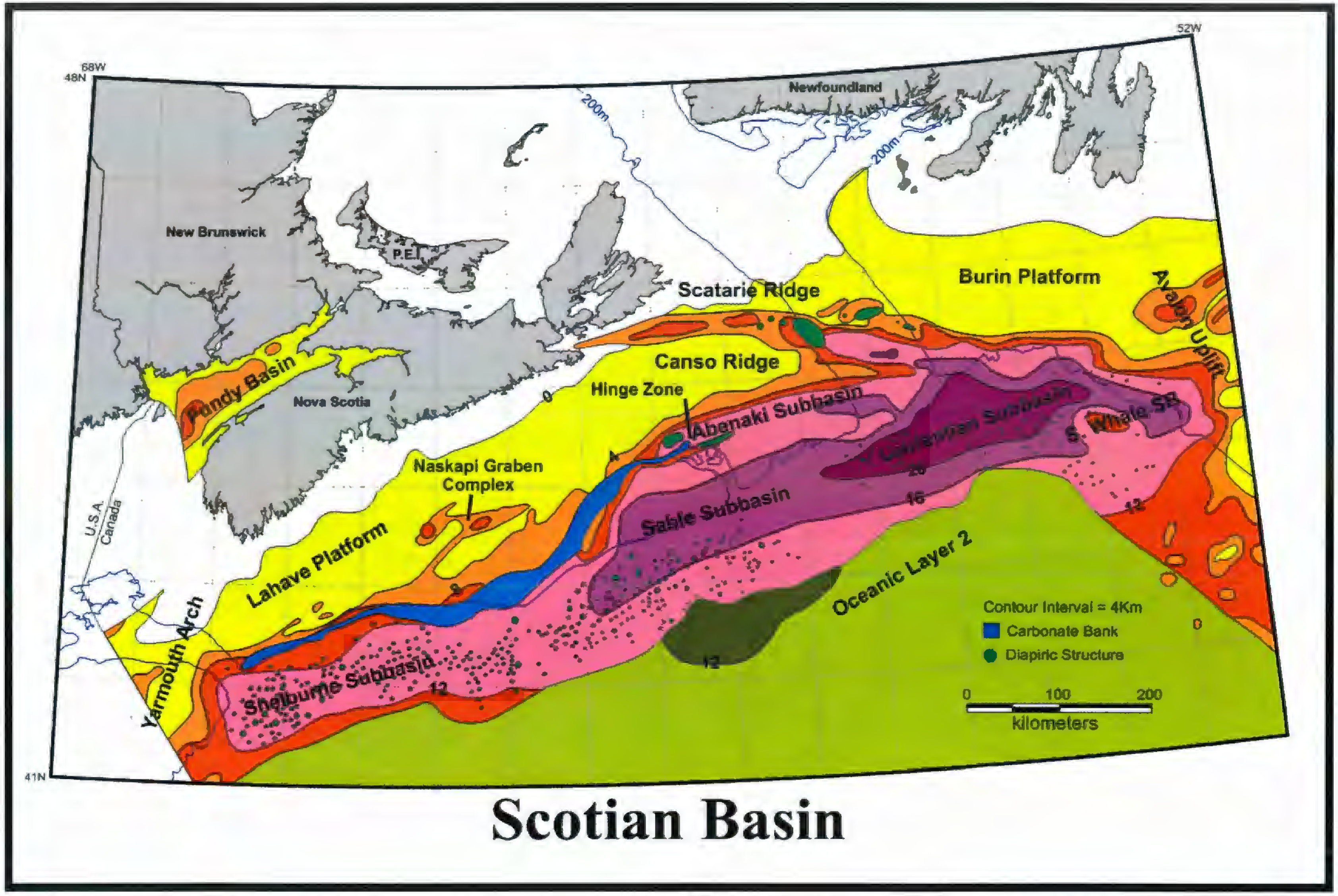


Figure 2.7

Regional Structural Map of Scotian Basin with various sub-divisions. Contours represent depth to basement, and the 200 m bathymetric contour is also shown to roughly outline the shelf edge. In this instance the Laurentian Basin ("Subbasin" in the figure) has been centred on the 20 km depth to basement contour. Modified after GSC map from Natural Resources Canada website: http://gsc.nrcan.gc.ca/marine/scotianmargin/images/scotianfig1.gif

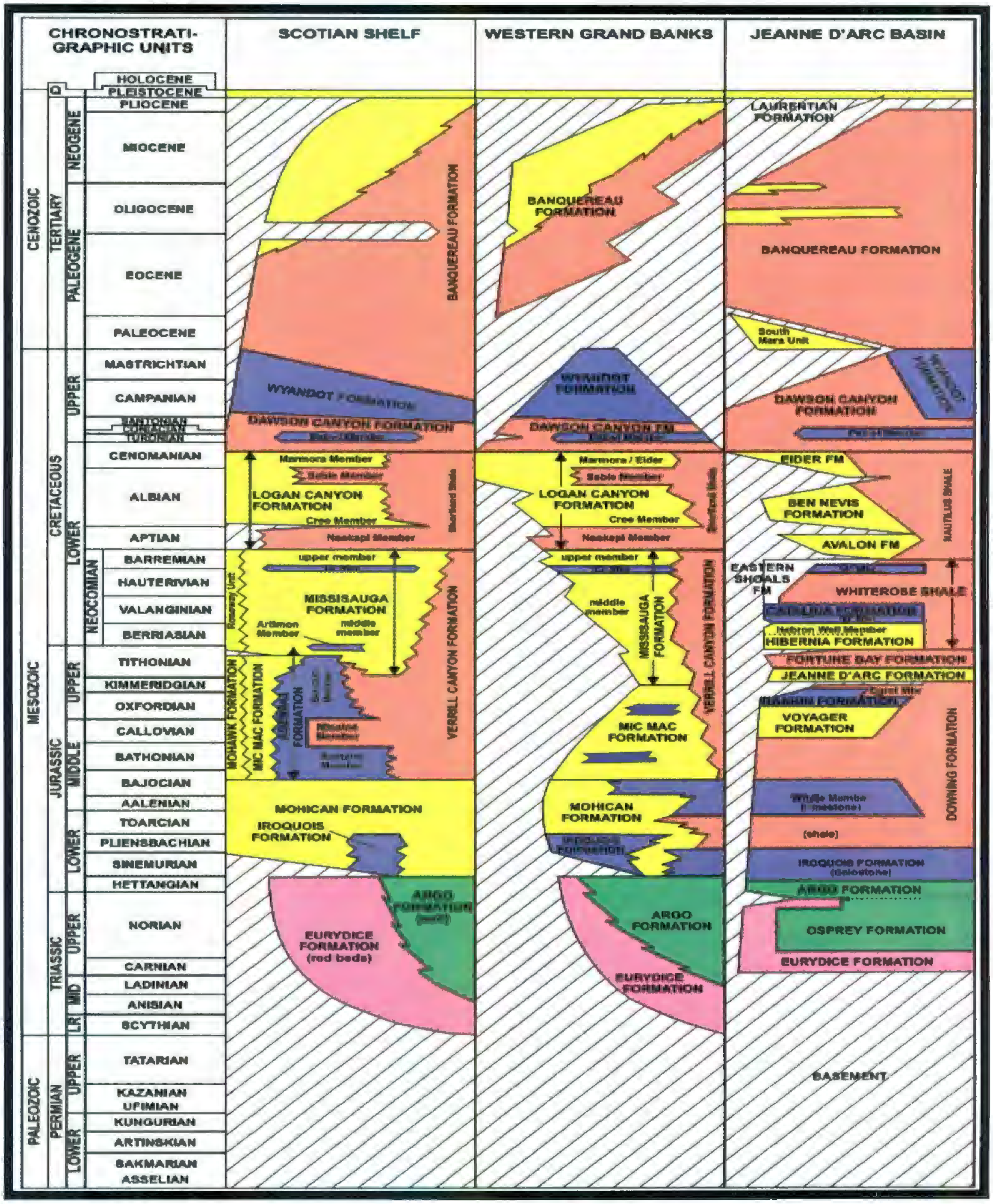


Figure 2.8

Stratigraphic chart for Scotian Shelf, Western Grand Banks and Jeanne d'Arc Basin. Modified after Williams et al. (1990), who had modified after Wade and Maclean (1990) and Grant and McAlpine (1990).

hemipelagic and pelagic sediments as one moves basinward. As discussed in Section 2.1, local deposition throughout the basin would have been strongly influenced by regional tectonic events, including: uplift driven by rifting of the Grand Banks to the east; and, localized compression and extension resulting from movement along strike slip faults. The best example of this is the Late Jurassic – Early Cretaceous rise of the Avalon Uplift which caused severe erosion of the Jurassic section across the southern Grand Banks and westward into the Laurentian Basin. With cessation of the Avalon Uplift, the eastern half of the Scotian Basin, including the Laurentian Basin, joined the western half in the passive margin stage. As uplift and tectonism gave way to subsidence, non-marine to marginal marine sedimentation gave way to a general transgression that culminated in the blanketing of the shelf by deep water carbonates in the Late Cretaceous. A drop in sea level (Figures 2.9 and 2.10) at the close of the Cretaceous (possibly associated with the KT asteroid impact and mega-tsunamis) is marked by the Base Tertiary Unconformity which can be mapped across the entire Atlantic Canada margin. During the Tertiary the Scotian Basin continued to tilt seaward, which combined with eustatic sea level changes to create a prograding mix of marine clastics and minor carbonates which were topped off by glacial and marine sediments of the Quaternary.

Following is a discussion of the major stratigraphic intervals. Formation thicknesses quoted are from the GSC's "Basins" website (http://basin.gsca.nrcan.gc.ca/wells/index_e.php) with tops picked by MacLean and Wade.

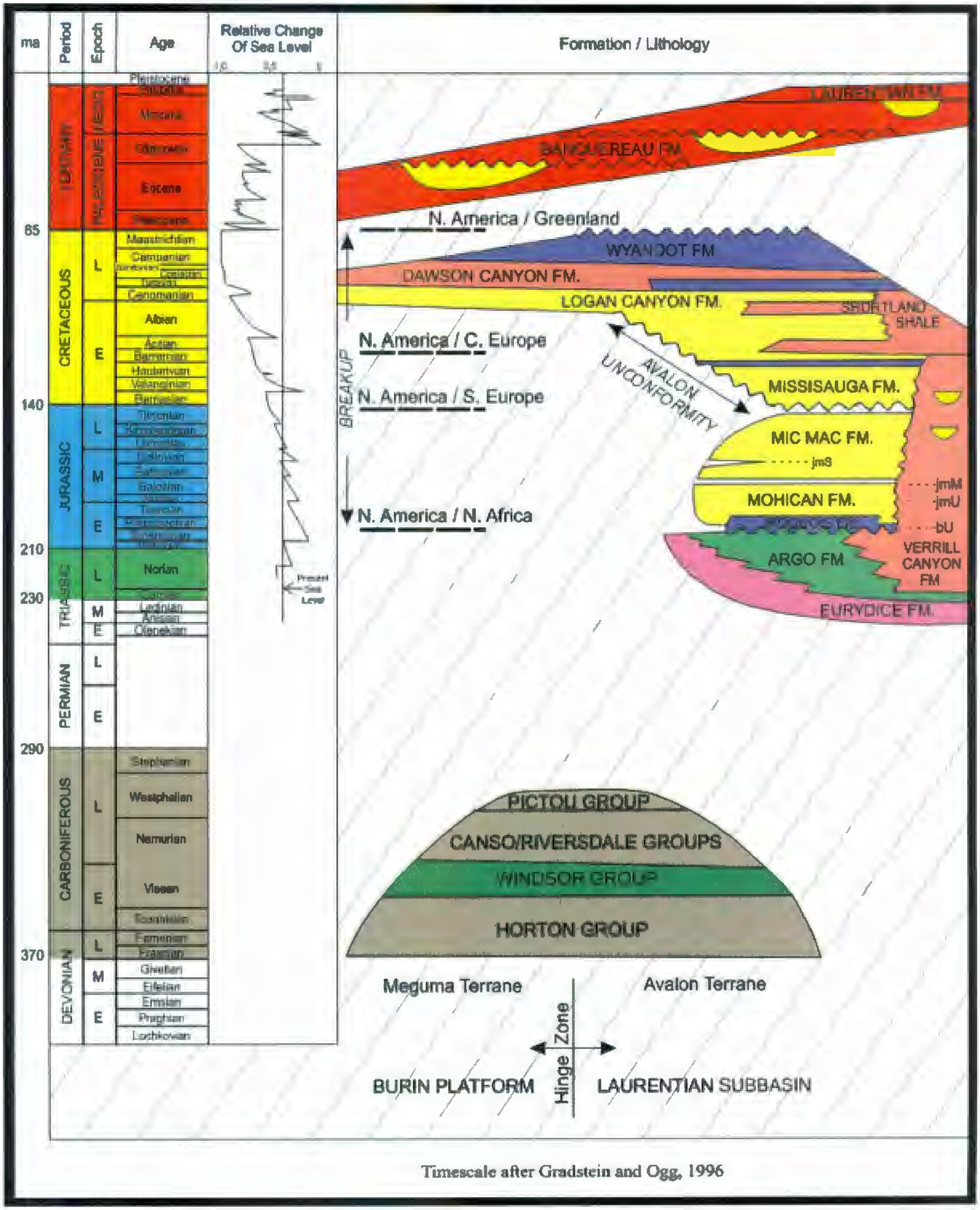


Figure 2.9

Laurentian Basin stratigraphic chart. Modified after MacLean and Wade (1992). Sea level chart from Vail et al. (1977, 1984) and Vail and Mitchum (1979) reproduced in Williams, et al. (1990).

Paleozoic Rocks

The oldest basement of the Scotian Basin consists of the Avalon and Meguma terranes which were sutured at the closing of Iapetus in the late Paleozoic (Williams, 1984). The Avalon Terrane is believed to be a detached margin of Gondwana and is characterized by low-grade metamorphic, igneous, and sedimentary rocks (Atlantic Geoscience Society, 2005). The Avalon Zone is locally overlain by Devonian to Late Carboniferous sediments of the Horton, Windsor, Canso-Riversdale and Pictou Groups (MacLean and Wade, 1992). The Hermine E-94 well, in the northeast corner of the study area, encountered roughly 1500 m of Carboniferous section, including sands and shales of the Canso-Riversdale-Pictou groups and evaporites of the Windsor Group. It is not clear that Carboniferous sediments overlie Meguma basement, and MacLean and Wade (1992) speculate that the Meguma may have been uplifted and eroded at this time. The Meguma Terrane is of more mysterious origins than the Avalon Terrane and the details of its emplacement against the Avalon in terms of oceanic contacts and subduction zone are not well known (Wade and MacLean, 1990). The Meguma is exposed in southern mainland Nova Scotia, where it is principally characterized by a thick succession of Cambrian to Ordovician turbiditic meta-sandstones and slates overlain by thinner Silurian to Devonian volcanics and shelf sediments (Williams, 1984; Atlantic Geoscience Society, 2005). The Meguma Terrane has not been penetrated by wells offshore, but northeast trending folds in the Meguma in Nova Scotia give rise to linear magnetic anomalies which swing south (Figure 2.3) across the Georges Bank, suggesting that the Scotian Shelf is underlain by the Meguma terrane (Bell and Howie, 1990).

<u>**Mesozoic Rocks**</u>

Unless otherwise noted the geologic ages quoted below are from Wade and MacLean (1990), and absolute times (approximate) have been obtained by visual correlation to "A Geologic Timescale 2004" by Gradstein et al. (2004).

Eurydice Formation

Age: Norian to Hetangian – Sinemurian: 216 – 196 my (20 my)

This thick sequence of red sandstones, siltstones and shales was deposited in the original intra-continental synrift grabens that extended across the Scotian Shelf, Grand Banks and conjugate margin basins. Up to 1.5 km of Eurydice has been drilled on the Lahave Platform (Figure 2.7). The nearest wells to the study area that encountered Eurydice were about 160 km west in the Orpheus Graben, where almost 600 m of an estimated (from seismic) 3 km sequence was drilled (Welsink et al., 1989; MacLean and Wade, 1992).

Argo Formation

Age: Carnian to Hettangian – Sinemurian: 228 – 196 my (34 my)

As the continental rift grabens were gradually invaded by the sea the Argo evaporites were coevally deposited with the Eurydice Formation in the western periphery of the Tethys Sea, including the Scotian Margin and extending into the basins of the Grand Banks, to at least the Cumberland Transform (Enachescu, 1987; MacLean and Wade, 1992). Equivalent evaporites were deposited in Morocco, Tunisia, Algeria, Spain, France and the Gulf of Mexico (Northcor, 1985). Evaporites are much less predominant on the eastern seaboard of the United States, but Sheridan (1989) reports the presence of diapiric features on seismic data from the Baltimore Canyon, Carolina Trough and Bahamas Basin. The Argo Formation consists primarily of salt which interfingers with the Eurydice along the rift margins. Jansa and Wade (1975b) estimate that the autochthonus Argo was about 1800 m thick, but where it has flowed into diapirs it can measure up to 10 km from top to base. Salt doming in the Scotian Basin is most prevalent in deep water, below the continental slope, particularly in the "Slope Diapiric Province" which extends from Georges Bank to the Western Grand Banks (Figure 2.7; Wade and MacLean, 1990; Kidston et al., 2002). In terms of seismic interpretation, the Argo is the most recognizable sequence below the Avalon Unconformity in the Laurentian Basin and provides important clues to the age of surrounding sequences. The Argo Formation was not encountered in any of the wells drilled in the study area.

Break-up Unconformity

As noted previously, the Break-up Unconformity (BU) is associated with uplift at the start of seafloor spreading and hence marks the top of the synrift sequence. In the Scotian Basin this occurred during the Pleinsbachian (Maclean and Wade, 1990; Wade and Maclean, 1992). Although the BU is a regional event within the basin it is difficult to pick on seismic data. The BU may have been crossed by the Emerillon B-56 well in the study area (Maclean and Wade; Basins website).

However, as this well was drilled above the hinge line in a small graben, it does not provide a good tie that can be carried into the basin. Having no good well ties to this horizon in the Laurentian Basin, the BU was interpreted in this study as the first regional unconformity above the domes and swells of the diagnostic Argo Formation.

Iroquois and Mohican Formations

Age: Late Sinemurian to Bathonian: 194 -164 my: (30 my)

With renewed subsidence after the Break-up Unconformity, clastic sedimentation resumed along the margin of the basin with the deposition of a thick molasse sequence known as the Mohican Formation. Further from shore the Argo salt was overlain by evaporitic dolostones of the Iroquois Formation (MacLean and Wade, 1992). The Iroquois, which is coeval with the base of the Mohican Formation, was deposited in a neritic environment (Williams et al, 1990) but was ultimately overstepped and buried as the Mohican molasse prograded seaward. Approximately 800 m of Iroquois was drilled at Bonnet P-23 on the Scotian Shelf which had zones of fair to good intercrystaline and vuggy porosity (Petro-Canada, 1984; Wade and MacLean, 1990). Sinclair (1988) indicates that the Iroquois has been identified as an effective source for oil and/or gas condensate in the Cormorant N-83 well (well history report available from the C-NLOPB), and that heavy oil has been reported in the formation in several other Grand Banks wells. Emerillon B-56 was the only well in the study area to encounter the Mohican – Iroquois. Maclean and Wade's (Basins website) tops for this well show 248 m of Mohican(?) and 164 m of Iroquois(?), including a 21 m volcanic intrusive within the Mohican.

Mic Mac Formation

Age: Bathonian to late Tithonian; 167 to 145 my (23my)

With the widening of the ocean and continued subsidence, the Mohican Formation was conformably overlain by a suite of sedimentary successions deposited in an environment ranging from inner to outer neritic, with occasional marginal marine episodes, that make up the clastics and carbonates of the Mic Mac Formation (Williams et al., 1990). Conditions varied throughout the Scotian Basin with a major carbonate bank (Abenaki Formation, see Figure 2.7) developing along the hinge zone in the western half of the basin and more localized and intermittent limestones deposited as one moves eastward into the Laurentian and South Whale basins. The Mic Mac Formation is 4 to 5 km thick southeast of Sable Island (Wade and MacLean, 1990) and thins to a depositional / erosional zero edge as one moves landward across the hinge zone. At Dauntless D-35 on the western side of the study area the Mic Mac is 1003 m thick, consisting of sandstones, shales and carbonates. At Emerillon B-56 at the north eastern corner of the study area MacLean and Wade (1993; Basins website) interpret the presence of 934 m of Mic Mac equivalent(?), consisting of predominantly carbonates. Age equivalent sediments to the Mic Mac are increasingly eroded by the Avalon Unconformity as one moves eastward towards the Avalon Uplift, and where they have been drilled in the South Whale Basin they are mainly clastics. However, there are occasional carbonate and shale units that may be correlated to the Abenaki and Verrill Canyon Formations of the Scotian Shelf (Northcor, 1985). The Voyager Formation is the approximate equivalent age formation within the Grand Banks basins (Grant and McAlpine, 1990).

Avalon Unconformity

During the Late Jurassic – Early Cretaceous the South Eastern Grand Banks was arched upward (Figures 2.1 and 2.7) as seafloor spreading was being initiated between the Grand Banks and Iberia (Jansa and Wade 1975b). This break-up unconformity led to severe erosion of Jurassic sediments on the southern Grand Banks and environs and is one of the more easily correlatable horizons in the eastern half of the Scotian Basin. The Avalon Unconformity can be traced westward from the Avalon Uplift to where it eventually becomes conformable on the eastern margin of the Abenaki Sub-Basin (Figure 2.7) (MacLean and Wade, 1990). Moving northeastward from the Avalon Uplift into the Jeanne d'Arc Basin, the presence of additional unconformities in the Late Jurassic to Late Cretaceous sections has led to some confusion in nomenclature, as several of these events have been referred to as "Avalon Unconformity" (Wade and MacLean, 1990). Approaching the Avalon Uplift from the southwest, the unconformity is onlapped by progressively younger Cretaceous sediments culminating in the Cenomanian transgression (Barss et al., 1979; Wade and MacLean, 1990). As the Avalon Uplift slowly and intermittently subsided, additional and more localized erosional events occurred which are, in places, difficult to distinguish from the Avalon Unconformity (Wade and MacLean, 1990).

Mississauga Formation

Age: Berriasian to Aptian: 145-125 my (20my)

As regional subsidence recommenced after the Avalon Uplift, the Scotian Basin was dominated by a major river system that resulted in the deposition of the largely clastic Mississauga Formation (Welsink et al., 1989). The alluvial plain, delta plain and pro-delta sequences of this important hydrocarbon reservoir are best known in the Sable Island area, where the Mississauga has been drilled to a thickness of 2100 m (Wade and MacLean, 1990). The sequence is also widespread in the South Whale Basin where 803 m were drilled in the Puffin B-90 well (Figures 2.4B and 2.6). The Mississauga has been divided into three major units (McGiver, 1972; Given, 1977). The lower Mississauga unit has been drilled only in the Sable Island area and contains delta front with possible barrier bar, beach, and tidal channel sequences that grade upward into a pro-delta environment. The middle and upper Mississauga units, which are separated by a transgressive limestone known as the "O" marker, include alluvial and delta plain sequences (Wade and MacLean, 1990). Even with the general subsidence that was occurring at this time and recognizing the transgressive interlude represented by the "O" marker, an abundant sediment supply made the Mississauga a predominantly regressive sequence. Significantly from a petroleum exploration perspective, this general regression moved sand seaward over the shelf edge and its deep water equivalent the Verrill Canyon Formation (a source rock). In the study area Dauntless D-35 drilled the middle and upper Mississauga units, including 425 m of the middle unit, 100 m of "O" Marker limestone and 247 m of the upper unit. The middle unit included a sandstone and shale sequence and the upper unit was predominantly sandstone with a thin limestone. An 84 m sandy section in the Emerillon C-56 well was identified as Missisauga (?) by MacLean and Wade (Basins website) but the formation was not encountered at the Hermine E-94 well.

Verrill Canyon Formation

Age: Bathonian to Aptian: 167 to 125 my (42 my)

The Verrill Canyon Formation is the distal shale equivalent of the Mic Mac / Abenaki and Mississauga Formations. Its regional depositional environment varies from outer neritic to pro-delta to bathyal and it is expected to be present all along the Scotian Margin - which is important from an exploration perspective as it is the key source rock for the natural gas and condensate discoveries of the Scotian Shelf. The Verrill Canyon was not encountered in the Dauntless D-35 well (although a shale interval is noted in the carbonate dominated part of the Mic Mac Formation) nor in the Hermine E-94 well, but 94 m of it was encountered at Emerillon B-56 (MacLean and Wade, Basins Website). At the Puffin B-90 well, about 80 km southeast of Emerillon, 920 m of Verrill Canyon was encountered beneath a section of Mississauga sandstones.

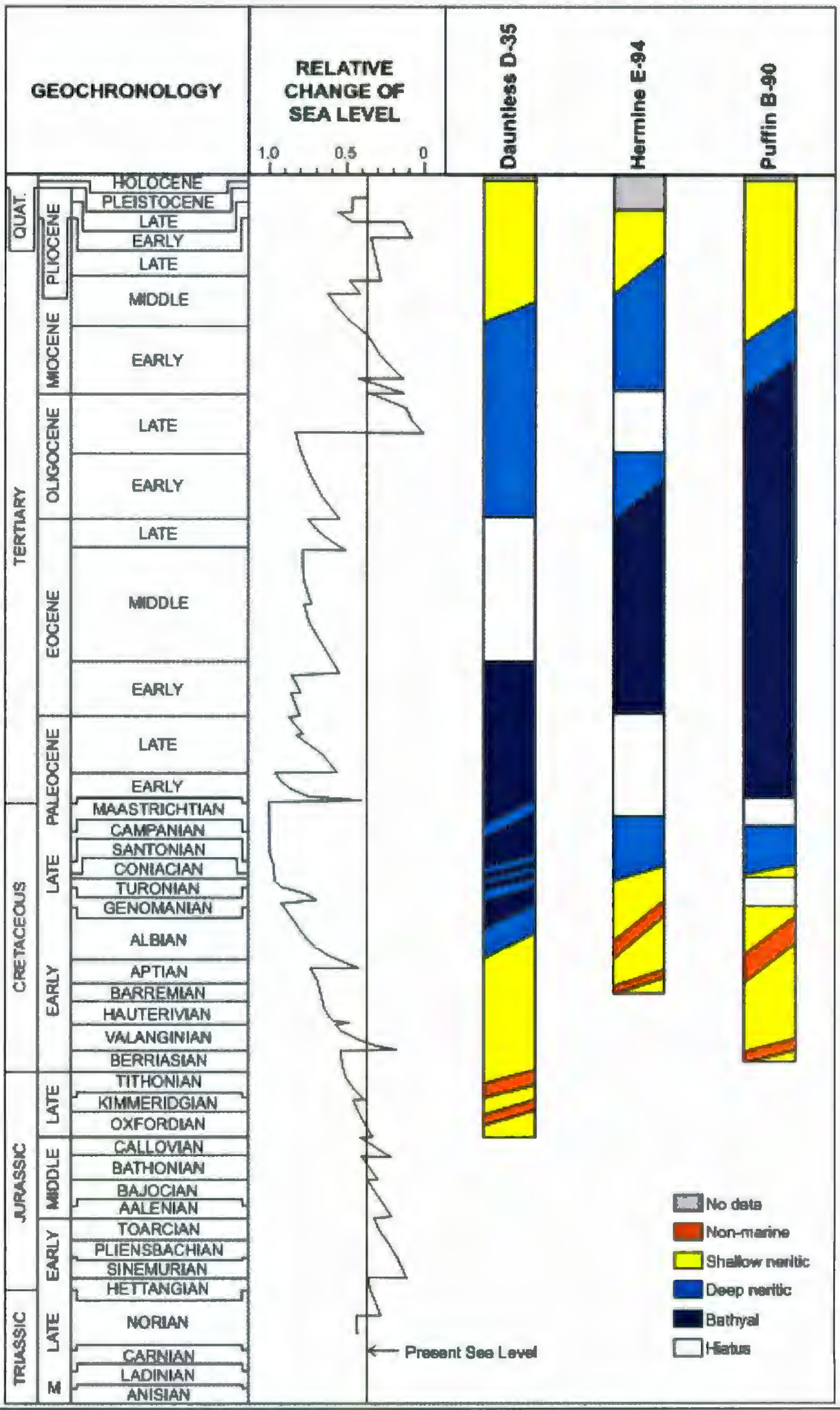


Figure 2.10

Depositional Environments in the Mesozoic and Cenozoic for Dauntless, Hermine and Puffin wells. Modified after Williams et al, 1990. Sea level chart from Vail (1977, 1984) and Vail and Mitchum (1979) reproduced in Williams et al 1990.

Logan Canyon Formation

Aptian to Early Cenomanian (Barss et al., 1979): 125 to 99my (26my)

As passive margin subsidence continued across the basin and combined with a eustatic sea level rise (Figures 2.9 and 2.10) the regressive depositional phase of the Mississauga formation gave way to a slow transgression. This resulted in the deposition of the fining upward sands of the Logan Canyon Formation. These deeper water clastics advanced across the underlying delta plain and further landward, to ultimately onlap the Avalon Unconformity (Figure 2.9). The distal equivalent of the Logan Canyon Formation is the Shortland Shale (Wade and MacLean, 1990). Two prominent shale sequences (Naskapi and Sable Members; Figure 2.9) are testament to instances where the transgression had reached generally bathyal conditions but was then temporarily pushed back by a lowering of sea level or by increased sediment input. The sea level chart in Figures 2.9 and 2.10 shows eustatic drops in the Aptian and Cenomanian which correlate reasonably well with the upward termination of the Naskapi and Sable members, supporting the former of these options. The Logan Canyon does not contain any good regional seismic markers but it is approximately bracketed between the "O" Marker below and the Petrel Limestone above. A basal transgressive marginal marine sand identified by Amoco and Imperial (1973) on the southern Grand Banks, which they named the Eider Unit, has been roughly correlated with the upper sands of the Logan Canyon Formation on the Scotian Shelf (Wade and MacLean, 1990). All of the wells in the study area have encountered the Logan Canyon formation. Dauntless D-35 hit 775 m of Logan Canyon, including 188 and 107 m of the Naskapi and Sable shales respectively. Emerillon hit 159 m of

Eider and 59 m of Naskapi(?), and Hermine drilled 175 m of Eider. The Puffin well to the east encountered 79 m of Naskapi and 156 m of Eider (MacLean and Wade, Basins website).

Dawson Canyon Formation

Age: Early Cenomanian to Santonian (Doeven, 1983): 99 to 85my (14my)

By the early Cenomanian to Santonian subsidence and eustatic sea level rise had combined to bring deep neritic to bathyal conditions to the Scotian Basin (Williams et al., 1990). This, combined with a low relief hinterland (Kidston et al., 2002), led to the widespread deposition of marine shales, chalks and minor limestones of the Dawson Canyon Formation (DCF), which ranges in thickness from about 700 m in the South Whale Basin to only 100 m in sediment starved areas such as the outer Sable Sub-basin (Wade and Maclean, 1990). The Dawson Canyon includes the Turonian aged Petrel Limestone which generally thickens from southwest to northeast in the Scotian Basin, and provides a good seismic marker over much of the Atlantic Canada margin. Within the study area thick sections (513 m and 520 m) of DCF were encountered at the Hermine and Emerillon wells respectively, including 100 m thick Petrel sections. At the Dauntless well the DCF was only 332 m thick with 14 m of Petrel, which is likely a reflection of diminished sedimentation in this more distal location on the shelf. The relatively thin Petrel at this location may be an indication that the Petrel limestone is gradually shaling out as one moves basinward. At the Puffin well the DCF was 453 m thick including 58 m of Petrel.

Wyandot Formation

Age: Santonian to Campanian - Maastrichian* (Doevan, 1983)*: 85 to 70my (15 Ma)

With continued subsidence and a sustained high eustatic sea level during the Late Cretaceous, transgression continued across the Scotian Shelf and Grand Banks Basins (Williams et al., 1990). Within the Scotian Basin the diachronous Wyandot Formation advanced generally towards the northeast which is consistent with the paleogeography of the time. The very low sedimentation rates of the time (average of .9 cm per ka; Wade and MacLean, 1990) allowed for the widespread deposition of chalks, chalky mudstones, marls and minor limestones that make up the Wyandot Formation. The Wyandot ranges in thickness from less than 50 m in some wells in the Sable area to about 400 m on the southeastern Scotian Shelf, and is missing over extensive areas due to Tertiary erosion (MacLean and Wade, 1992). In the study area the Wyandot is approximately 100 m thick at both the Hermine and Emerillon wells but almost four times as thick at Dauntless D-35. Wade and MacLean (1990) attribute the thicker Wyandot at Dauntless to accelerated subsidence of the Laurentian Basin in the Late Cretaceous. Being north of the hinge zone the Emerillon and Hermine well locations would not have experienced this increased rate of subsidence and/or the Wyandot may have been subjected to more severe KT erosion at this more landward position. At the Puffin well the Wyandot is only 28 m thick which is perhaps a reflection of variability in deposition based on currents or paleogeographical conditions in that area.

Banquereau Formation

Age: Campanian – Maastrichtian to Pliocene: 70 to 5 my (65 million years)

The Banquereau Formation includes the entire Tertiary section plus the portion of the Late Cretaceous that lies above the Wyandot Formation (McGiver, 1972). In the dip direction the formation takes the approximate shape of a lens that thins to a landward zero edge. It is generally thickest (> 4 Km) along the continental slope, and thins again as one continues seaward (Wade and MacLean, 1990). The Tertiary began with a lowering of sea level (Figures 2.9 and 2.10) that may be related to the KT asteroid impact (Alvarez et al., 1980) in the Gulf of Mexico which would have vaporized a tremendous volume of seawater and also driven a huge “mega-tsunami” onto the surrounding landmasses. The tsunami (or series of tsunamis) would have impacted the study area and moved large amounts of material landward and then seaward off the shelf in a series of erosional pulses. In fact, the change from Wyandot conditions started approximately three million years before the KT catastrophe and the Vail et al. (1977,1984) and Vail and Mitchum (1979) sea level chart (Figures 2.9 and 2.10) shows only a small reduction in eustatic sea level at this time. If age datings of the base of Banquereau are correct, then it can be concluded that the change in sedimentation from the Wyandot to the Banquereau was caused by local conditions rather than an eustatic event. The Williams et al. (1990) biostratigraphic chart (Figure 2.10) indicates that the area was entering persistent bathyal conditions, and so the switch from chalks and minor limestones to fining upward clastics is more likely related to an increase in sediment supply than a retreat to shallower sea conditions. The same chart shows that depositional environments at the Dauntless, Hermine and Puffin wells generally progressed from bathyal to shallow neritic conditions from the Paleocene to the Pliocene, which is consistent with a prograding regressive sequence. Seismic data in the Laurentian Basin indicate a seaward tilting of the basin at this time which may have also involved an upward flexure of the hinterland. The resulting increase in sediment supply, prograding into a subsiding basin, would have experienced frequent over-steepening, slumping and subaqueus erosion of older beds. The increased loading in the thickest part of the basin, near the shelf break, would have induced greater subsidence along this front and, possibly, a peripheral bulge along the seaward perimeter of the basin. In the study area the wells show the expected thickening of the Banquereau as one moves seaward towards the continental shelf, with 847 m at Hermine, 1156 m at Emerillon and 1432 m at Dauntless. The Puffin well, located near the shelf break, had 2261 m of the Banquereau sequence.

Laurentian Formation

Age: Pliocene to present: 5 my

The Laurentian is the youngest formation in the Scotian Basin and is composed of glaciomarine and marine sands silts and clays. The formation is not picked in any of the wells within the study area, where it is likely thin or absent, but it can reach a thickness of 1500 m on the outer shelf and slope. (King, 1970; Wade and MacLean, 1990).

Chapter 3
Dataset

3.1 Reflection Seismic

As has been the case for several decades, the reflection seismic survey is the most effective subsurface imaging technology available to the geoscientist – particularly with regard to the mapping of offshore sedimentary basins. This study contains a detailed geophysical interpretation of the Laurentian Basin using the GSC Atlantic regional seismic grid, supplemented by industry data provided by GSI, Western Geco, and GX Technology, along with public domain regional gravity/mag data, high resolution magnetic data donated by Fugro, and results from nearby exploration wells. The digital reflection seismic data available for this study is listed below.

Digital Seismic Data Used in This Study

Company/Organization	Vintage	Number of Km
GSC	1984, 1987	3072 km
GSI	1982, 2000, 2001	8950 km
Western Geco	1998, 1999	4050 km
GX Technology	2003	1300 km
Total		**17,372 km**

In addition to these datasets ConocoPhillips provided three lines in hardcopy which were used to assist in tying to wells east of the study area. ConocoPhillips also allowed the author to spend a week interpreting their proprietary digital 2D

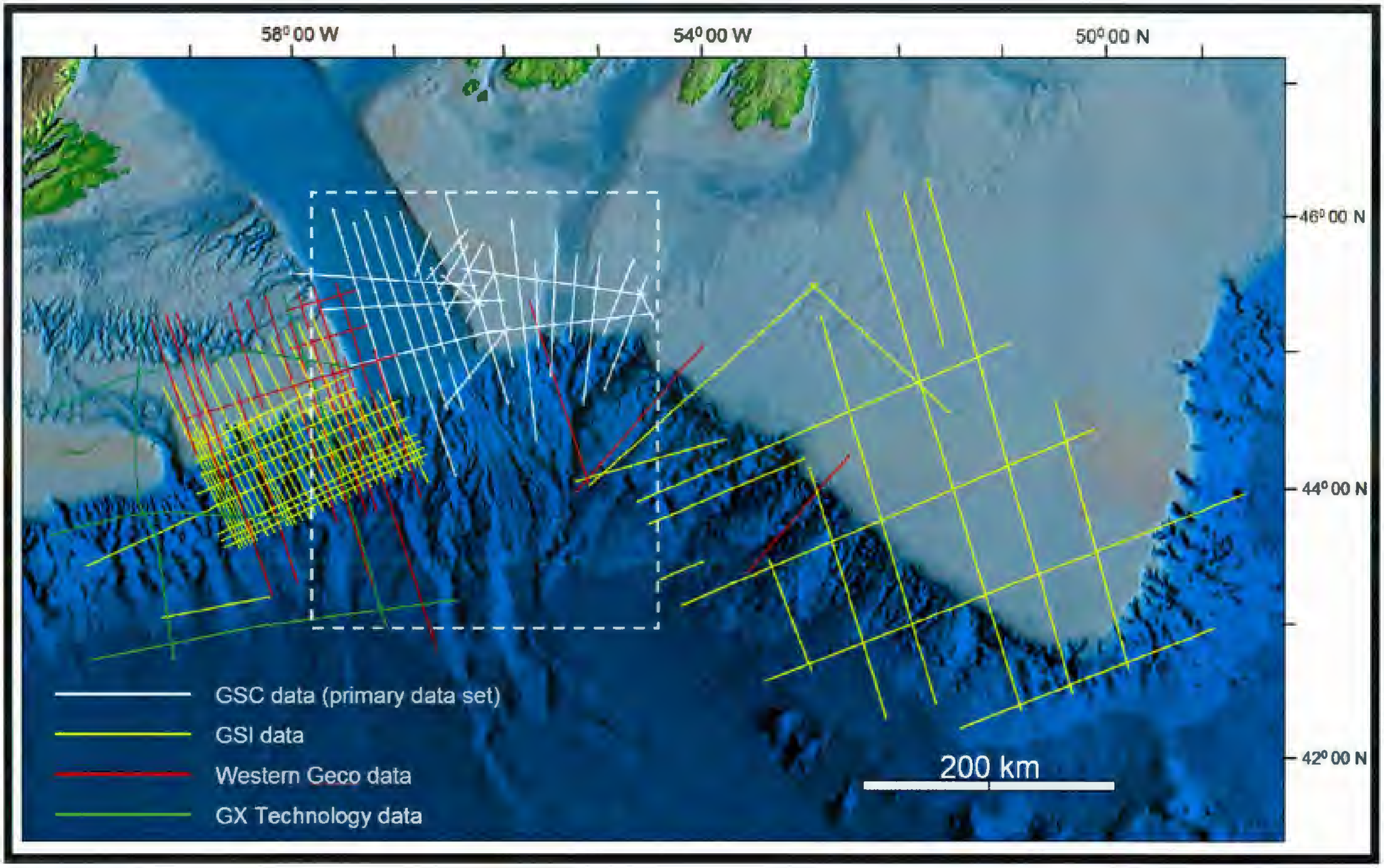


Figure 3.1

Bathymetry map showing the location of seismic lines used for this study. Only the lines lying inside the study area were interpreted in detail. The study area shown by a dashed white rectangle. Bathymetry map from the GSC and Canadian Hydrographic Service. See Figure 1.1 for colour legend.

seismic data at their office in Calgary, and the insights gained from that experience were then applied to interpreting the digital data listed above.

Figure 3.1 shows the locations of the digital seismic lines available for the study. As noted above the core dataset consisted of the 3072 km of data acquired under contract by GSI and Western Geophysical for the GSC in 1984 and 1987 (shown in white in Figure 3.1) and re-processed in 2005. The acquisition parameters for the GSC data were (Negut et al., 2007):

- *Source:*
  - Depth: 7 m
  - Array Volume: 4075 cu.in.
  - Pressure: 2000 PSI
  - Shot Interval: 25 m
- *Streamer:*
  - Channels: 120
  - Group Interval: 25 m
  - Streamer Depth: 13
  - Streamer Length: 3000 m
- *Instruments:*
  - Model: DFS V
- *Record Length:* 7 sec
- *Sample Rate:* 4 ms
- *Tape Format:* SEG-B
- *Low Cut Filter:* 5.3 Hz
- *High Cut Filter:* 90 Hz

Data collection in the area faced a number of challenges including:

- A hard water bottom which generated strong multiples and decreased energy penetration;
- Complex structure and steep dips relating to extensional and localized compressional effects, and salt structures;
- Transitioning from the shelf to deep water, with energy loss across the slope break;
- A strong Pre-Rift unconformity reflector in the northern part of the basin where the Tertiary is underlain by Paleozoic rocks;
- A strong "pre-Cretaceous" unconformity reflector (Avalon Unconformity), south of the hinge zone, below which imaging is generally weak; and
- The presence of mass transport deposits and canyons along the continental slope.

Arcis Corporation reprocessed the data in 2005 with a careful focus on the removal of multiples and improving the migration (Negut et al., 2007). Key processing steps included:

- **Statistical Designature**: to statistically estimate and remove the source wavelet:
- **Tau-P Predictive:** to identify general ringyness in the data and water bottom multiple energy;
- **High Resolution Radon Transform**: to suppress ringyness and water bottom multiple energy; and

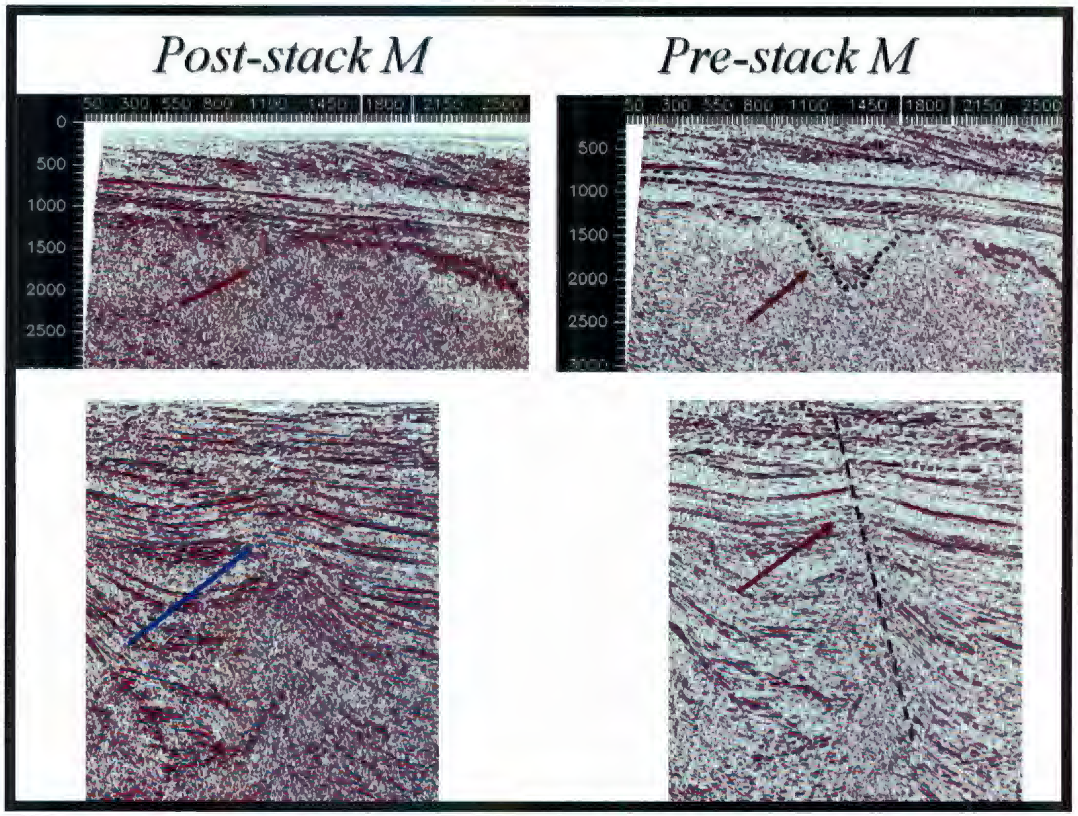


Figure 3.2

Examples of how pre-stack time migration improved the imaging for the GSC's STP reflection lines. The left hand panels show a channel (top) and fault (bottom) that can be interpreted with much greater confidence in the Pre-Stack Time Migration dataset (new processing). Images from Negut et al., 2007.

Full Line Pre-Stack Time Migration: to improve overall imaging, particularly in areas of complex structure. (Negut et al., 2007)

Reprocessing resulted in significant improvement to the data, particularly in the shallower sections where the signal to noise ratio is higher.

Figure 3.2 shows examples of how the Arcis re-processing was able to make improvements in the imaging of a channel and a fault. The examples provide evidence of how the application of current processing methods can give new life to data that were acquired decades ago, and when combined with new geological data and knowledge that has been gathered in the interim, can present exciting new opportunities to both researchers and explorationists.

But even with the notable reprocessing improvements achieved by Arcis, the data still presented some serious interpretation challenges. Figure 3.3 is a gray scale plot of line STP 001 which runs all the way from the Tertiary / Paleozoic section in the north, southward across the hinge zone into the Tertiary / Mesozoic / Paleozoic(?) section and down the slope to the deepwater basin. The north side of the line is dominated by the Pre-Rift Unconformity and its interbed multiple with the seabed. Salt features are noted in the Paleozoic section (Early Carboniferous Windsor Salt) and again as one crosses the hinge into the Mesozoic section (Late Triassic Argo Salt). The Avalon Unconformity (AU) is typically one of the stronger reflectors in the Mesozoic section, and energy penetration below it is weak over large areas. This is particularly evident where the AU is directly underlain by carbonate rocks. Crossing the shelf – slope break there is energy loss possibly relating to the presence of a harder water bottom in this area. Additionally, the fact that the seabed slopes away to the south may lead to greater energy loss due to refractions, wave conversions, and energy being reflected beyond the streamer. Also, as the water bottom multiples cut across the stratigraphy in this part of the section, the multiple removal programs cause some deterioration in the continuity of primary reflectors.

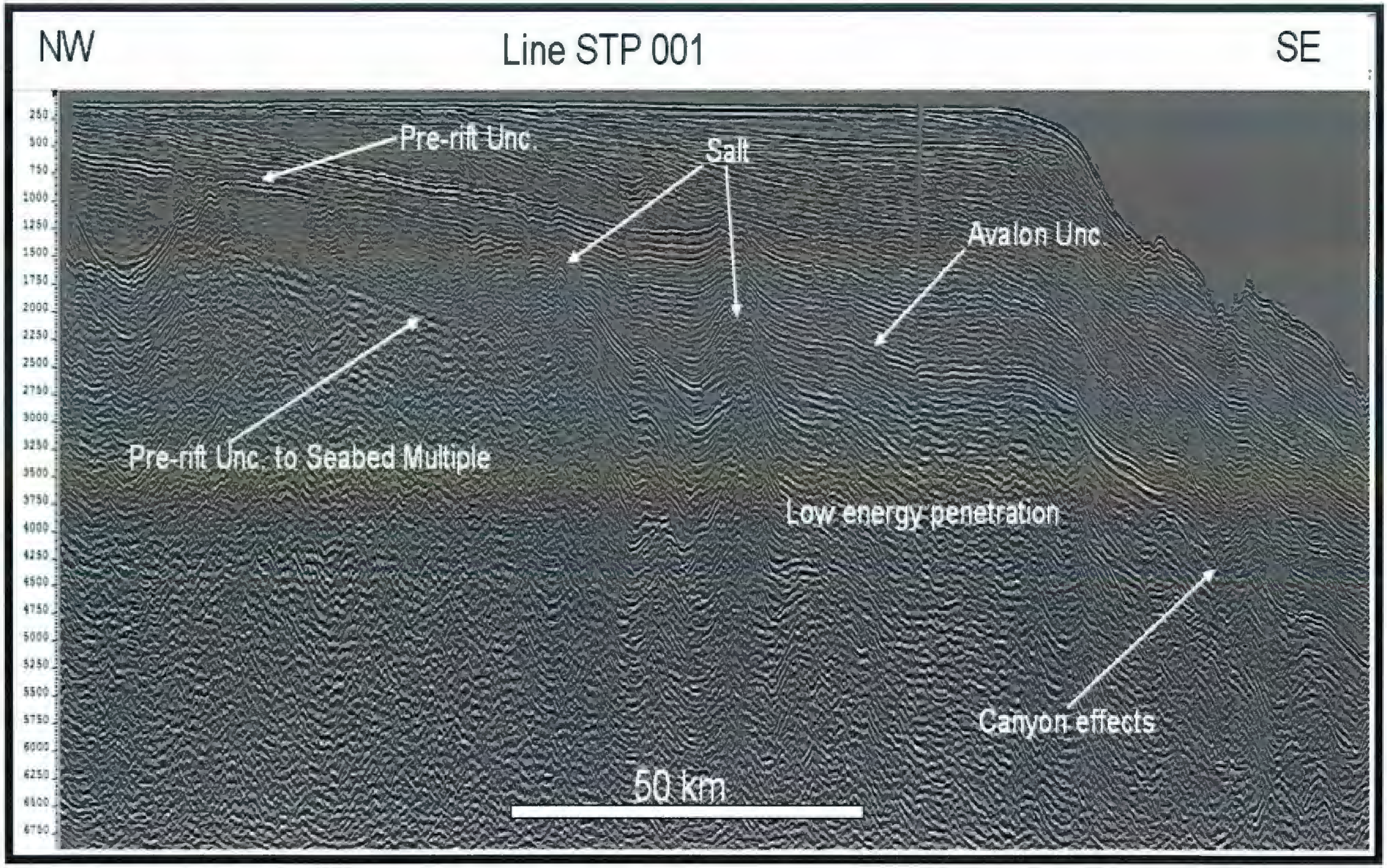


Figure 3.3

Seismic line STP 01 shows some of the interpretation challenges characteristic of the Laurentian Basin GSC dataset, including: strong Pre-Rift and Avalon unconformity reflectors below which imaging is difficult; a strong reverberating Pre-rift Unconformity to seabed interbed multiple in the northern part of the basin; salt tectonic features in both pre-rift and post–rift sections; low energy penetration as one approaches the slope, especially below the Avalon Unconformity; and, multiples and velocity anomalies caused by canyons. Seismic reflection time in milliseconds.

Figure 3.4 is a grey scale plot of line STP 005 illustrating additional interpretation challenges. On the NW end of the line we see complex geology relating to the possible presence of, and dynamic interaction between, the Carboniferous Windsor Salt and the Triassic Argo Salt. Matters are further complicated in this area by what appear to be compressional features associated with strike slip movement along the northern margin of the basin. We see further evidence of the difficulty in imaging the Jurassic – Triassic section with weak energy penetration below the Avalon Unconformity, which results in a low confidence level in mapping of this part of the section. Mass transport deposits located at the seabed and deeper in the section, combined with localized deep erosional channels within the Tertiary sequence produce velocity anomalies. The said anomalies can degrade the imaging of underlying events by scattering seismic energy and by causing "false structuring" in underlying horizons by delaying the arrival of waves passing through lower velocity material within the channels. The intense deformation of the off-shelf sediments by salt tectonics is clearly evident on this section, and suggests that pre-stack depth migrated 3D seismic surveys are likely needed to resolve the geology of this area. The line also shows that the seven second recording time is inadequate in the deep water areas to map the Pre-Rift section. Fortunately, a significant portion of the additional data provided by GSI, Western Geco and GX Technology were recorded to thirteen seconds and allowed for a deeper interpretation that could be extrapolated into this area.

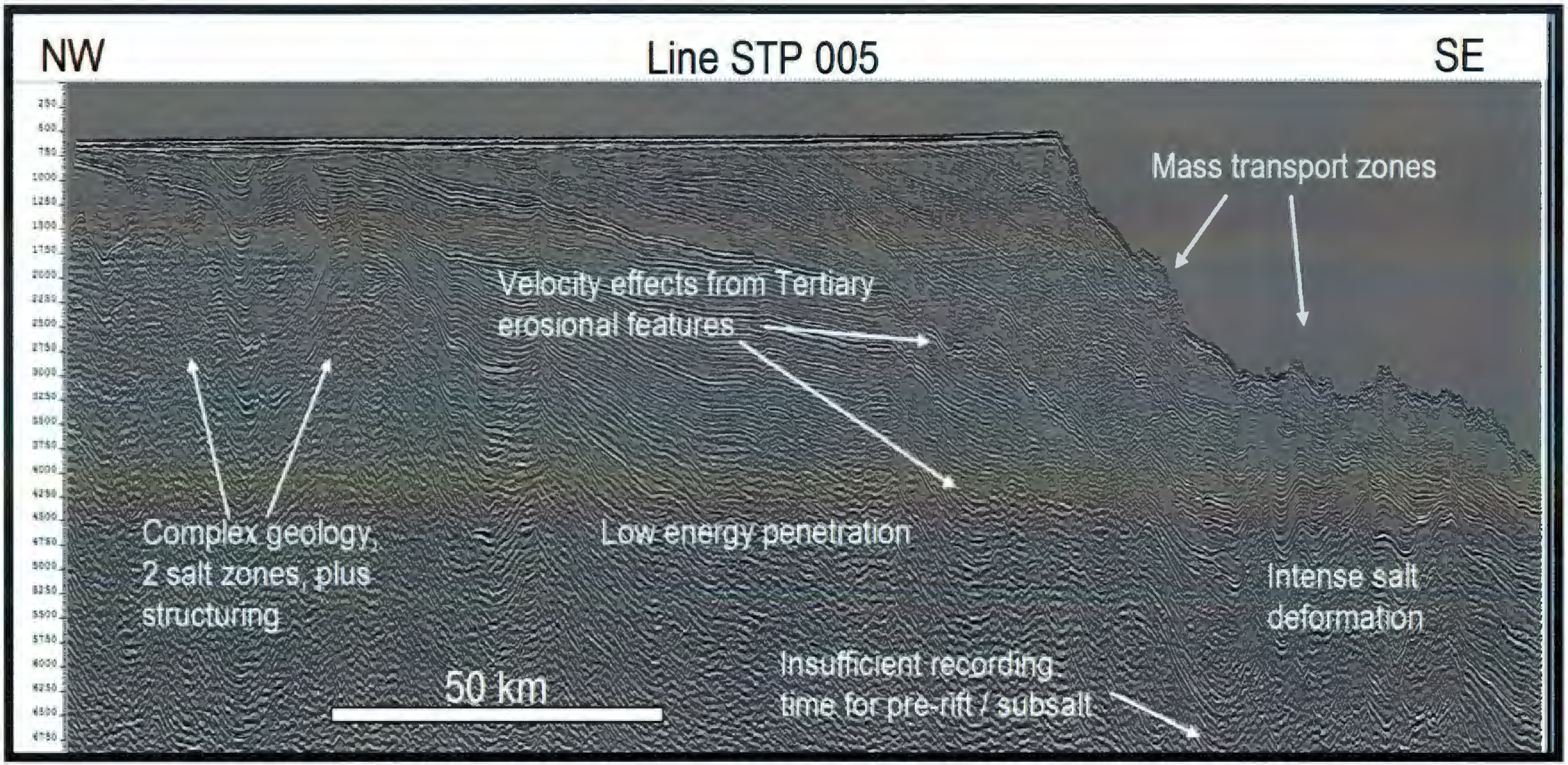


Figure 3.4

Seismic line STP 05 shows some additional data interpretation challenges in the Laurentian Basin GSC dataset, including: complex geology involving salt structures and possible strike slip fault movement; velocity anomalies from Tertiary erosional features; low energy penetration in the Jurassic - Triassic section; and intense salt deformation in the off-shelf area. Also given the water depth off-shelf and thickness of the sedimentary section, seven seconds was insufficient recording time to image pre-rift and subsalt sedimentary sequences in the off-shelf part of the basin. Seismic reflection times in milliseconds.

3.2 Well Data

Only four wells are located within the study area, (locations shown in Figure 3.5), of which one well (Bandol #1) is still under confidential status. Stratigraphic columns for the three public domain wells are presented as Figures 3.6 to 3.8. The *Mobil Tetco Dauntless D-35* well (Figure 3.6) was drilled in 1971 on the western margin of the study area in 69 m of water. It encountered 1433 m of Tertiary (Banquereau Fm.), 2189 m of Cretaceous sequences and 1033 m of the Jurassic Micmac Formation. A core from the Upper Mississauga sandstone was analyzed and indicated porosities ranging from 25 – 40% (GSC Basins Website). The *Elf Hermine E-94* and *Elf et al Emerillon C-56* wells are located on the eastern margin of the basin lying just north of the hinge zone. The Hermine E-94 well (Figure 3.7) was drilled in 1971 in 83 m of water and encountered 848 m of Tertiary and 972 m of Cretaceous, including about 200 m of Eider sandstone sitting directly upon the Base Cretaceous Unconformity. The Cenomanian Unconformity has been picked by the C-NLOPB (Basins website) within the Eider, but it cannot be followed with much confidence on the seismic data within the study area. The presence of the Eider and/or Mississauga sands just above the Avalon Unconformity has important sealing implications for possible stratigraphic plays subcropping against this regionally prominent event. When considering such plays it will be important to identify areas where these sands have been eroded or shaled out. Below the Avalon Unconformity the well passed through 819 m of Carboniferous redbeds, followed by 813 m of Windsor Salt. No conventional cores were cut and no flow tests were conducted. With regard to seismic interpretation it is notable that the upper half of the evaporite sequence in

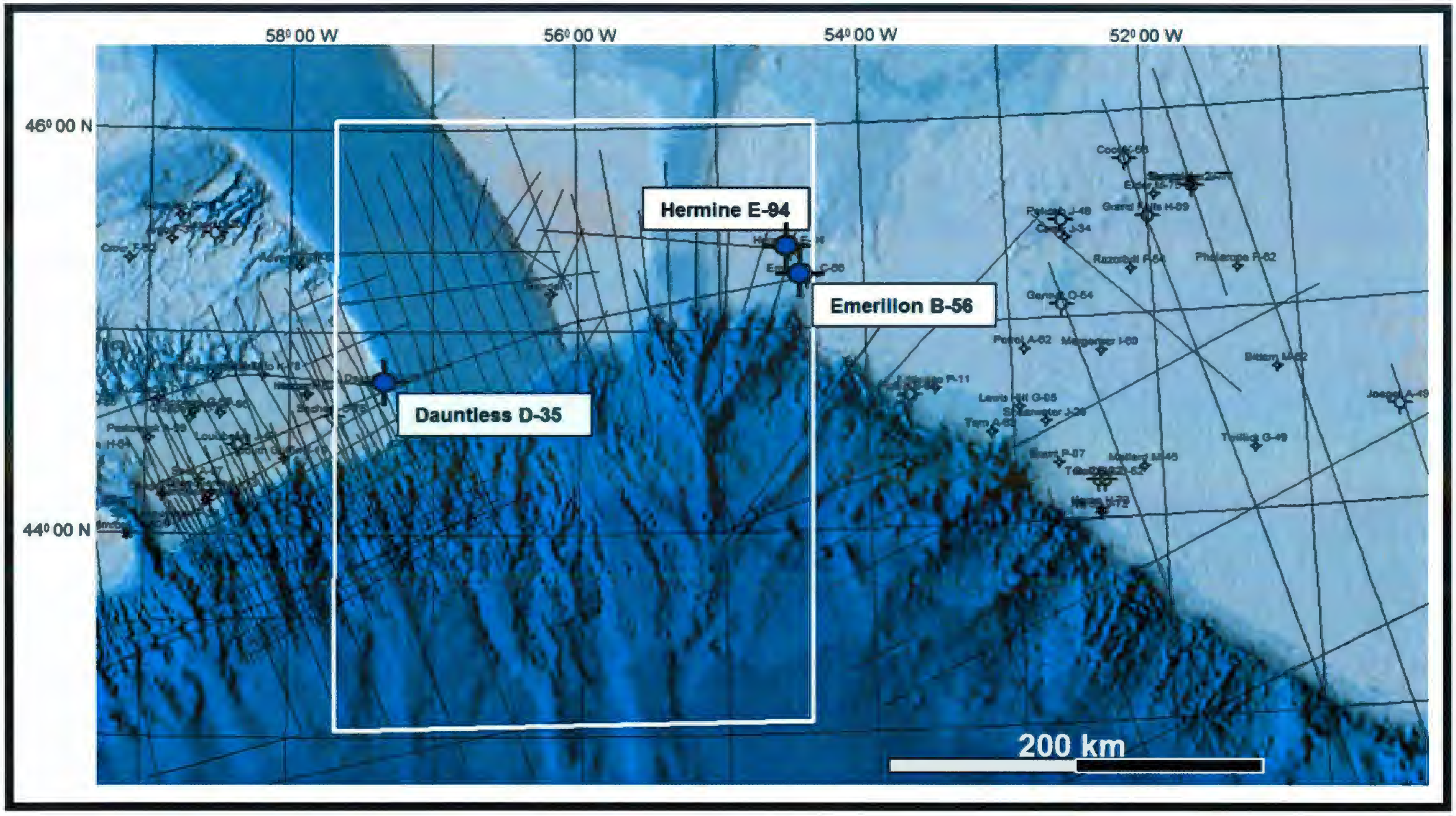


Figure 3.5

Bathymetry map with well and seismic line locations. Wells for which digital logs were available for this study are shown as larger well symbols. Wells for which seismic ties are presented in Figures 3.9 to 3.11 are highlighted. Bathymetry map from the GSC and Canadian Hydrographic Service. Study area is outlined in white. See Figure 1.1 for colour legend.

this well included some seismically imaged anhydrite and dolomite stringers. This serves as a reminder that what we call the salt interval must be properly considered as an "evaporite interval", and will quite often include strong intra-formational reflectors.

The *Elf et al Emerillon C-56* well (Figure 3.8) was spudded in December 1973 in 119.8 m of water, and drilled 1156 m of Tertiary (mostly shale), followed by 932 m of Cretaceous and 1316 m of Jurassic sequences. The C-NLOPB has interpreted the last 159 m of the hole to be Windsor evaporites, whereas MacLean and Wade (Basins website) interpret it as "Iroquois Formation(?)". In any case it is overlain by the Sinemurian unconformity (i.e. Break-up Unconformity), which marks the base of the post-rift sequence and is an important if tenuous seismic marker throughout the basin. As this well was drilled in a graben above the hinge zone it provided only an uncertain jump tie to the main basinal sequences, and cannot be said to have provided a definitive tie to the Break-up Unconformity.

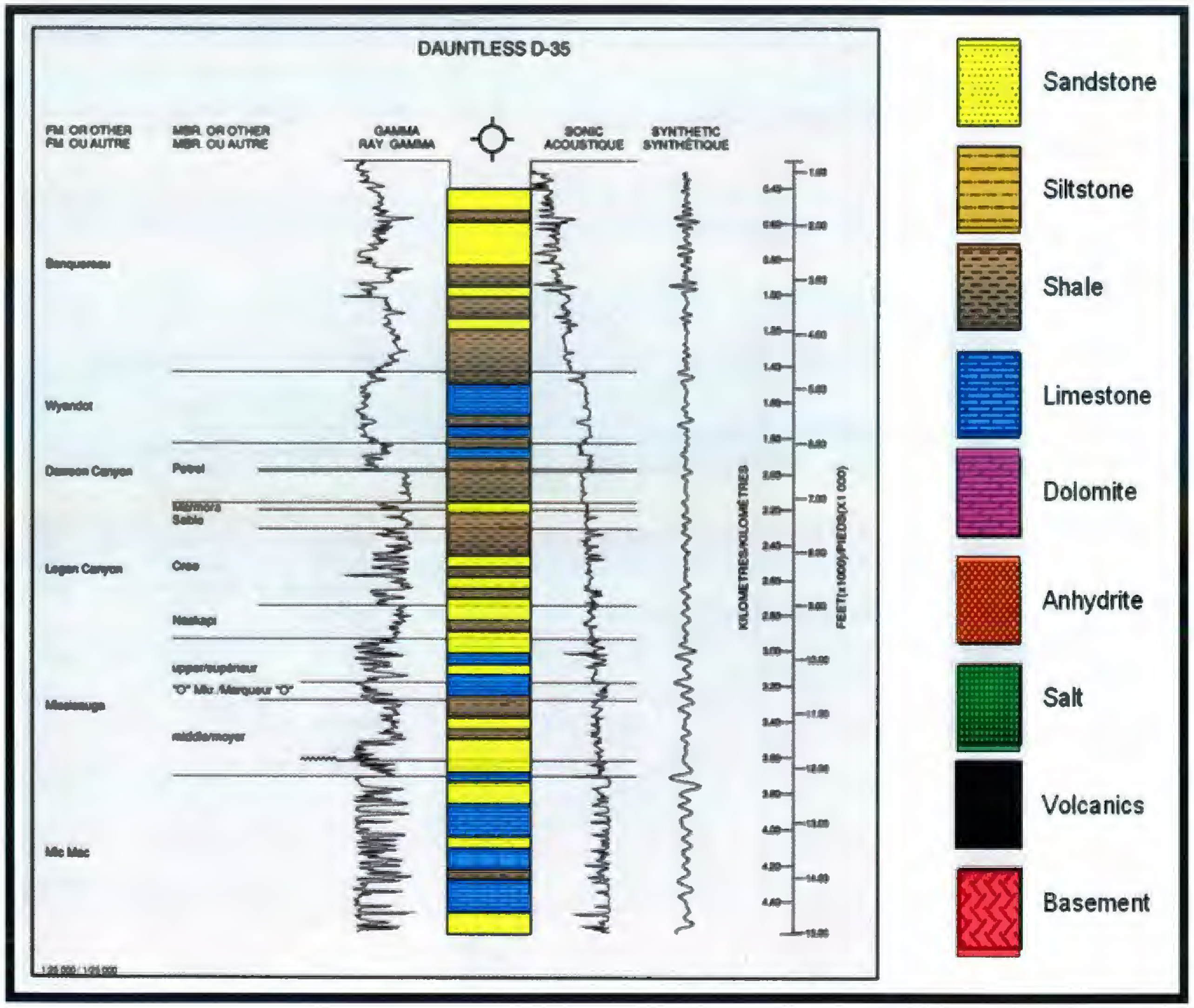


Figure 3.6
Stratigraphic column and representative logs for the Dauntless D-35 well. Modified from GSC "Basins" website. http://apps1.gdr.nrcan.gc.ca/mirage/show_image_e.php?client=mrsid2&id=221116&image=gscecbas_sm_b_1993_nt057.sid

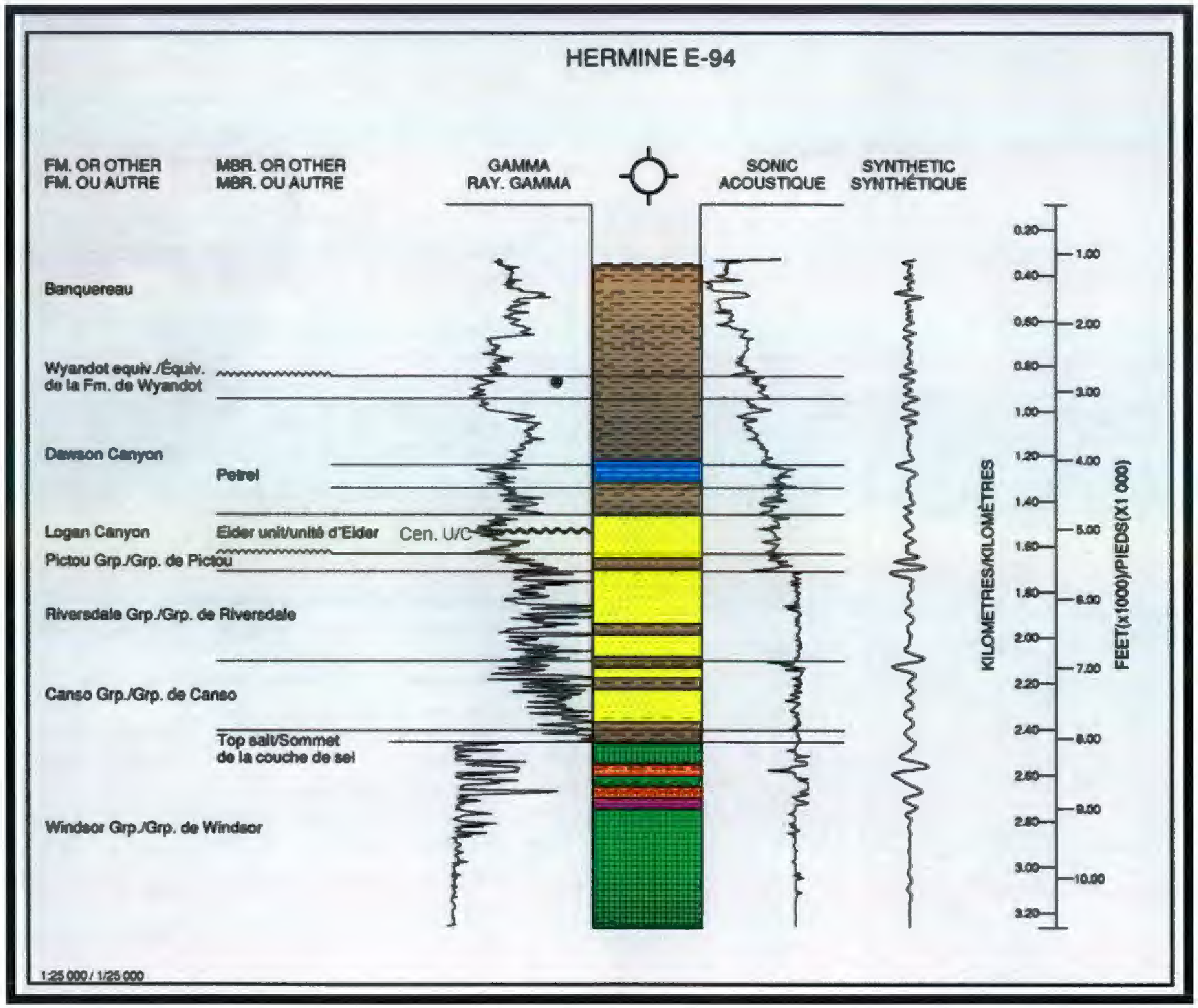


Figure 3.7

Stratigraphic column and representative logs for the Hermine E-94 well. See Figure 3.6 for legend. Modified from GSC Basins website.
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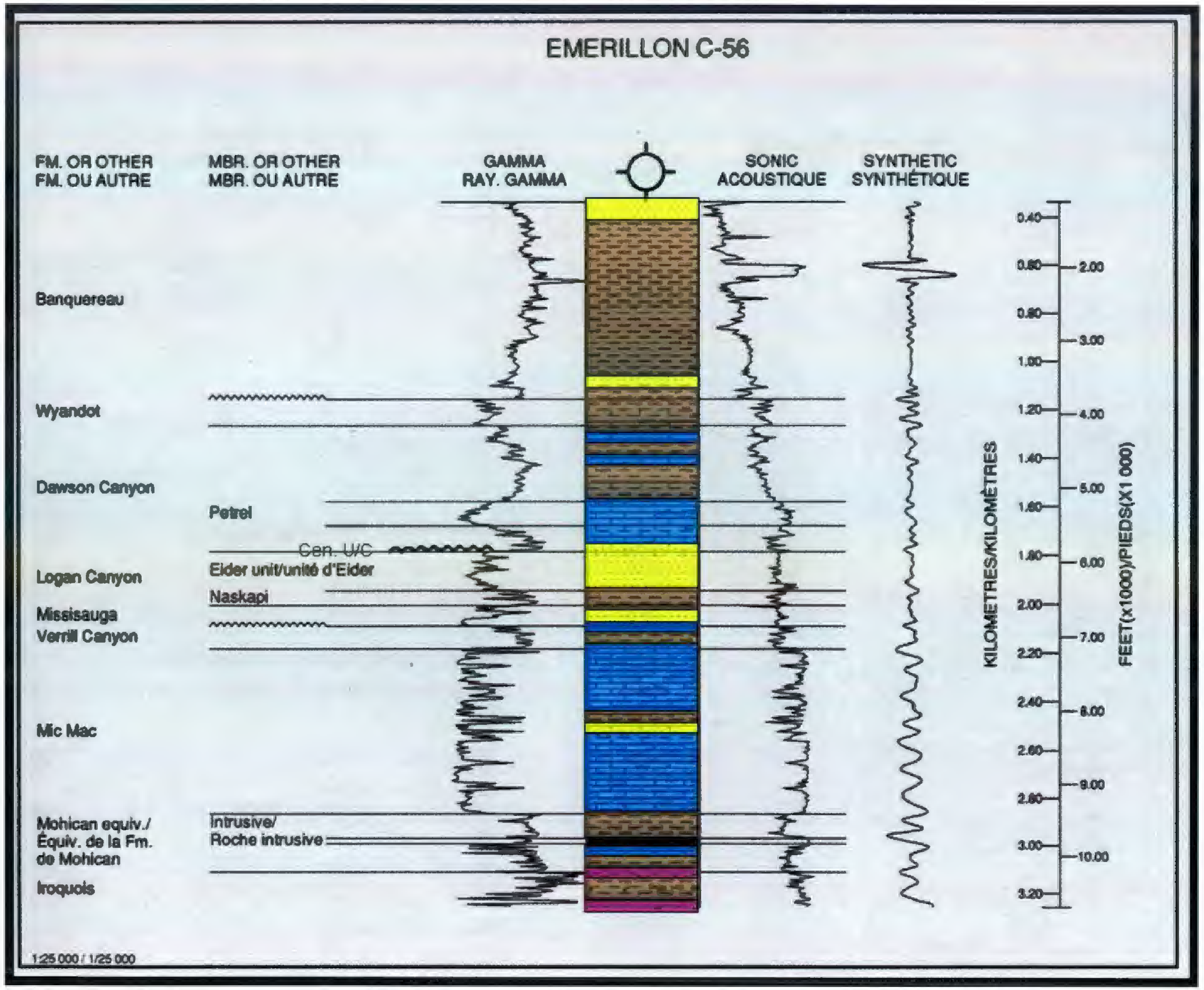

Figure 3.8

Stratigraphic column and representative logs for the Emerillon C-56 well. See Figure 3.6 for legend Modified from GSC Basins website..
http://apps1.gdr.nrcan.gc.ca/mirage/show_image_e.php?client=mrsid2&id=221116&image=gscecbas_sm_b_1993_nt065.sid

3.3 Well Ties to Seismic Data

IHS Inc. donated digital logs (LAS format) for fourteen wells on the eastern Scotian Shelf, Laurentian Basin and South Whale Basin, including: Coot K-56, Dauntless D-35, Emerillon C-56, Gannet 0-54, Grand Falls H-09, Gull F-72, Jaeger A-49, Louisbourg J-47, Pelican J-49, Sachem D-76, Sandpiper J-77 and Tors Cove D-52.

Digital synthetic seismograms were generated from LAS files provided by IHS for the Emerillon C-56, Dauntless D-35, Narwhal F-99, Puffin B-90, Louisbourg J-47 and Sachem D-76 wells (Figure 3.5). Tops were imbedded in the files provided by IHS and cross checked by log character against picks by MacLean and Wade in Figures 3.6 to 3.8 (GSC “Basins” website). The synthetic ties were generally good in the Tertiary - Cretaceous section, but more complicated in the Jurassic and Carboniferous section. The section from the Wyandot to surface was simply referred to as the “Banquereau” formation, with no breakdown of the individual stratigraphic members on the government websites, or in the IHS data provided. In this study two unconformities were interpreted within the Banquereau Formation, whose ages were estimated by correlating with the Vail et al (1977, 1984) and Vail and Mitchum (1979) sea level charts.

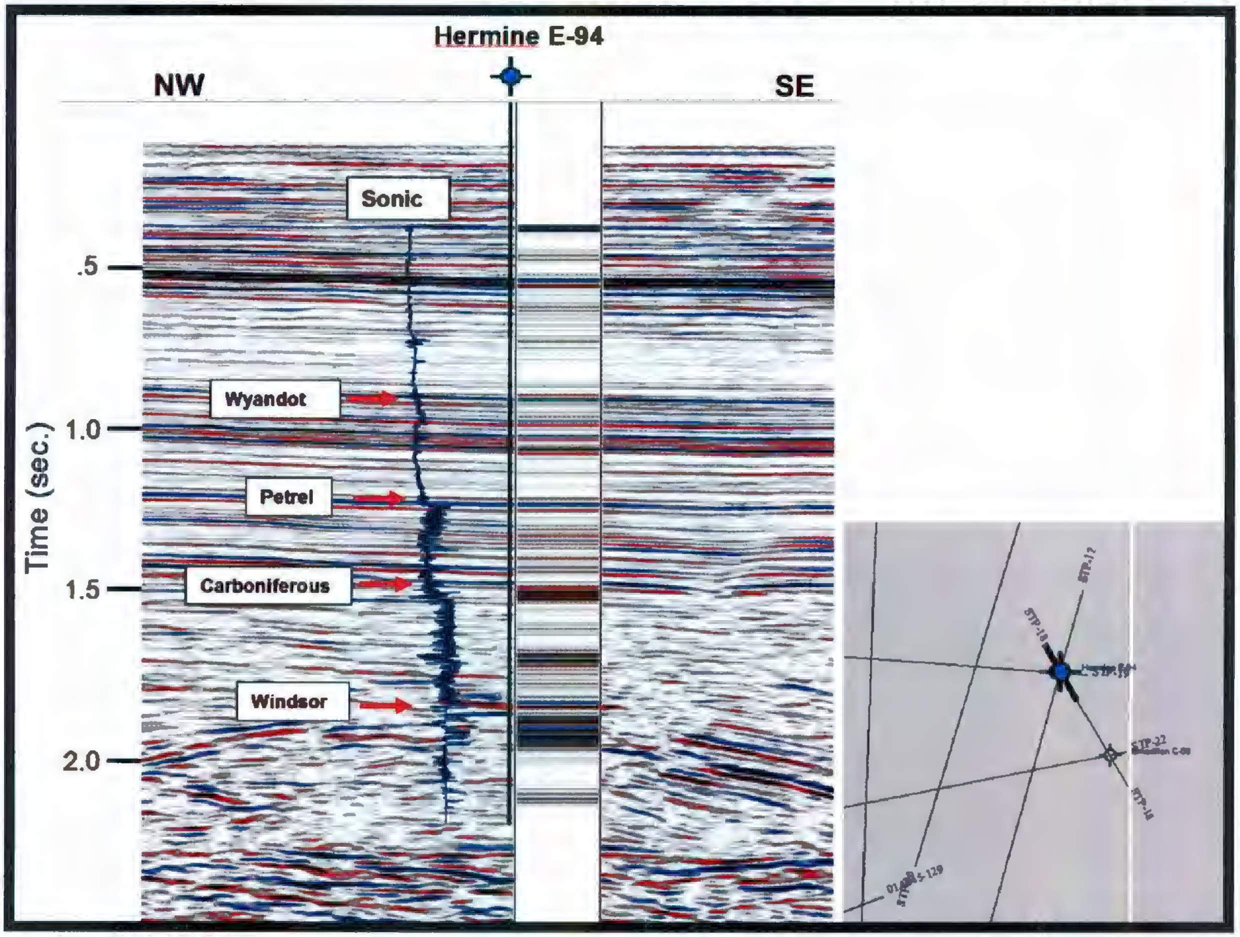

Figure 3.9

Synthetic seismogram tie of the Hermine E-94 well to seismic line STP 18. Digital log courtesy of IHS. Seismic data courtesy of the GSC. Insert shows location of seismic line with respect to the well.

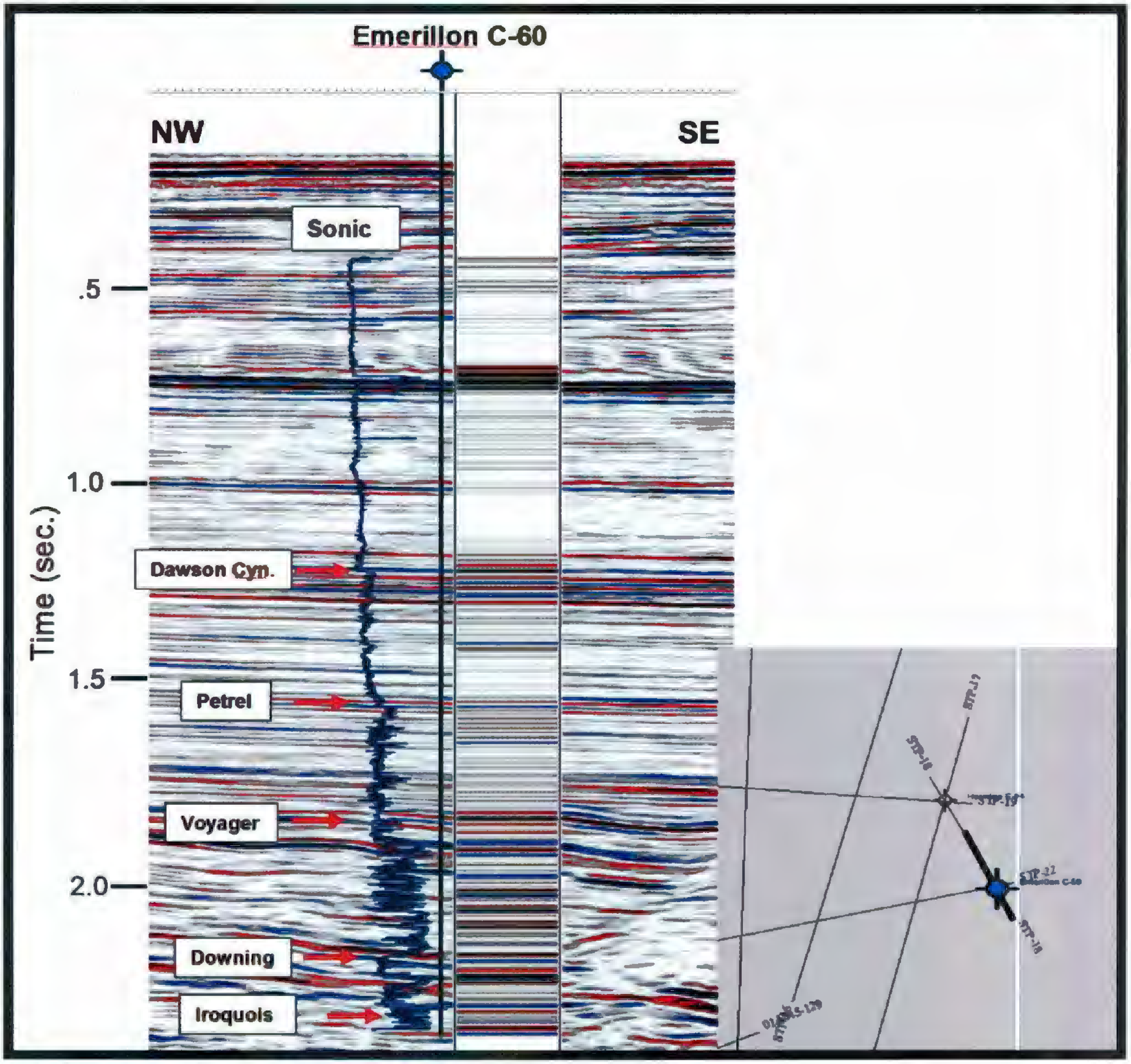

Figure 3.10

Synthetic seismogram tie of the Emerillon C-60 well to seismic line STP 018. Digital log courtesy of IHS. Seismic data courtesy of the GSC. Insert shows location of seismic line with respect to the well.

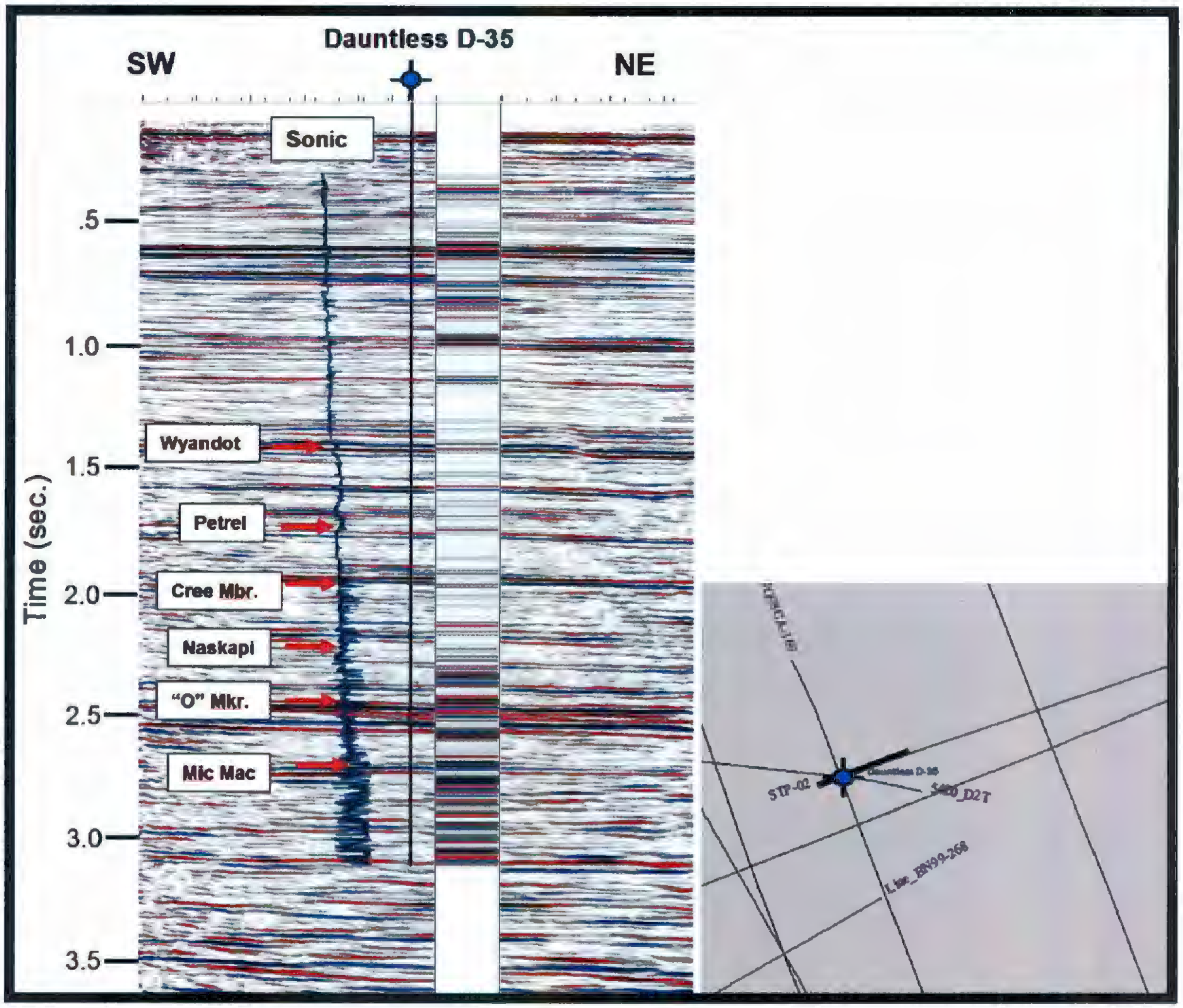

Figure 3.11

Synthetic seismogram tie of the Dauntless D-35 well to seismic line STP 02. Digital log courtesy of IHS. Seismic data courtesy of the GSC. Insert shows location of seismic line with respect to the well.

3.4 Gravity and Magnetic Data

Regional GSC gravity (GSC, 1988a) (Bouguer onshore and Free Air offshore) and magnetic data (GSC, 1988b) were utilized to help correlate major structural and tectonic features. These data were supplemented by high resolution aeromagnetic data donated by Fugro (Figure 3.12). Although no potential field modeling or data manipulation were carried out in this study, the gravity/mag data were used to spot major lineaments likely to be related to faulting and the presence of depocentres or basement highs.

The Fugro grid is based on 71,348 line km of non-exclusive data acquired from July 16 to October 10, 1999. The magnetometer was flown at an altitude of 100 m (average) with a tolerance of $\pm$20 m from nominal over a distance greater than 3 km. Lines were recorded over 1 X 3 km grid flying constant latitude and longitude with a tolerance of $\pm$150 m. The high resolution total magnetic intensity (TMI) map (Figure 3.12 A) ties quite well with the regional grid, suggesting a general NW – SE trending structural grain within the northern part of the study area, with a sharp step down into the basin. The first derivative of TMI (Figure 3.12 B) enhances some of the trend expressions seen in the TMI, particularly in the southernmost part of the survey, where anomalies are seen roughly on trend with the East Coast Magnetic Anomaly (Figure 2.3).

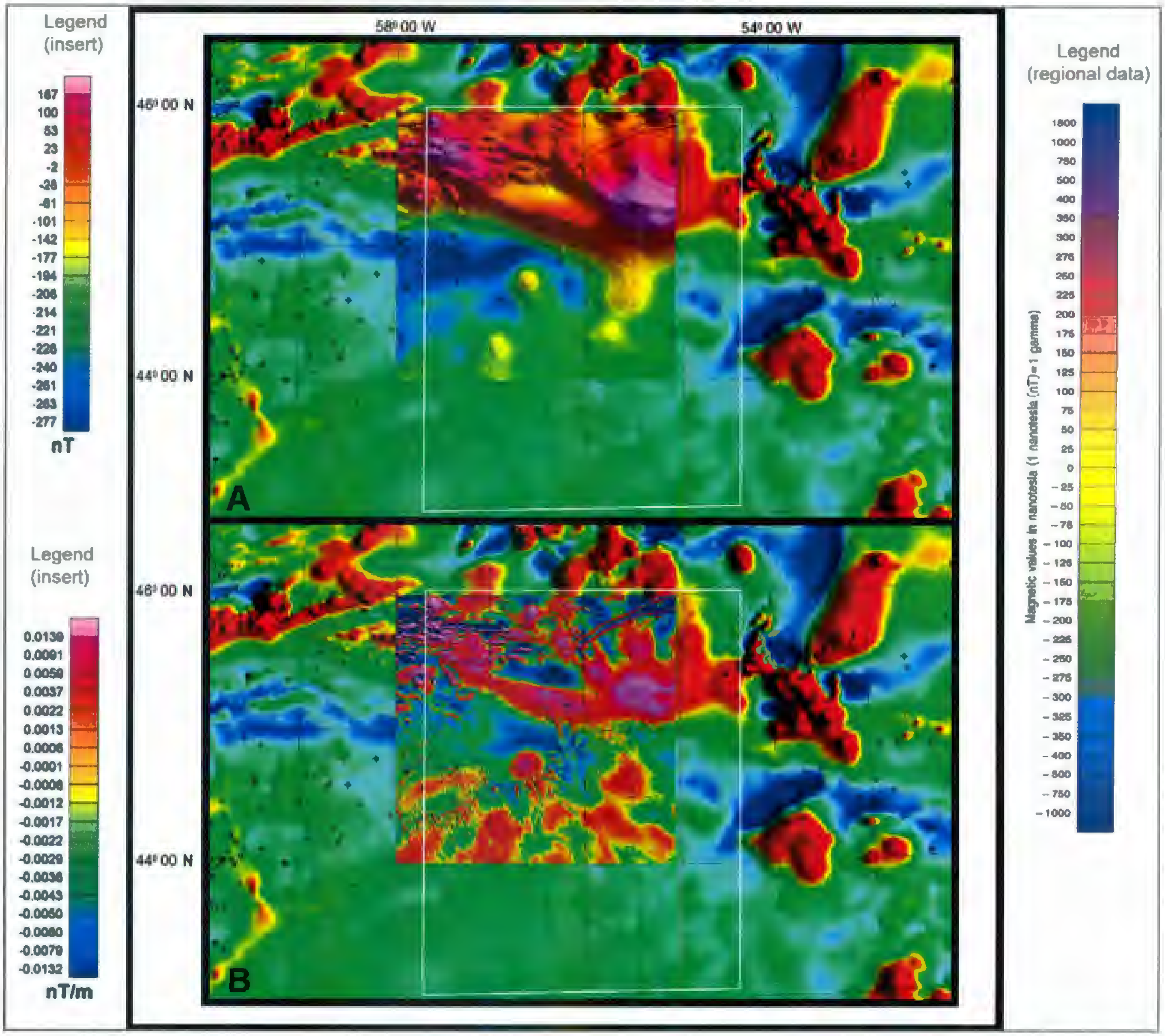

Figure 3.12

High resolution aeromag map, provided by Fugro, inserted within the regional GSC total magnetic intensity (TMI) grid. Figure "A" shows Fugro high resolution TMI insert and "B" shows the first vertical derivative of the TMI insert. With permission of Fugro. White outline indicates study area.

3.5 Cable Break Locations

Figure 3.13 shows the location of the epicentre of the 1929 earthquake and the locations of cable breaks with respect to seismic lines and wells in the area. The yellow circles indicate where cables broke "instantaneously", which can be interpreted to mean that these were part of the source area for the turbidite, while the orange circles indicate cable breaks within the study area that occurred later. What this illustrates is that a huge area, spanning 275 km along strike, and about 120 km down slope (33,000 km^2) was part of the source area for the flow! Given the very large source area for this turbidite, it follows that very large sedimentary deposits can be created by this process, and proportionately large deep sea fan type hydrocarbon traps. This will be particularly true where an elbow in the shelf acts to funnel the sediments into a narrower area – as has been the case in the Laurentian Basin since the Mid-Jurassic.

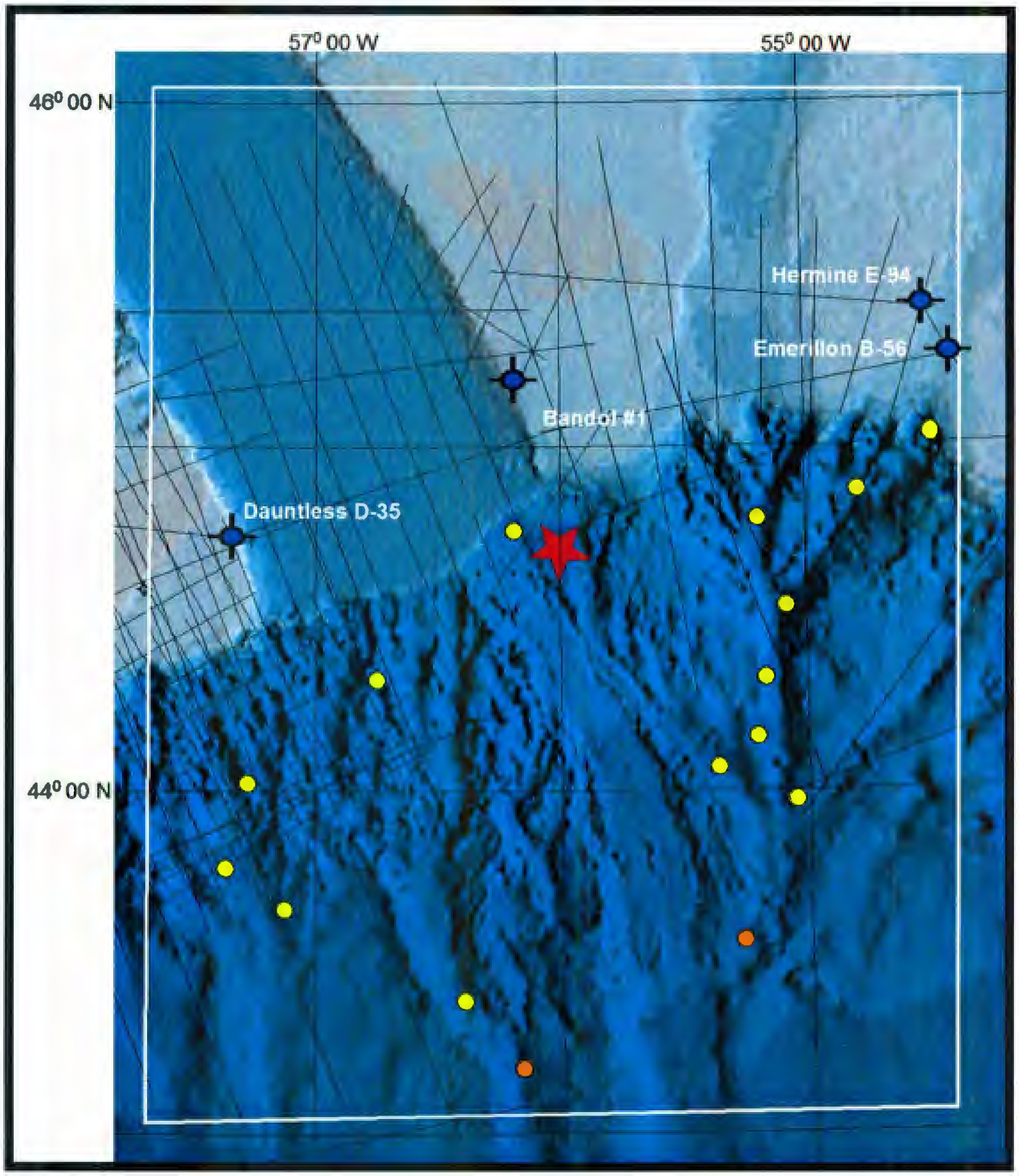

Figure 3.13

Laurentian Basin Bathymetry Map showing the locations of wells and seismic lines in the study area along with yellow circles indicating the locations of "instantaneous" cable breaks associated with the 1929 earthquake / turbidite flow, and orange circles representing delayed cable breaks. Other cable breaks occurred south of the study area. The red star indicates the location of the earthquake epicentre. Bathymetry map from the GSC and Canadian Hydrographic Service. Epicentre location and cable break locations from the Atlantic Geoscience Society (2001). See Figure 1.1 for colour legend.

Chapter 4
Interpretation

4.1 Seismic Interpretation

As pointed out in Chapter 3 the seismic data in the Laurentian Basin presented some considerable challenges to the interpreter because of data quality and geological complexity. However, it must also be said that data quality in the shallower sections, above the Avalon Unconformity, is actually very good. But, given that one of the key goals for this project was to investigate the relationship of the basin structure to the pre-existing basement fabric, it was necessary to interpret the deeper events, including the Pre-Rift horizon and the Break-Up Unconformity - where the signal to nose ratio is generally poor. Figure 4.1 is a modified tectono-stratigraphic chart for the Laurentian Basin based on the chart initially published by MacLean and Wade (1992). This is a repeat of Figure 2.9 with original additions indicating basin evolution, main seismic markers and reservoir zones that have flow-tested significant oil and gas on the Scotian Shelf and in the Carboniferous basins throughout Atlantic Canada. It is presented here to provide a reference for the forthcoming seismic interpretation.

Figure 4.2 shows the interpreted and uninterpreted version of the seismic line STP 017, located on the eastern side of the study area. The line is fairly typical of the quality of the core dataset (the GSC STP lines). Figure 4.2 clearly illustrates that there is a dramatic change in both data quality and geological complexity beneath the easily recognizable Avalon Unconformity.

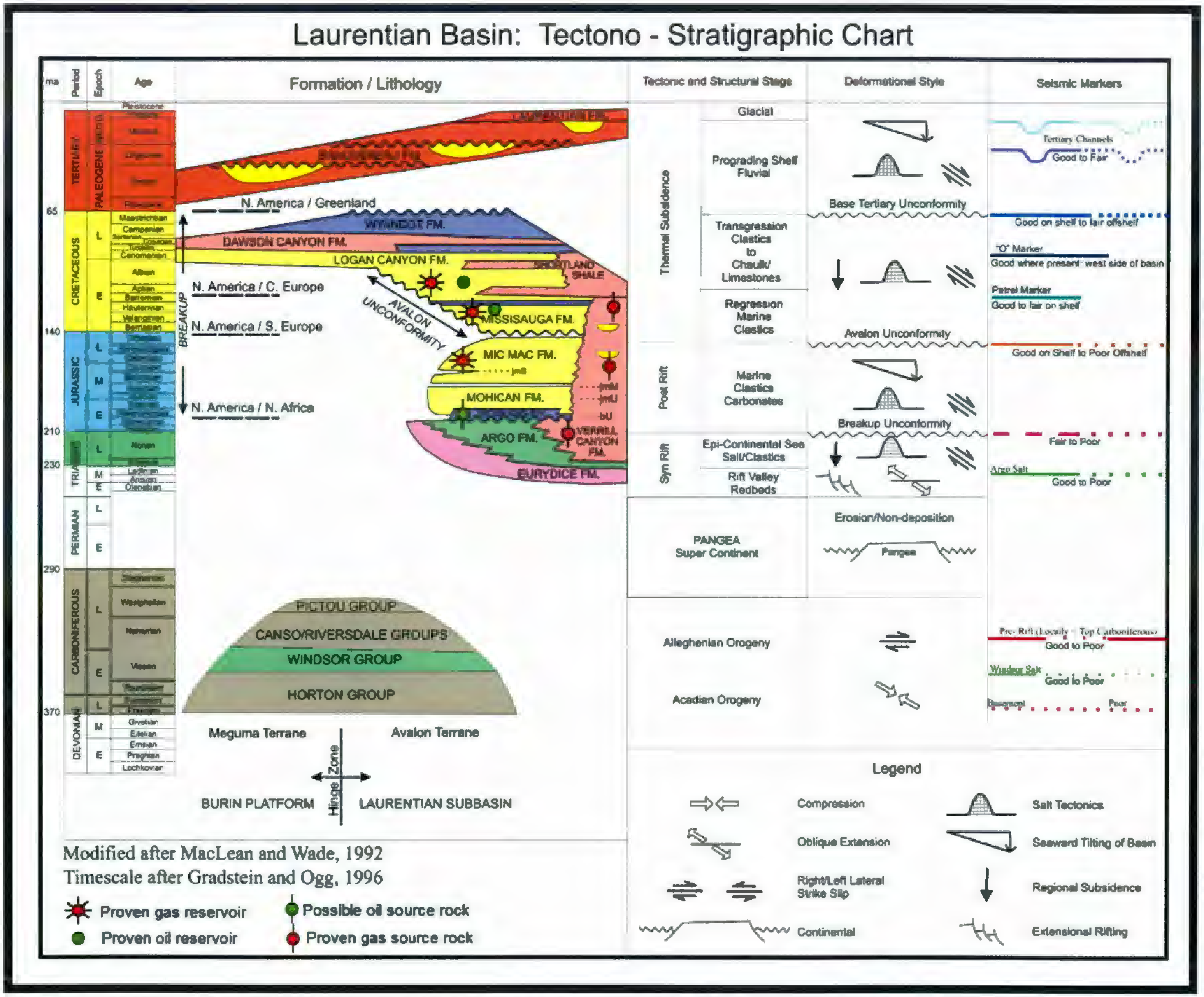

Figure 4.1

Tectono Stratigraphic Chart of the Laurentian Basin, including: oil and gas reservoirs and source rocks; deformation styles; and main seismic markers. Modified after Maclean and Wade (1992), with timescale from Gradstein et al (2004).

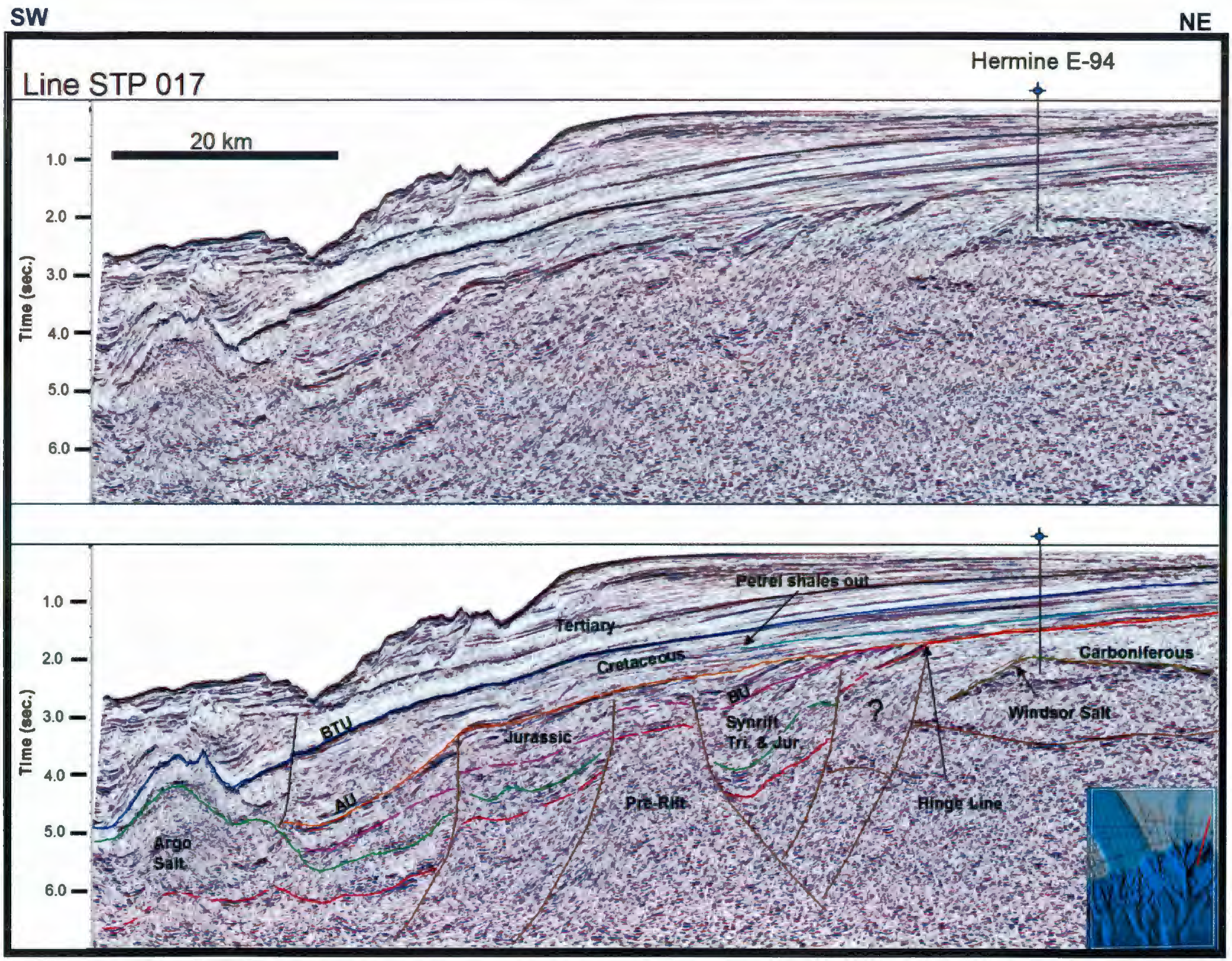

Figure 4.2

Seismic Line STP 017; uninterpreted (above) and interpreted (below). The line shows gently dipping, parallel beds above the Avalon Unconformity (AU) with a faulted and folded sequence below it. The AU merges with the top Pre-Rift horizon (red) at the hinge line. The BTU (Base Tertiary Unc.) is a coherent regionally correlatable marker. Seismic line courtesy of the GSC.

Several Tertiary and Cretaceous seismic horizons can be recognized in this section and correlated with a high degree of confidence, while the deeper reflectors leave a lot of leeway to the interpreter. In accordance with the goals of the project there was no attempt to interpret every reflector on the seismic data and so only certain key horizons were selected for both correlation and mapping of the major sequences. These include the:

- Mid Miocene(?) Unconformity
- Late Oligocene(?) Unconformity
- Base Tertiary Unconformity
- Avalon Unconformity
- Break-up Unconformity
- Top of the Pre-Rift section (Pangea Unconformity)

Additionally the Petrel limestone was correlated where present, as was the "O" Marker, the top of the Argo Salt, top of Windsor Salt and the Base of Windsor Salt. Figure 4.2 shows how the Petrel Limestone, which is a good regional marker throughout the Scotian Shelf and Grand Banks Mesozoic basins is a rather tenuous event in the Laurentian Basin. The "O" Marker is an important stratigraphic and seismic mapping horizon on the Scotian Shelf but is only present on the western side of the study area. The top and base of Windsor Salt can only be mapped with confidence north of the hinge line (Figures 4.2 and 4.6A&B), and mostly towards the eastern side of the Basin. The Argo Salt, on the other hand, is widely distributed in the basin and by its doming and pillowing character provides the key to estimating the ages of the seismic horizons lying above and below it. This is not, however, a straight forward arrangement, particularly in the case of younger formations which, in many cases, have been pierced by Argo salt intrusions. Also, in some parts of the basin (particularly in the northwestern corner), it is not clear whether the "pillowing" character is representative of the Argo Salt or the Windsor Salt – or due to inversion/compressional folding. Nevertheless, by combining the observations on one line with those on the adjacent lines, and by establishing regional trends (with some help from the gravity and magnetic field maps), interpretation maps of the Pre-Rift horizon and the Break-up Unconformity were completed.

The Pre-Rift horizon can be easily tracked to the north of the hinge line, where it merges with the Avalon Unconformity, representing the top of the Carboniferous section in this area. South of the hinge line the horizon becomes weak and discontinuous, and in many places is not visible at all. In such cases other interpretation criteria are brought to bear. For example, immediately south of the hinge line (just above the question mark in Figure 4.2) it marks the base of a coherent sequence, below which can be seen a discontinuous "Pre-Rift basement" character. Continuing south we see what is interpreted as Argo Salt pillowing (although Windsor Salt is a possibility too) and I correlate the Pre-Rift to a higher energy package sitting just below it. Well data indicate that the first sequence below the Argo Salt within the synrift grabens should be the Eurydice

Formation (continental clastics). However, this formation is not very well imaged in this area, and for the purpose of mapping gross basinal structure, the Eurydice Formation, where it is present at depth, should reflect the Pre-Rift geomorphology to a reasonable degree. Further south, the seismic character suggests the presence of a major ridge bounded by normal faults, indicating that the Pre-Rift event should be picked higher in the section. With no definitive reflection to pick it has been placed within a higher energy package at the top of the discontinuous "basement character". We also observe normal faults stepping down into the basin accompanied by Argo Salt structures. Although a clearly correlatable Pre-Rift event is not always present further down the line, I am guided to a "best estimate" pick by the direction of throw on these faults and the requirement that it be placed below the base of the Argo Salt. Using the above reasoning patterns, after many iterations through the dataset, an interpretation of the top of the Pre-Rift horizon was completed. To indicate the level of confidence of the Pre-Rift horizon correlation on the seismic sections presented either solid or dashed lines are shown – solid for higher confidence and dashed for lower confidence picks.

The Break-up Unconformity (BU), also a tenuous pick, was interpreted as the first regional unconformity above the Argo Salt. Although the BU horizon is a challenging pick on line STP 017 (pink horizon; Figure 4.2), it is more easily recognized in other parts of the basin (e.g. line STP 005, Figure 4.5). In addition to its relationship to the Argo Salt, the BU can be identified as sitting roughly atop the local synrift grabens. In Figure 4.2 we see that this is the case in the first graben located to the south of the hinge line. It is also quite evident in Figure 4.3A which shows a composite seismic line running northeastward along strike from the Scotian Shelf and across the Laurentian Basin. On this line we observe that the Break-up Unconformity has been interrupted in places by reactivation of rift faults in the later Jurassic sag phase, during which significant seaward tilting of the basin occurred. Faulting of the BU has occurred to varying degrees throughout the basin and is an indication that tectonic activity did not completely stop with the start of seafloor spreading. Post BU faulting may also be related to salt tectonism, uplift associated with the Avalon Uplift and strike slip movement along the NFZ and CC fault systems.

The Avalon Unconformity (AU) is an easily recognizable marker throughout the Laurentian Basin and in the basins to the east. As noted in Chapter 2 there has been some historic confusion in correlating this event over large distances because various erosional events associated with the Avalon Uplift occasionally merge and diverge. An additional complication is presented by the presence of a Cenomanian Unconformity, picked in the Hermine E-94 well (Figure 3.7), that lies very close to the AU and may also merge with it in some areas. To work out the intricacies of these unconformities and the associated erosional events lies beyond the scope of this study. However, a major widespread, easily recognizable unconformity spanning a period from approximately latest Jurassic to pre – Late Cretaceous can be correlated with confidence across the study area. Moving westward onto the Scotian Shelf the event becomes conformable (Maclean and Wade, 1992) and marks the top of the Mic Mac Formation. The available sonic logs for the wells within the study area (Figures 3.6, 3.7 and 3.8) show a sharp velocity contrast across this unconformity. This is particularly true where the AU is underlain by Carboniferous sediments or by Jurassic carbonates.

The Turonian aged Petrel Limestone is an important seismic and stratigraphic horizon in the basin as it marks the top of a major clastic sequence that includes economically significant sandstone reservoirs of the Logan Canyon and Mississauga Formations (Figure 4.1). Figure 4.2 shows how the Petrel Marker fades as one moves seaward from Hermine E-94, likely due to the limestone thinning or shaling out. Figure 4.3A also shows how, in places, the Petrel Marker is not a single event but a series of events representing limestone stringers. This East–West composite seismic section shows that when correlating the Petrel Limestone Marker from the wells on the eastern side of the basin, the event fades as one approaches the Laurentian Channel. When following the Petrel Limestone Marker eastward from well ties on the western side of the basin we observe that it is truncated in the middle of the Laurentian Channel by the Base Tertiary Unconformity. We also observe that it sits at a slightly higher stratigraphic level than the event of the same name that we had correlated from the east.

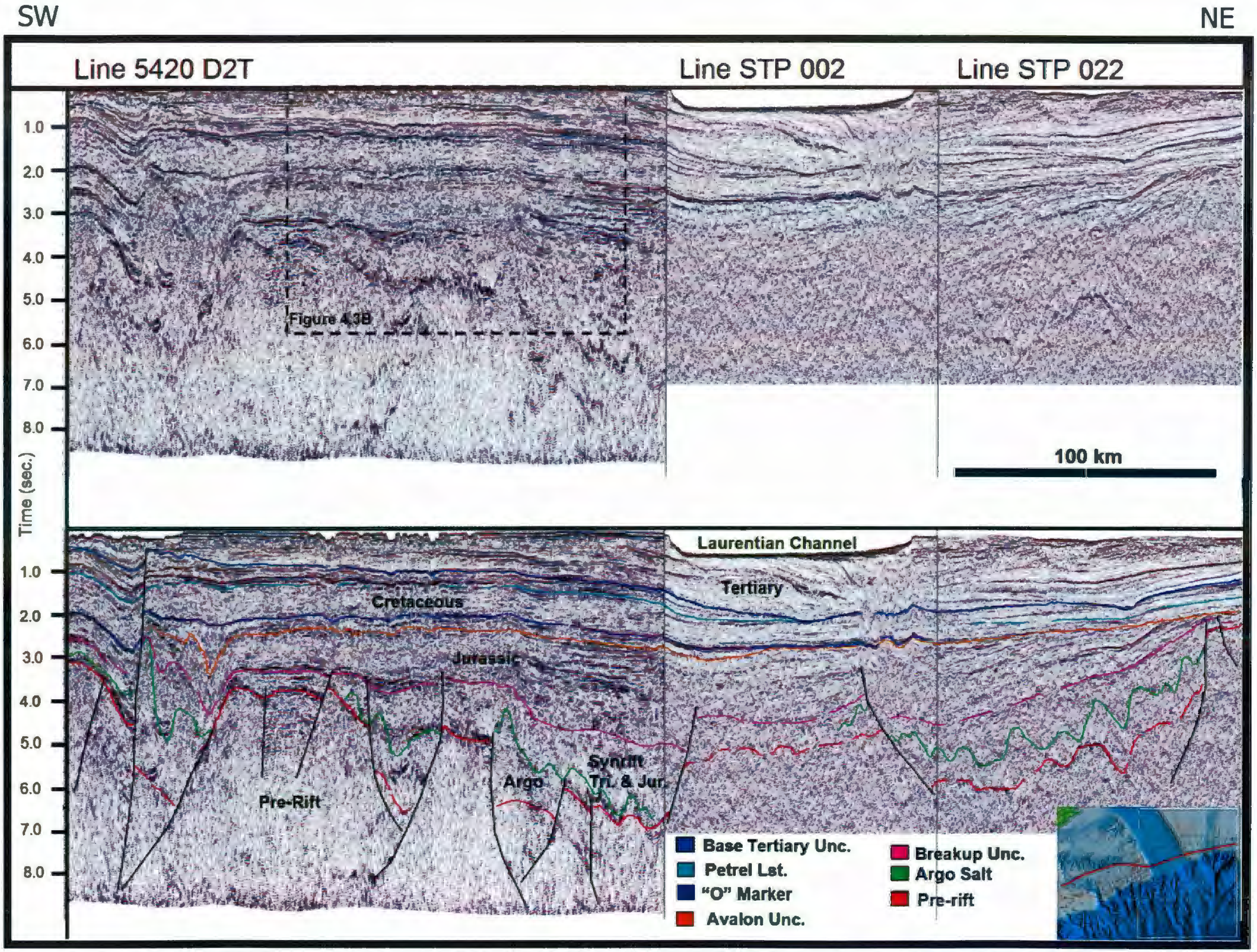

Figure 4.3A

Composite strike seismic line running from the Scotian Shelf (western Abenaki sub-basin) to the eastern margin of the Laurentian Basin. Line 5420 courtesy of GX Technologies. Lines STP 002 and 022 courtesy of the GSC.

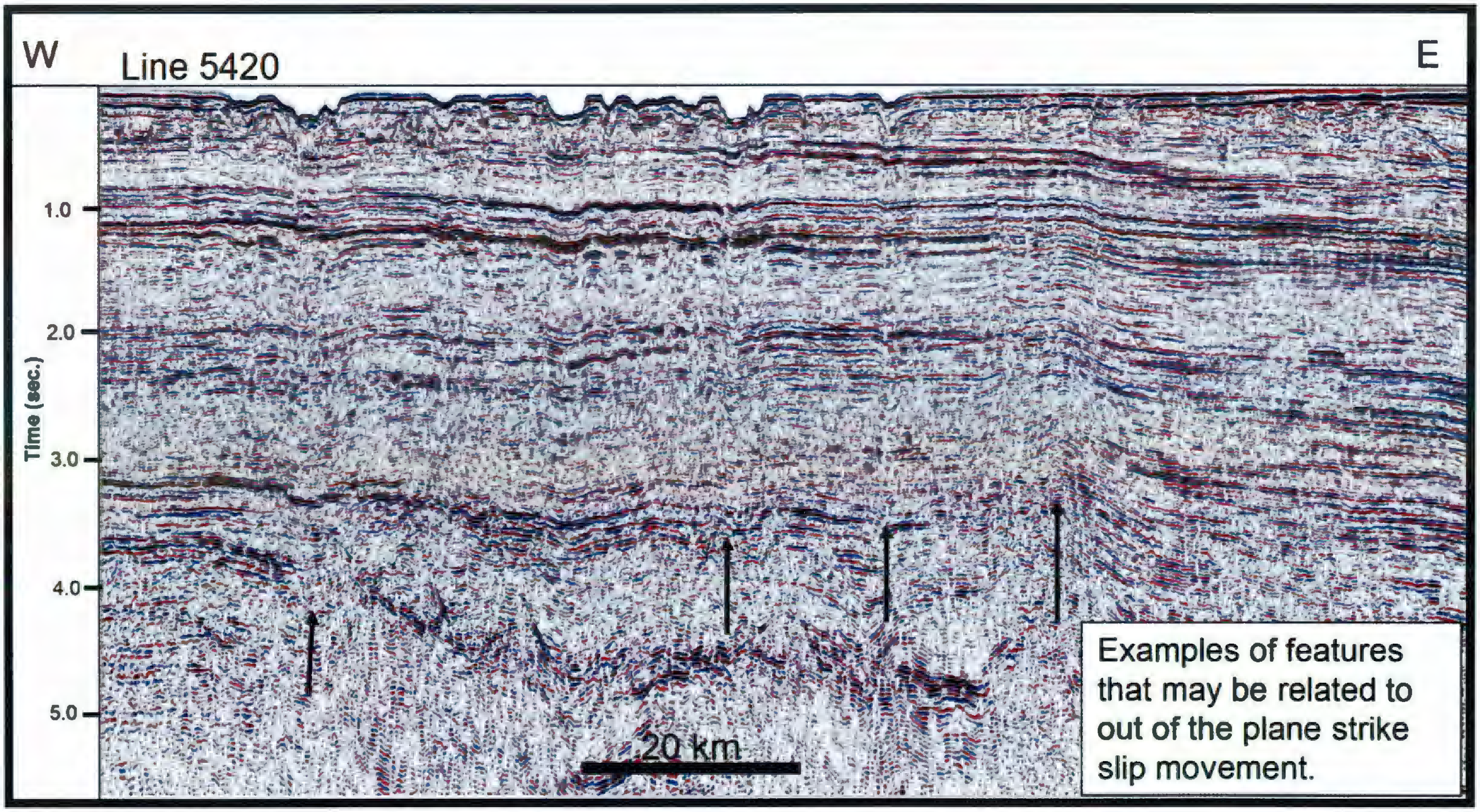

Figure 4.3B
Examples of features on seismic lines that may be caused by strike slip faulting (highlighted by arrows). Such features may be attributed to velocity effects from the overlying channels. The location of the channels may in fact be a result of subtle strike slip faults that reach the surface. See Figure 4.3A for location of seism section. Seismic line courtesy of GX Technologies.

Figure 4.3A illustrates a number of important points that are relevant to my tectono-stratigraphic interpretation. The Avalon Unconformity and the Base Tertiary Unconformity are the two most easily correlatable horizons across the region, indicating that they were the result of very large scale events. Also note the dramatic improvement in the imaging achieved below the Avalon Unconformity on line 5420, which was acquired in the year 2003 (as compared to 1984 and 1987 acquisition for the STP lines). Besides improvements in acquisition technology, line 5420 has the advantage of having been processed by prestack depth migration, prior to being converted back to a time display.

At the west end of the section we see a major strike slip fault (transfer fault) which appears to be associated with a NW-SE trending magnetic lineament near the eastern edge of Sable Island (Figure 4.8A). This lineament also truncates the weakened remnants of the ECMA. Magnetic lineaments such as this, suggest the presence of oblique transfer faults in a variety of areas offshore Atlantic Canada, but the predicted faults are not always as easy to recognize on seismic data. This interpretation challenge is, arguably, always a matter of data quality, but it is also true that these faults can be hard to image if they do not involve significant vertical offset. For example, Figure 4.3B is an enlarged portion of line 5420 that lies to the west of the study area. There are a number of areas in this section where there are slight "unexplained" vertically coincident changes in the continuity of several events, and in other places beds appear suddenly folded for no apparent reason. Such events are often coincident with shallow or recent channels or canyons, which is perhaps no coincidence at all. Lying directly below such near surface velocity anomalies the subtle strike slip faults may go unrecognized.

Figure 4.3A also shows a number of horsts and grabens along the strike of the basin indicating the complexity of the initial basin extension. Some of these faults are extensional faults that cross the line at oblique angles but others are likely to be part of a transfer fault system. As one follows the Pre-Rift horizon eastward into the Laurentian Basin (roughly at the western edge of the Laurentian Channel), it becomes apparent how tentative the mapping of this event is within the study area. In fact there are few places on lines STP 002 or STP 022 (Figure 4.3A) where the Pre-Rift event can be correlated at all. However, the Pre-Rift marker interpretation in this area is predominantly based on ties to dip lines. It is somewhat surprising to observe a Pre-Rift horst directly beneath the Laurentian Channel, where it would be more likely to expect a graben. However there are a number of Pre-Rift horsts and grabens running obliquely across the Laurentian Channel, and the seismic cross-section just happens to cross what is interpreted to be one of these horsts.

Seismic line 2000 (Figures 4.4A and 4.4B) is a dip line on the western side of the study area that runs all the way from the shelf to the base of the continental slope. Moving from northwest to southeast along this line the interpreted Pre-Rift horizon outlines a large down-to-the-basin half graben, followed by a horst and is then offset by a series of down-to-the-basin normal faults. The Pre-Rift picks as one moves basinward of the half-graben are highly interpretive, but the presence of similar structural features on other seismic lines lends greater confidence to the interpretation of a large ridge at this location. A significant feature on this seismic line is the scale of the Argo Salt structures. The salt thickness is estimated at 3.5 km on top of the horst and about 9 km in the highest dome! However, the presence of allochthonous salt sequences that can be several km thick is commonly observed on published seismic data from rift basins around the world such as the example from the Santos Basin shown at this website: http://www.searchanddiscovery.net/documents/2009/10193gomes/images/fig02.htm

The presence of thick salt over the top of the interpreted horst is also noteworthy. Given that sedimentary loading proceeded from the north it is unlikely that the salt flowed from south to north. What is more likely is that although this horst is a relative high today, during the Late Triassic to Early Jurassic it was part of a broad "sagged" area within the basin – a relative low that was covered by thick autochthonous salt which thinned to feather edges at the northern and southern boundaries of the basin. The northwest boundary would have been formed by the shoulder of the rifted area and the southeast boundary by rising oceanic or transition crust. A rough textured reflection is observed at the south end of line 2000 (Figures 4.4A and 4.4B). Due to lack of IODP drilling in the area and the ambiguity of the seismic velocities derived from reflection data we are not certain

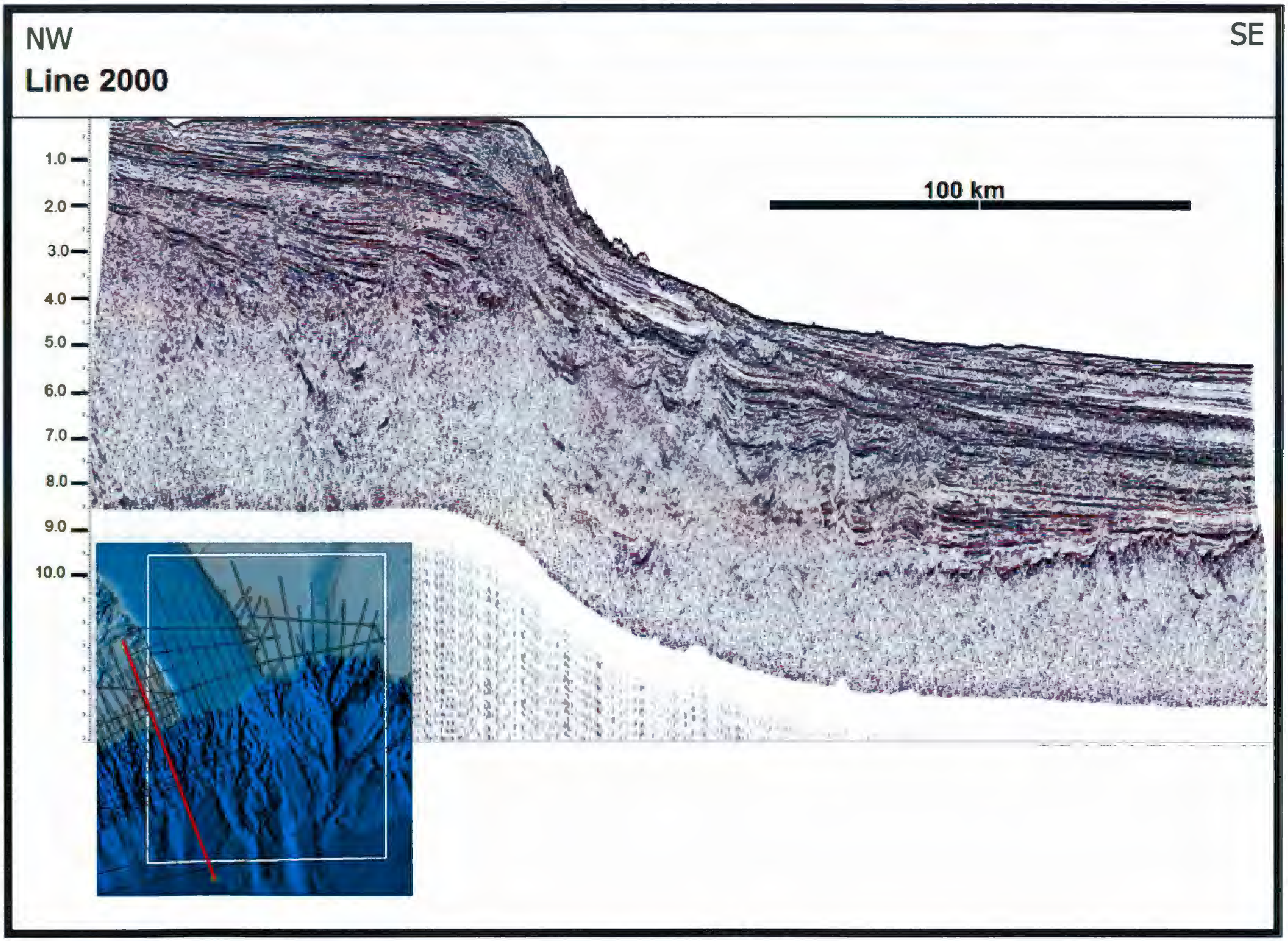

Figure 4.4A

Uninterpreted version of seismic line 2000. Seismic line courtesy of GX Technologies.

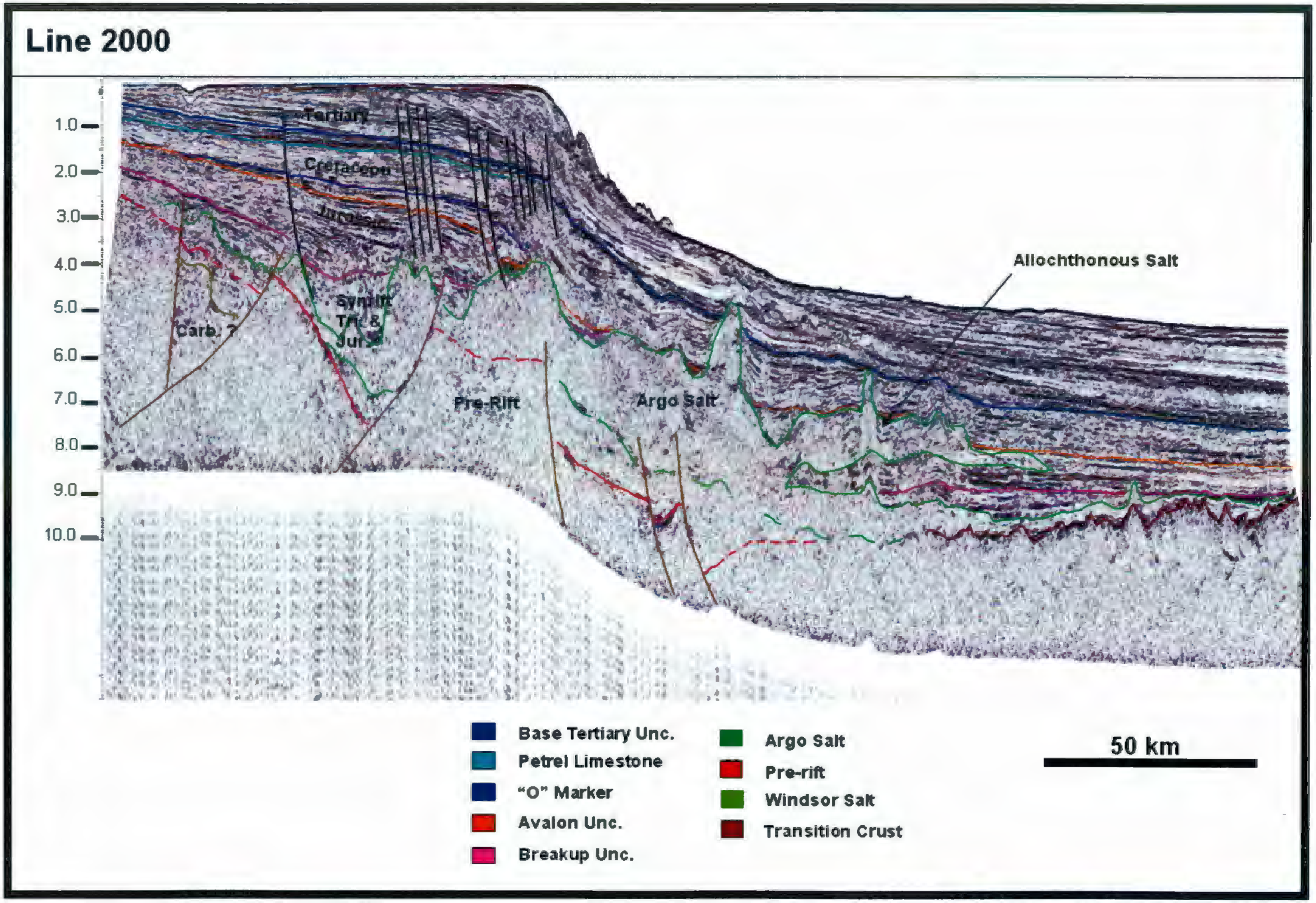

Figure 4.4B

Interpreted version of seismic line 2000. Seismic line courtesy of GX Technologies.

if this represents transitional (serpentinite) or oceanic (basalt or gabbro) crust. However, considering that transitional crust was encountered during ODP drilling on the Newfoundland and Iberian margins (Sibuet et al., 2007), I interpret it as transitional crust. The interpretation of this seismic character as transitional crust is also consistent with that of Louden et al (2005) who developed a series of velocity model profiles across the eastern Canadian continental margin based on reflection and wide angle refraction seismic data. Notably, salt appears to sit atop this horizon for some 75 km to the end of the line. It is possible that some of this salt gravity flowed into this position, but given the general lack of disturbance in the overlying reflections it is more likely to be autochthonous. The major horizontal allochthonous salt flow occurred later when the oceanic crust cooled, subsided and the basin tilted to the south (Kidston et al. 2002).

The Break-up Unconformity (BU) is interpreted to terminate against the salt and the Avalon Unconformity in this cross-section. It is also interpreted to be present again south of the “halokinetic disturbed zone”. If this interpretation is correct and the BU extended all the way across the basin, from the rift shoulder to the oceanic ridge, then the salt could not have been significantly mobilized at that time or it would have been removed by the BU. An alternate interpretation is that the BU was emergent only on the shelf, and the equivalent event picked on the seaward side of the salt is a conformable surface of approximately the same age. The latter interpretation would be consistent with a BU caused by crustal flexure as hypothesized in section 2.1. In either case, loading during the Jurassic would

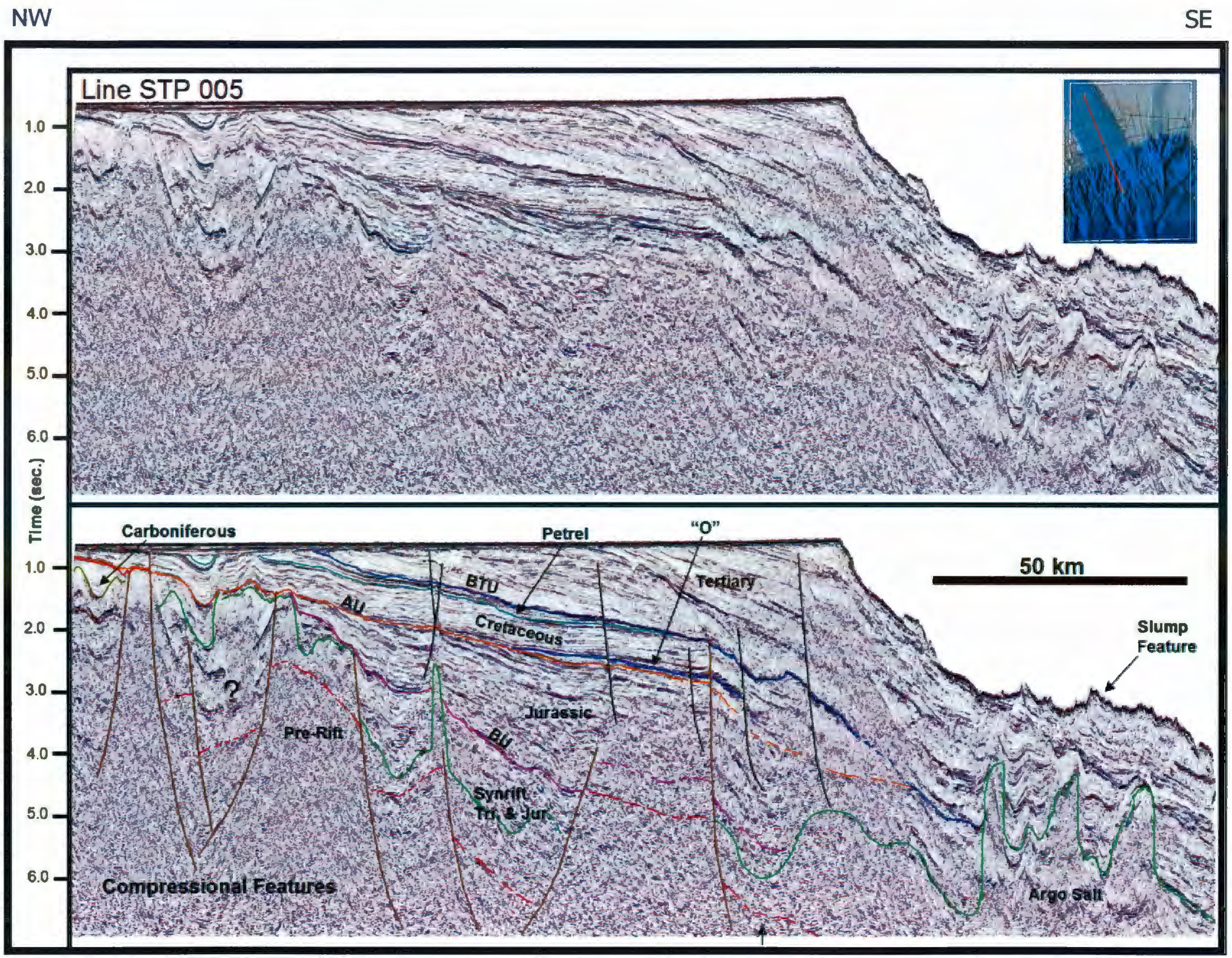

Figure 4.5

Uninterpreted and interpreted version of line STP 005. Compressional features (upturned beds between ridges, folding of the Cretaceous section and faults extending to surface) are interpreted at the NW end of the line. Acronyms: BTU (Base Tertiary Unc.), AU (Avalon Unc.) and BU (Breakup Unc.). "O" refers to the "O" Marker. Arrow shows location of magnetic anomaly discussed on page 105 Seismic line courtesy of the GSC.

have mobilized the salt and most sediments sitting above the domed salt would have been then eroded by the Avalon Unconformity (AU). This is exactly what I interpret on line 2000 as there is very little sediment present between the salt and the AU (Figure 4.4b). A seaward thickening Jurassic section is also noted, which indicates basinward tilting at this time. So it is likely that the AU reflection represents a surface that was emergent to the north and became submerged as one moves south – likely near the point where the AU first touches the salt.

A final point to note on line 2000 is that moving up section from the AU to the Base Tertiary Unconformity (BTU) we see evidence of some seaward thickening in the Cretaceous section, but it is less pronounced than observed in the Jurassic section. It is likely that although some seaward tilting persisted through the Late Cretaceous, the area was undergoing a more broadly balanced subsidence in the aftermath of the Avalon Uplift. However, moving above the BTU we have evidence of significant seaward tilting again as the Tertiary sequence thickens dramatically toward the shelf edge, then thins across the slope due to mass transport erosion and then thickens again in deeper water. These phases of the basin's evolution along with information on the seismic markers are summarized graphically in Figure 4.1.

Seismic line STP 005 (Figure 4.5) runs from the Laurentian Channel onto the continental slope in the west central portion of the study area. One of the most striking features on the line is the entirely flat and very strong seabed reflection along the shelf, indicating the presence of a hard bottom. This presents a challenge to getting good energy penetration during seismic acquisition. The second remarkable feature is the very different structural character of the sedimentary infill at the northwest end of the line. Here we see what appears to be complex salt mobilization that may involve both the Windsor and Argo salt sequences. We also observe compressional features characterized by tightly folded reflections between steep ridges, folding of the Cretaceous section and faults extending to the seabed. Interpretation in this area is once again tenuous, and is further complicated by the likely presence of both the Windsor and Argo salts in close proximity to one another, and by the occurrence of strong seabed multiples. The area identified as having compressional features in Figure 4.5 is part of the Cobequid-Chedabucto Fault system, which also forms the northern boundary of the Mesozoic portion of the Laurentian Basin. As discussed in Chapter 2 this is a major strike slip fault that runs westward to the Bay of Fundy (approximately 600 km from this line). It can be argued that the folding and faulting in the Cretaceous section is caused by the salt tectonics, and it is likely that some of it is. However, independent evidence of Cretaceous deformation onshore Nova Scotia (Pe-Piper and Piper, 2004) indicates that this fault has remained active well beyond the initial rifting stage. Additionally we see that one of the faults in this area extends very close to the surface, which admittedly can be explained by other mechanisms, but is nevertheless consistent with the presence of later tectonic activity.

Another feature of note on this line is that over part of the line we have good imaging of the Break-up Unconformity (pink) which allows extrapolation of the interpretation to other intersecting seismic lines. We also note that the “O” marker (purple) onlaps the Avalon Unconformity (orange) about halfway between the shelf edge and landward end of the line. On the continental slope we see evidence of major slumping within the Tertiary sequence.

Seismic line STP 011 (Figure 4.6A and B) runs from the shelf into deep water in the east central part of the study area. Within the Cretaceous and Tertiary sections, the data is of very good quality over the full length of the line. The Carboniferous units, below the AU are also well imaged on the northern one third of the line. As one moves seaward beyond the hinge line into the Mesozoic basin there is a strong suggestion of a major down-to-the-north normal fault beneath the modern shelf edge. I have interpreted the loss of reflectivity to the south of the fault as representing a basement ridge which is down faulted again before sloping away to the south. As we observe in Figure 4.4, it is possible that some salt resides atop this and other similar ridges. In this section we also note that the AU is clearly eroded by the Base Tertiary Unconformity (BTU). Beneath the continental slope we also see an interesting gravity driven detachment feature within the Tertiary section.

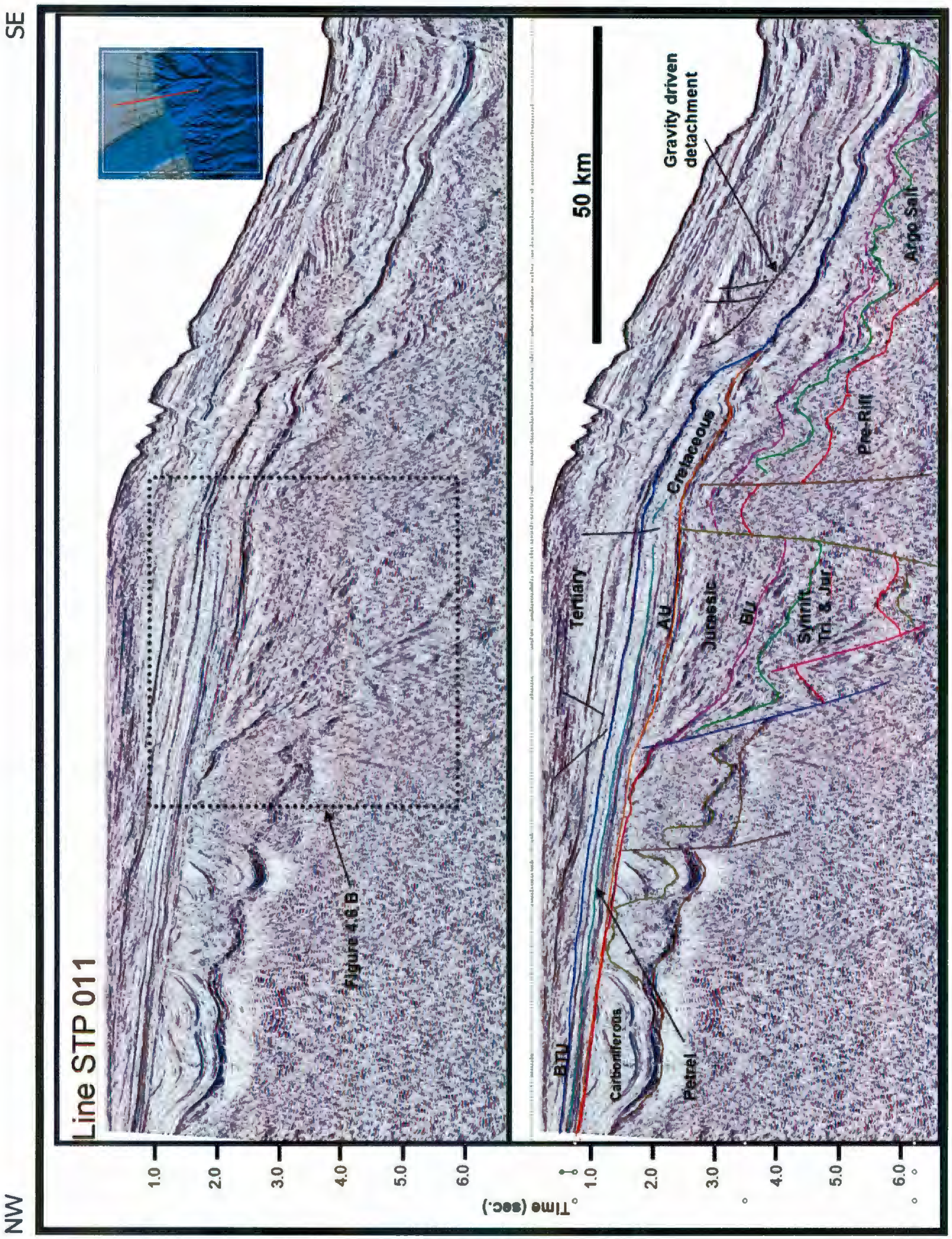

Figure 4.6A

Uninterpreted and interpreted version of line STP 011. Acronyms: BTU (Base Tertiary Unc.), AU (Avalon Unc.) and BU (Breakup Unc.). Seismic line courtesy of the GSC

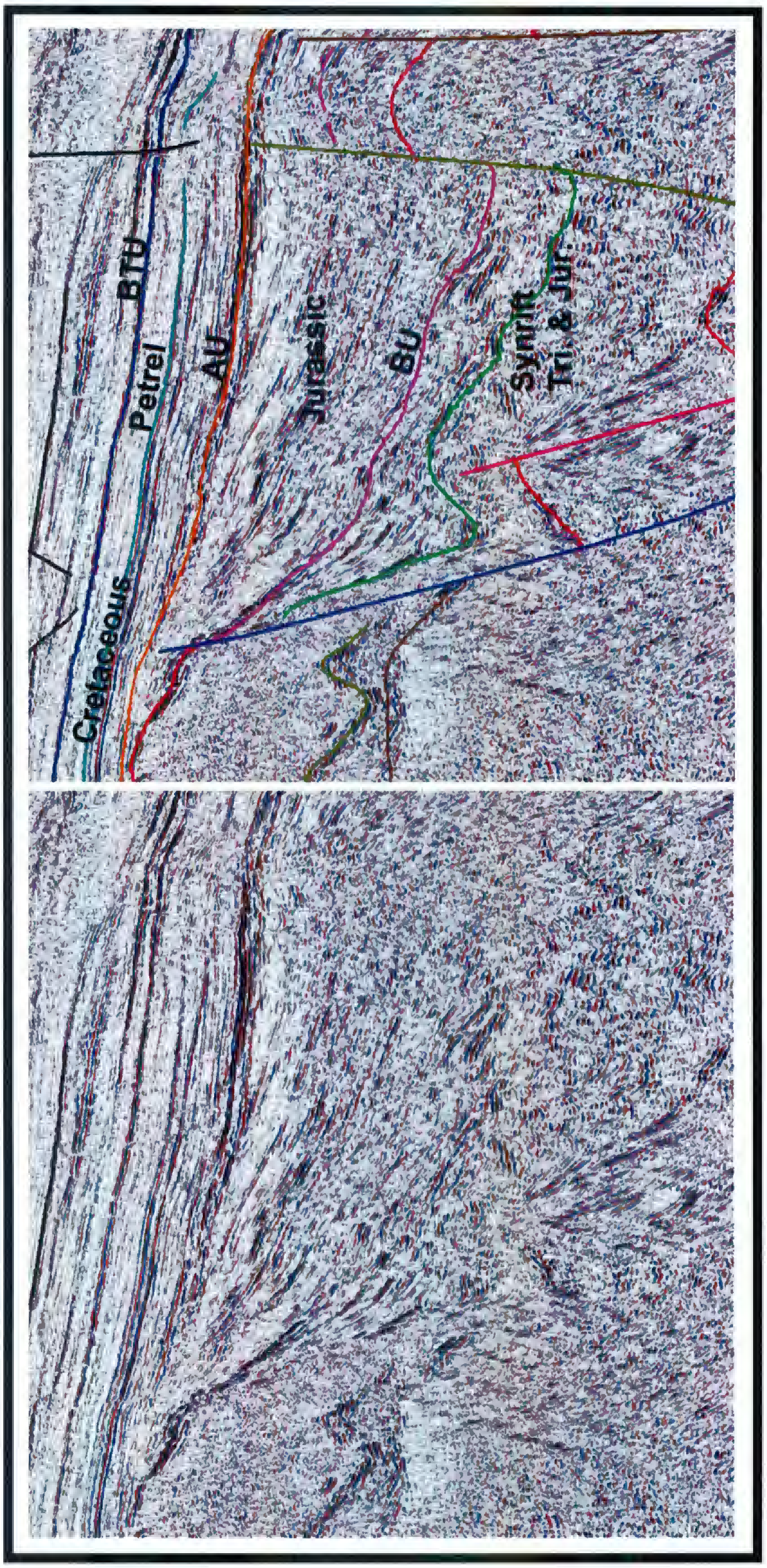

Figure 4.6B

Uninterpreted and interpreted portion of line STP 011, blown up to show the horizon picks. See Figure 4.5A for location. Seismic line courtesy of the GSC.

4.2 Seismic Mapping

Seismic maps were prepared for the Pre-Rift Basement (Pre-Rift), Break-up Unconformity, Avalon Unconformity, Base Tertiary and two younger Tertiary seismic horizons.

Depth Structure Map of the Pre-Rift Horizon

The Pre-Rift depth map (Figure 4.7) was created using a three layer velocity model of: (1) water column (1500 m/s); (2) seabed to AU (2500 m/s); and (3) AU to Pre-Rift (4500 m/s). The sediment velocities were obtained by averaging the velocity values from well ties in the study area and then rounding off to the closest one hundred m/s. Where the AU was not present or where correlation of the horizon was tenuous, a "phantom" AU marker was introduced allowing a rough depth calculation. This was necessary within the halokinetic disturbed zone (Figures 4.9 and 4.10), which generally begins just south of the shelf edge and continues to the oceanic - transition crust.

Depths to Pre-Rift range from about 2 km at the north end of the seismic coverage to about 17 km in the southwest corner of the map. A large "no data" zone exists in the lower middle region of the map, where the depth values have been extrapolated by the mapping software. The Transition Crust reflection was interpreted on three long lines in the southwest corner of the study area and extrapolated due east, as no similar seismic signature is observed on the deepwater seismic lines on the eastern side of the study area.

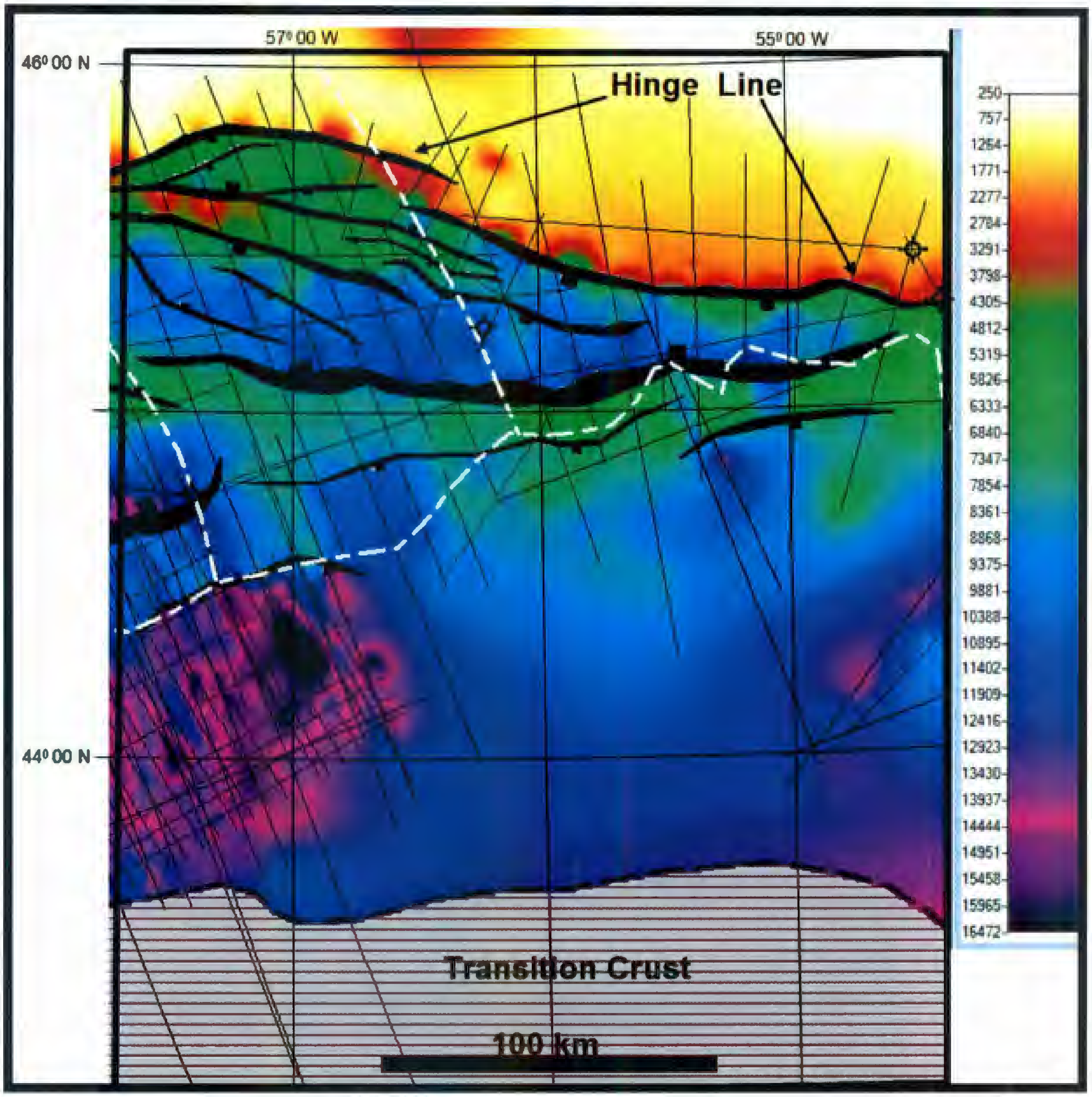

Figure 4.7

Seismic Depth Structure Map of the Pre-Rift horizon. Major faults are represented in black. Colour legend in metres. Dashed white line indicates approximate location of the shelf edge and Laurentian Channel.

The most striking aspect of the map is the general ESE to SE trend of the major faults in the northwest quarter of the map, which is interrupted by a more east–west trending system near the 45^{th} parallel. The map indicates the presence of a deep graben inboard of a large ridge, or series of ridges, that likely played a role in determining the location of the modern shelf edge.

Figure 4.8A shows the Pre-Rift faults plotted on the regional magnetic data with the high resolution magnetic data inset provided by Fugro. As one approaches the study area from the west along the northern boundary of the Orpheus Graben the longer wavelength magnetic anomalies gradually rotate from a NE trend (likely associated with Appalachian suturing) to a SE trend within the northern one third of the study area. This SE trend matches the interpreted faults from seismic data quite well, and is likely to be at least partly caused by SE trending shear stress projected into the area from the NFZ. In terms of tying the Pre-Rift depth structure to the pre-existing basement fabric, it is evident in this figure that the faults in the NW quadrant of the study area capture the trends of the CC-CA and NFZ fault systems. However, the large E-W trending ridge interpreted near 45^0 00 N runs roughly parallel to a magnetic low that extends into the Canso Ridge. A second ridge at about 44^0 30 and angled to the SW (parallel to the shelf edge), can be interpreted as being offset from the previously mentioned ridge by a strike slip fault. But more detailed mapping outside the study area would be required to confirm this interpretation.

Another interesting aspect of the high resolution magnetic map is that it shows a strong conical shaped anomaly just left of the centre of the study area. The conical shape is suggestive of a volcano or conical intrusive body. Three other similar but weaker anomalies are also noted. Given that this area is located near the convergence of two major fault systems it would not be unexpected to have volcanoes. Seismic line STP 005 (Figure 4.5) crosses this anomaly at the point indicated by a small arrow at the bottom of the section. At this location on the section there is nothing that clearly resembles a volcano. However, the Pre-Rift event is not well imaged and is interpreted to be just about to fall below the seven second recording time.

Figure 4.8B shows the Pre-Rift faults plotted on the regional gravity data. On this map the Orpheus Graben and some of the smaller imbricate grabens in the NW quadrant of the study area correspond, as one would expect, to gravity lows. Also in the NW quadrant, we observe that the gravity anomalies have a roughly SE trend, as already noted on the magnetic data. Moving south to where the E-W and SW trending ridges were interpreted, the gravity map is not effective in delineating these trends as it becomes dominated by the shelf edge anomaly. However, we do observe a strong positive gravity anomaly running roughly E-W along the northern flank of the Canso Ridge. This supports the possibility that easterly directed stress was introduced into the basin during the rift phase, as the Canso ridge pressed into the basin from the west - which translated into a series of E-W running rift faults.

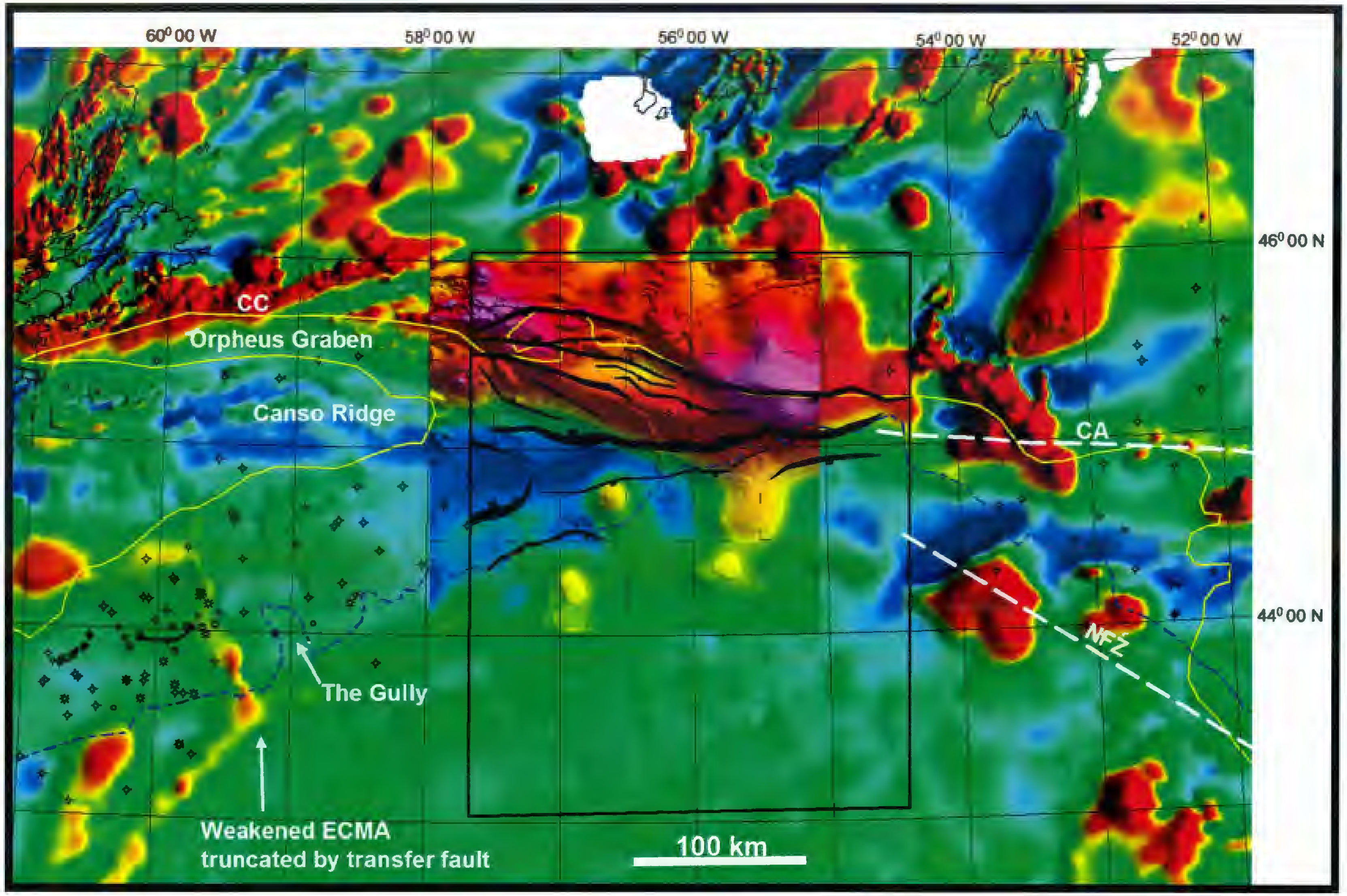

Figure 4.8A

Pre-rift faults (as interpreted in this study) overlain on regional magnetic map (total field) with high resolution magnetic map (total field) inset . Regional basin outline based on 4000 m depth to basement contour from GSC mapping is shown as a yellow line and the shelf edge is shown as a dashed blue line. Acronyms: CC (Cobequid-Chedabucto Fault), CA (Collector Anomaly) and NFZ (Newfoundland Fracture Zone). Regional magnetic map reference: GSC (1988b), and high resolution magnetic map courtesy of Fugro. See Figure 3.12 for colour legends.

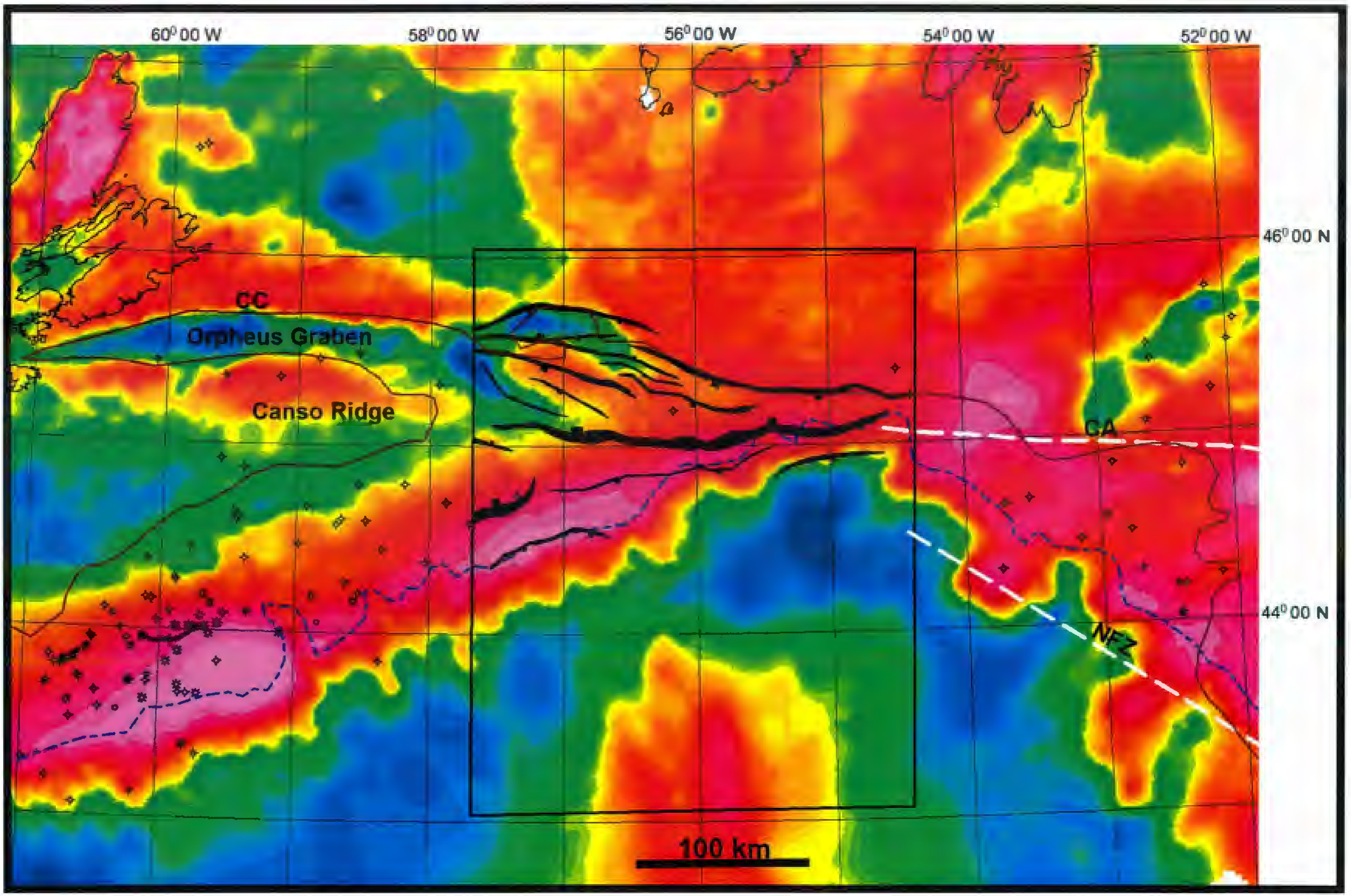

Figure 4.8B

Pre-rift faults (as interpreted in this study) overlain on regional gravity map (Bouguer onshore and Free Air offshore). Regional basin outline based on 4000 m depth to basement contour from GSC mapping is shown as a brown line and the shelf edge is shown as a dashed blue line. Acronyms: CC (Cobequid-Chedabucto Fault), CA (Collector Anomaly) and NFZ (Newfoundland Fracture Zone). Gravity map reference: GSC (1988a). See Figure 2.5 for colour legend.

As discussed in Chapter 2, the CC-CA is believed to have been active into the Cretaceous, while the NFZ which is linked to an oceanic transform fault extending to the mid ocean ridge is thought to have remained active into modern times (as postulated with regard to the 1929 earthquake). Returning to the seismic section in Figure 4.5, we observe that the only place where deep rooted faults and compressional features affect the shallow section is at the northwest end of the line. The Pre-Rift depth map (Figure 4.7) illustrates this complex faulting in the northwest quadrant of the map, which likely represents the point of convergence of the two strike slip fault systems. We may also be seeing some effects of the weaker BA lineament outlined in Figure 2.3, and which projects just to the south of the Bandol #1 well.

Time Structure Map of Break-up Unconformity

The time structure map of the BU (Figure 4.9) can be divided into four sectors. The northern sector, shown in white, indicates where the BU has been subcropped by the AU at or near the hinge line, which coincides with the CC fault system. South of the hinge line we enter the second sector which is dominated by a Mesozoic half graben behind a ridge system (also seen in Figure 4.7). The third sector, highlighted in green, is the halokinetic disturbed zone (a subset of a regionally disturbed zone known as the "Slope Diapiric Province") where the BU has been generally disrupted by the Argo Salt (Figures 4.2, 4.4B, 4.5 and 4.6A). South of the halokinetic disturbed zone is the fourth sector, where the BU re-appears and onlaps transition crust (Figure 4.4B). We also observe

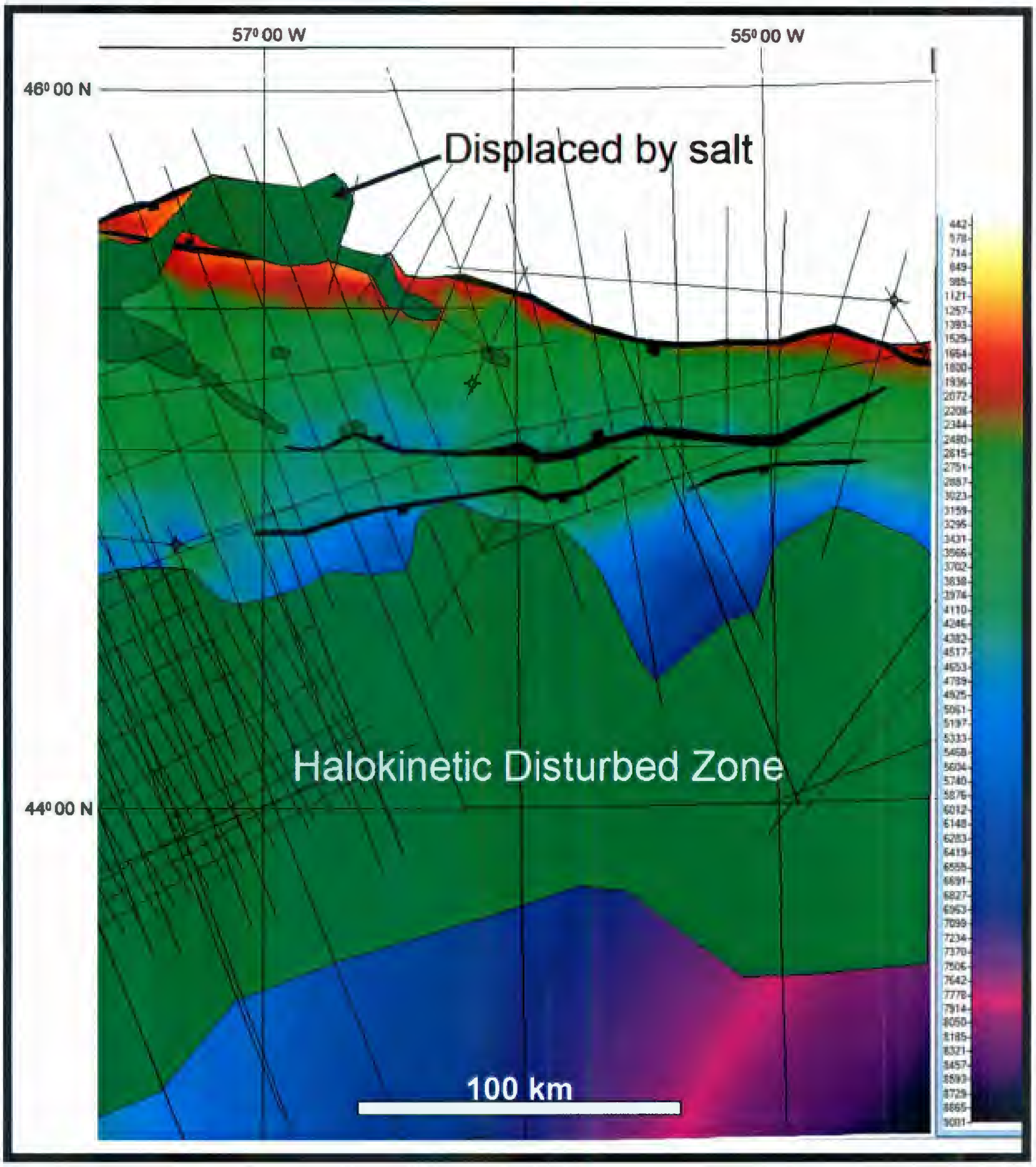

Figure 4.9

Time structure map of the Break-up Unconformity horizon in the study area. Colour legend represents two way time in milliseconds. Surface is intruded by salt in the northwest and affected by numerous Argo salt features in the halokinetic disturbed zone.

salt domes that have pierced the BU in the upper left corner of the map that have been drawn out in a southeasterly direction, suggesting shear stress along a vector that is roughly aligned with the NFZ. The BU is surprisingly undisturbed by faults, except along the previously noted ridge system. It is a fair question as to why, if the NFZ and its imbricates are still active in this area, there are not more faults penetrating into the shallow section. One possible answer is that the major stresses along this fault are concentrated in the basement section below the sediments (the hypocentre for the 1929 earthquake was at 20 km), and that the overlying sediments are detached from this action by the salt. Following this line of reasoning, we can speculate that there are only a few places where the deep stresses reach the surface, such as in the northwest corner of our map along the basin bounding fault system.

Time Structure Map of the Avalon Unconformity

The Avalon Unconformity (Figure 4.10) dips gently basinward and is broken by only minor faulting until it is disrupted by the halokinetic disturbed zone. The southeast trending faults projecting from the northwest corner of the map are related to the deeper basement extensional episode that shaped the basin, and have been re-activated from time to time by movement on the CC and NFZ faults. The other faults, running parallel and sub-parallel to the shelf edge are gravity induced down-to-the-basin listric normal faults.

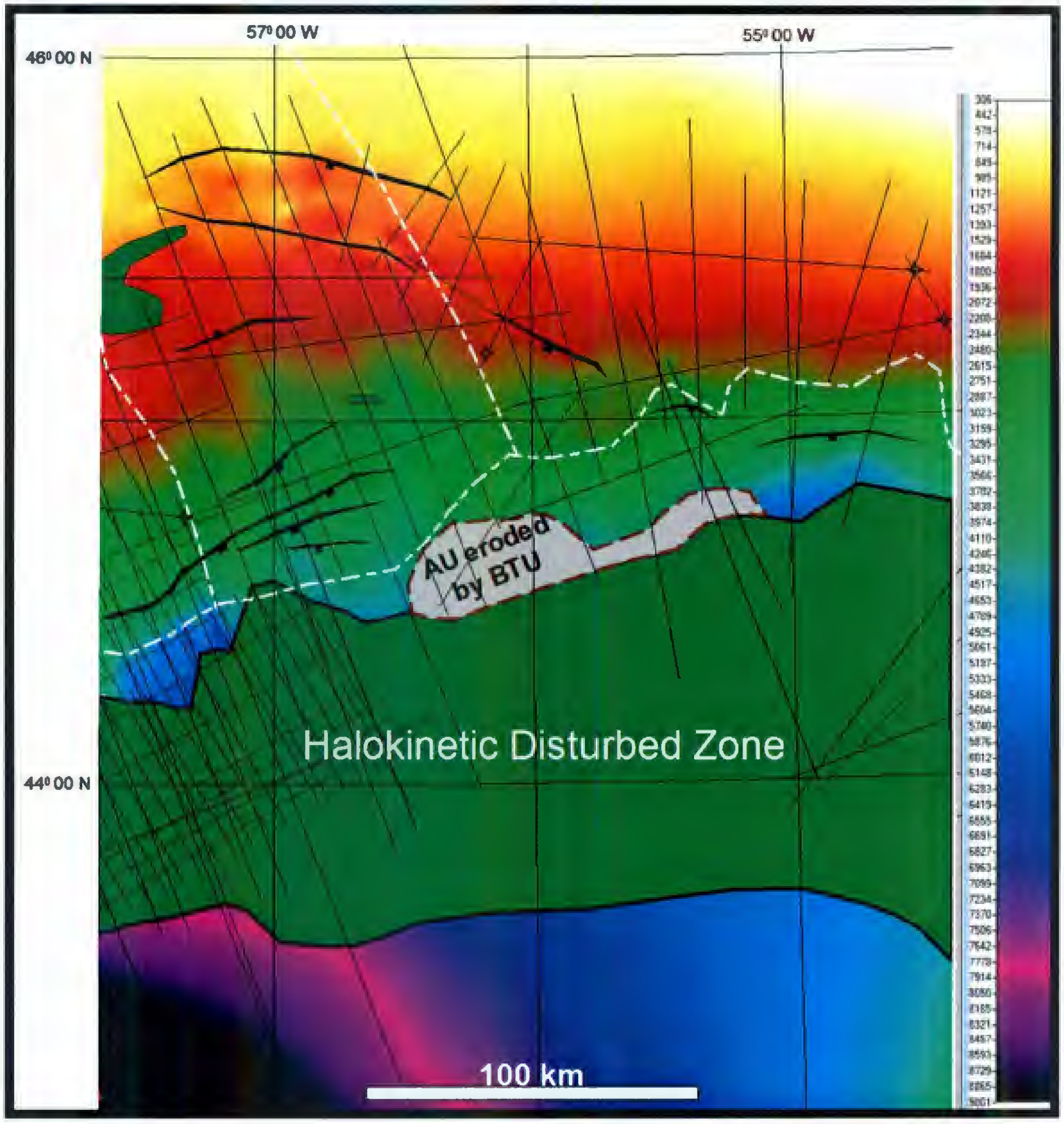

Figure 4.10

Time structure map of the Avalon Unconformity horizon. Legend is two way time in milliseconds. Shelf edge and Laurentian Channel are indicated by dashed white lines.

Unconformities

Figure 4.11 is an east – west seismic cross-section highlighting the unconformities that were correlated in this study. The deepest unconformity is the Pre-Rift horizon which represents the surface of the Pangea continent just before rifting started between North America and Africa/Europe. The Break-up and Avalon unconformities have been discussed above. MacLean and Wade (1992) also mapped a Middle Jurassic Unconformity which was not readily apparent to the author, although a number of Jurassic markers can be correlated (Figure 4.11). The Base Tertiary Unconformity is the most reliable marker in the study area, and is observed to erode more deeply into the Cretaceous section as one moves eastward. A number of dramatic erosional surfaces within the Tertiary section, with the deepest incision located on the eastern side of the Laurentian Channel, have also been correlated (Figure 4.11). Intense erosion and channelization of the younger Tertiary section complicates the interpretation of these unconformities, but the two most prominent ones have been correlated and mapped. As previously noted, no picks for events within the Banquereau Formation were provided, and so the two prominent unconformities were assigned tentative ages by correlating to the Vail et al relative sea level curve (Figure 4.11). Figure 4.12 shows how younger Tertiary erosional events have cut into older Tertiary sediments as one moves seaward, and younger horizons prograde seaward onto the diachronous Base Tertiary surface across the basin.

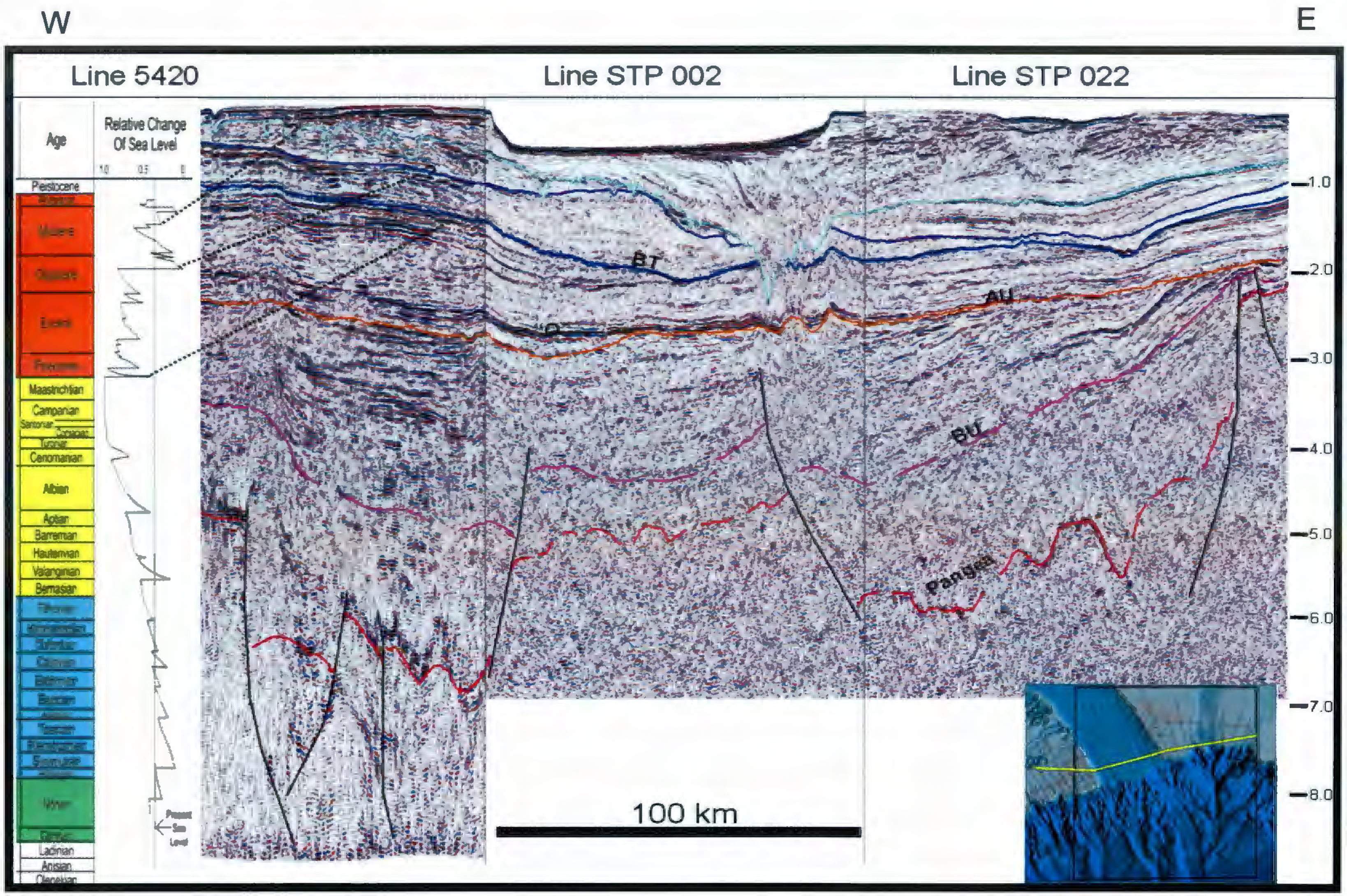

Figure 4.11

Seismic cross-section showing unconformities correlated in this study, including: Pangea (Pre-Rift), BU (Break-up), AU (Avalon), BT (Base Tertiary), and what have been interpreted as Late-Oligocene(?) and Mid-Miocene(?) unconformities. Where BU and Pre-rift horizons are tenuous in this figure they have been interpolated and/or tied from dip lines. Sea level chart from Vail et al (1977, 1984) and Vail and Mitchum (1979) in Williams et al 1990. Line 5420 courtesy of GX Technology and lines STP 002 and 022 courtesy of the GSC.

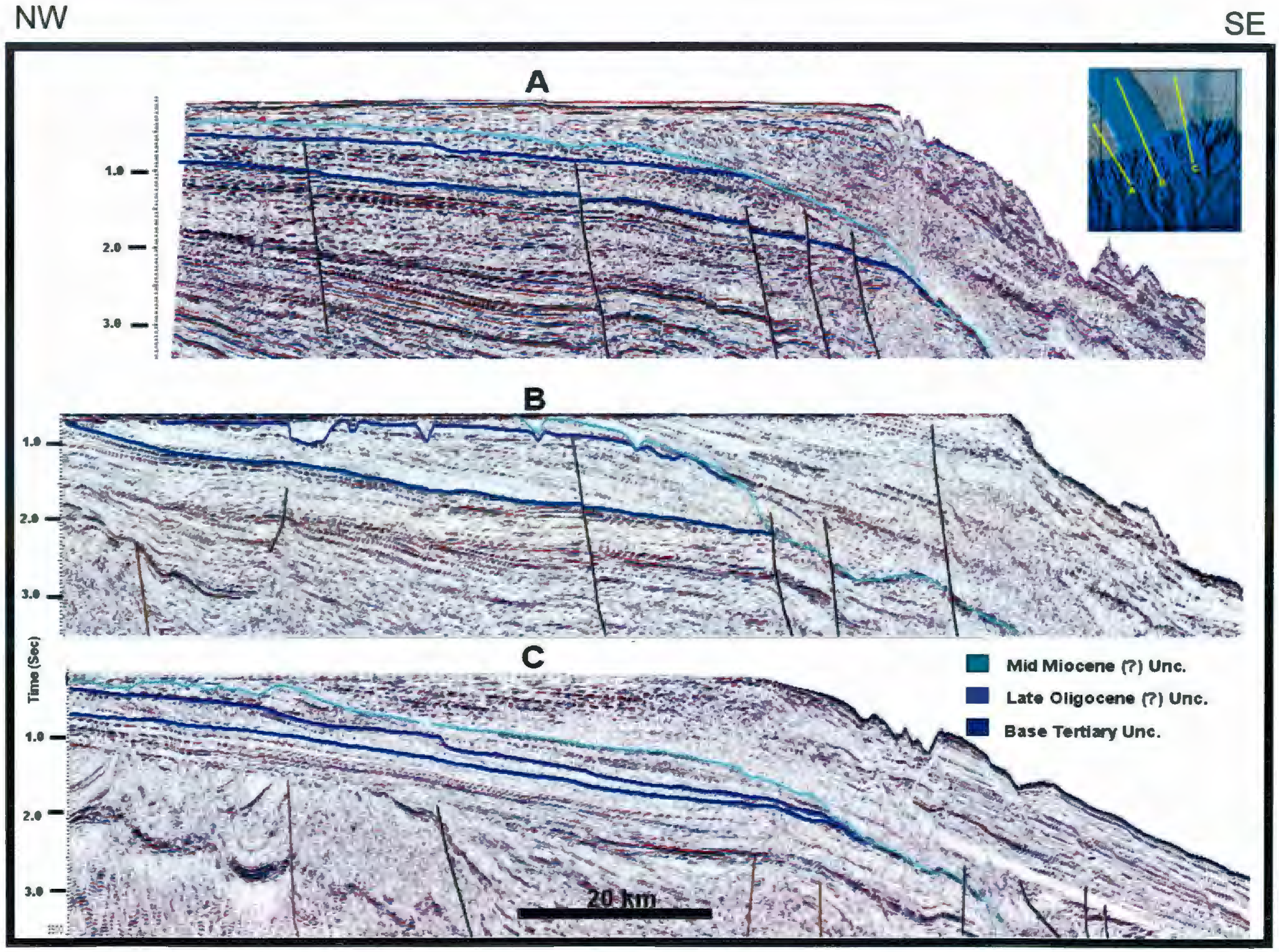

Figure 4.12

Dip seismic sections showing interpretation of how the Tertiary deposition and erosional patterns vary across the basin. Line locations shown in insert. Note the more dramatic erosion and progradation within the Laurentian Channel. Line "A" courtesy of GSI, and lines "B" and "C" courtesy of the GSC.

Base Tertiary Depth Map

The Base Tertiary depth map (Figure 4.13) was constructed based on a two layer velocity model, using a 1500 m/s water velocity and 2100 m/s (averaged from well ties in the study area) to calculate the seabed to Base Tertiary isopach. Salt piercements are outlined in green, and there are also a number of locations where the Base Tertiary marker is draped upward rather than pierced by the Argo Salt.

When generating regional maps for this study, only the more prominent faults have been picked and there are numerous other secondary and smaller faults that are not shown on this map. However, it is observed that the Base Tertiary is largely unbroken by faults on the eastern side of the map, and the great majority of faults affecting the Base Tertiary are down-to-basin gravitationally induced faults, located in the west central portion of the map. Additionally, a number of what are interpreted to be strike or oblique slip faults trending in a SE direction, are noted near the upper left quadrant of the map. Other points of interest in this map are that the Base Tertiary outcrops at the seabed on the upper left quadrant and that the modern shelf edge (outlined along with the Laurentian channel by a white dashed line) closely follows the shelf drop-off at the Base Tertiary level. We can also note that the area where we see the most significant gravitational faulting at the Base Tertiary marker is within a region where the modern shelf edge has prograded beyond the older drop-off at the Base of Tertiary.

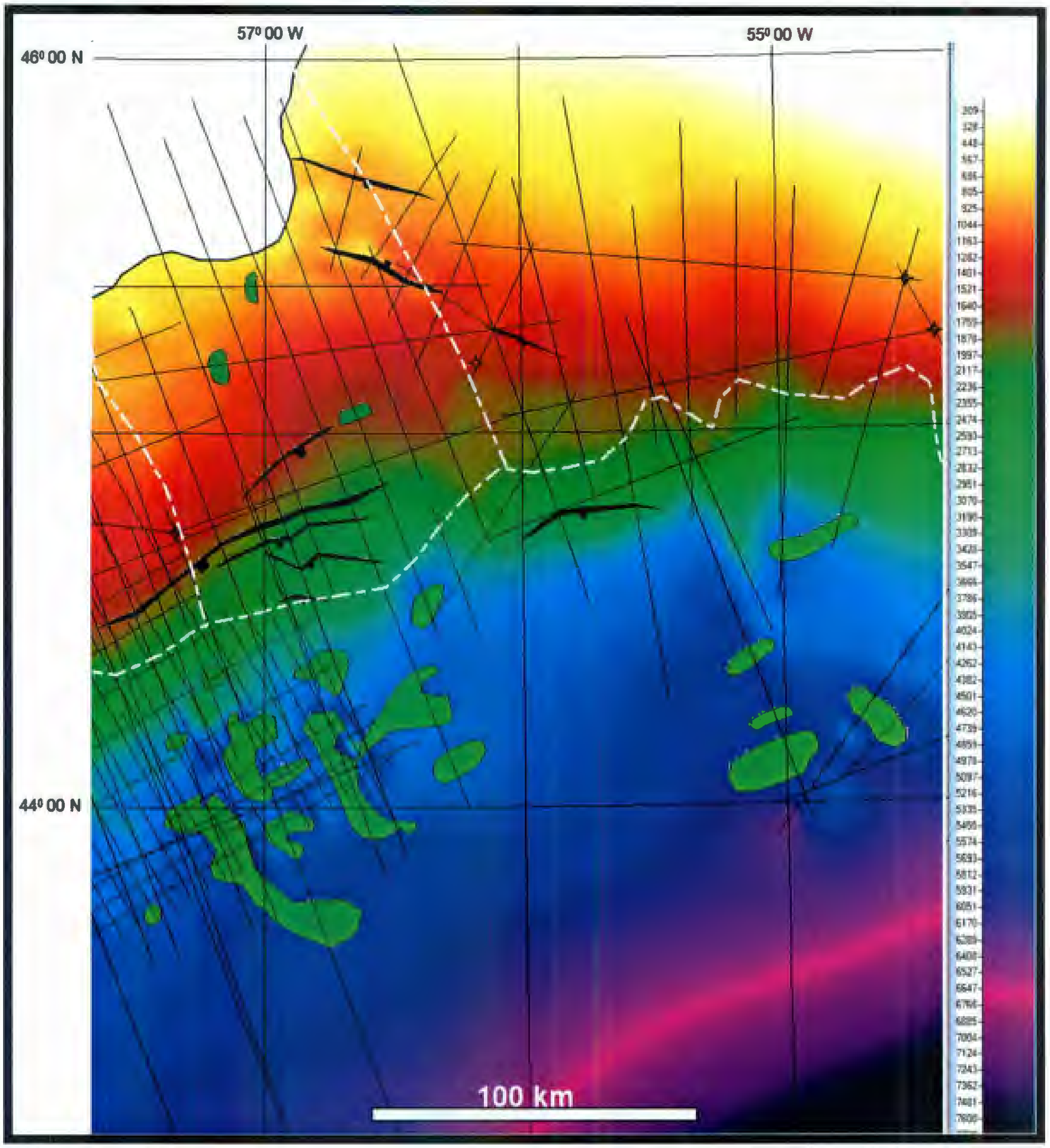

Figure 4.13

Base Tertiary Unconformity (BTU) Depth Map. Depth in m is shown on colour bar, salt piercements are shown in green, and the outlines of the shelf edge and Laurentian Channel are shown as dashed white lines. The Base Tertiary outcrops at the seabed in the upper left corner of the map (white area).

Late Oligocene (?) Depth Map

Figure 4.14 is a depth structure map of the Late Oligocene(?) Unconformity (LOU) based on the same two layer model and velocities used for Figure 4.13. The map likely overestimates the depth as one moves landward but is more accurate as one moves basinward where the LOU begins to merge with the Base Tertiary horizon. This map shows that the LOU either subcrops at the seabed or is truncated by the Mid Miocene(?) Unconformity (MMU) as one moves landward, and is once again truncated by the MMU as one moves seaward.

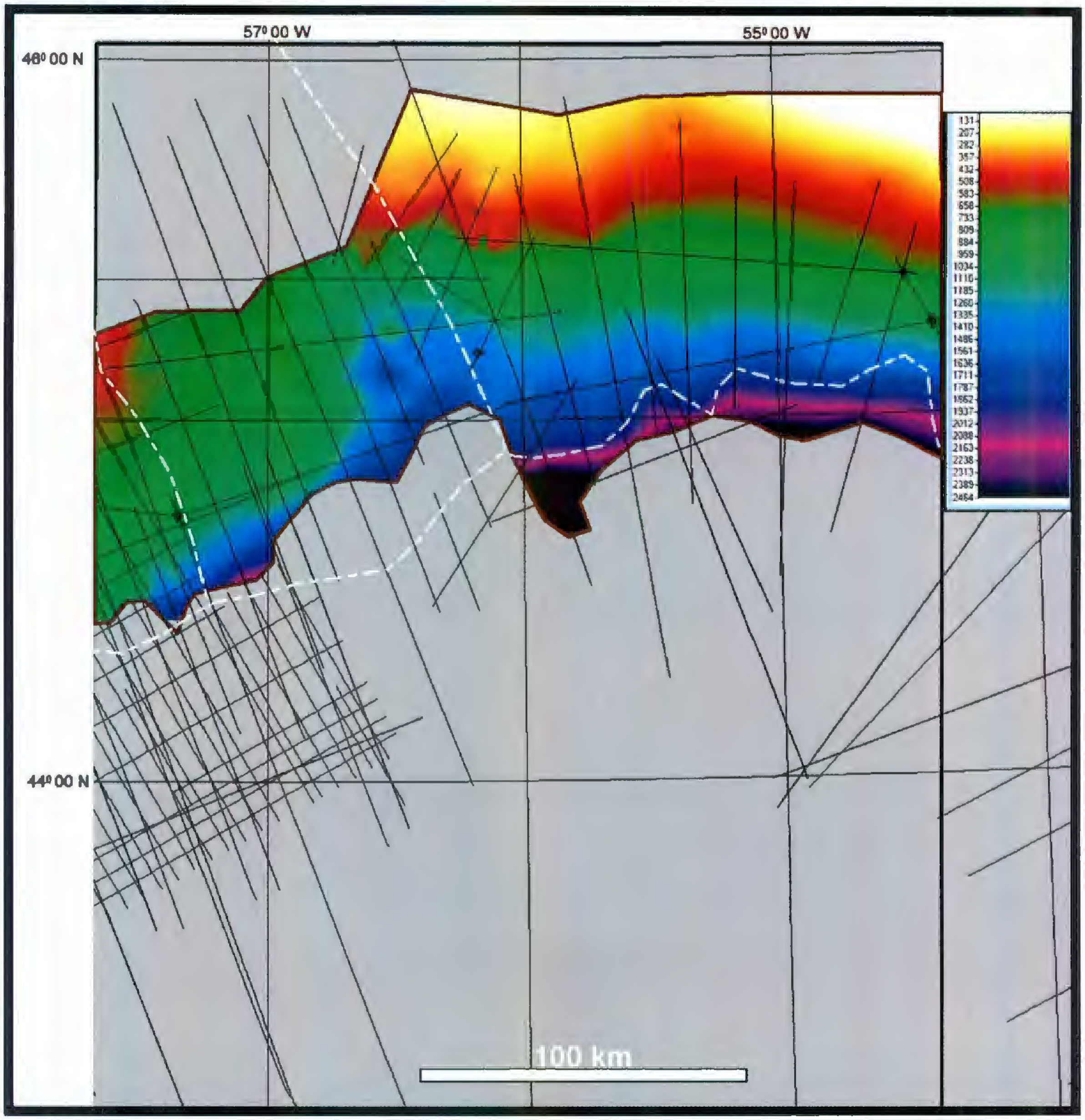

Figure 4.14

Late Oligocene(?) Unconformity (LOU) Depth Map. Depth in m is shown on colour bar, and the outlines of the shelf edge and Laurentian Channel are shown as dashed white lines.

Mid Miocene Unconformity Depth Map

Figure 4.15 is a depth map of the MMU, based on the same two layer velocity model used for Figures 4.13 and 4.14. Once again the map is likely to over estimate depth slightly as one moves landward and becomes more accurate as one moves basinward, but presents a reasonable first approximation of this geological surface. The map also reflects the severe erosion and channeling observed in Figure 4.11, as an “embayment” on the eastern side of the Laurentian Channel. The MMU either subcrops at the seabed or is truncated by later erosional events in the northern part of the basin (brown line in Figure 4.15). The map also indicates where the MMU erodes down and merges with the Base Tertiary Unconformity (BTU) to become the defacto BTU. This map differs from the BTU map presented in Figure 4.13 as this horizon was correlated over the tops of salt domes rather than picking them as piercements. This is an alternative and legitimate means of interpreting the horizon because, as seen in Figure 4.4A and 4.4B, the top of Argo Salt is in fact the Base Tertiary surface when the top of the dome lies within the Tertiary section. Points of note in this map are that we once again see deep erosion on the eastern side of the Laurentian Channel, and also the relatively close proximity of the paleoshelf with the modern shelf edge.

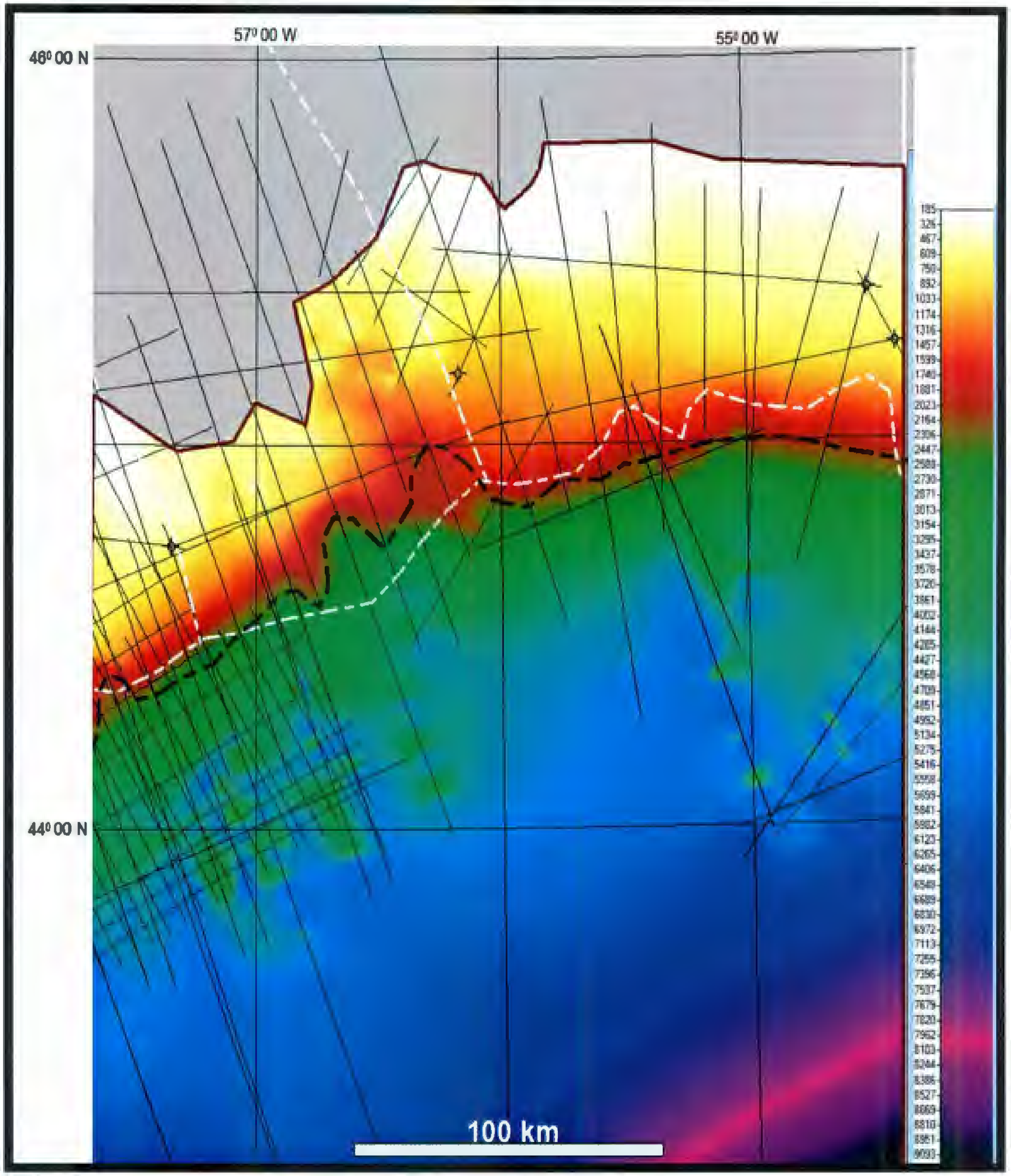

Figure 4.15

Mid Miocene (?) Unconformity (MMU) Depth Map. Depth in m is shown on colour bar, and the outlines of the shelf edge and Laurentian Channel are shown as dashed white lines. The brown outline at the top of the map indicates where the MMU subcrops to seabed or is eroded by a later event. The black dashed line indicates where the MMU merges with the Base Tertiary Unconformity (BTU).

Tertiary Isopach Map

A Tertiary thickness map, based once again on an average velocity of 2100 m per second from the seabed to the Base Tertiary horizon, is included as Figure 4.16. The map shows the Tertiary section generally thickening in a seaward direction, although if more seismic lines extended further seaward we would expect to see it thinning over the oceanic crust domain. The very thick section interpreted in the southeast corner of the map is a reflection of the lack of data in this area, combined with the mapping software's tendency to extrapolate regional trends. Where we have good seismic control we see dramatic variations in the thickness of the Tertiary sequence caused by canyonization of the seabed and thinning over salt or shale diapirs. The white dashed line in Figure 4.16 indicates where the MMU merges with the BTU and generally corresponds to an increased rate of thickening within the Tertiary section. If the age assigned to this event (Mid Miocene) is correct, it would appear that the majority of the off-shelf Tertiary sedimentation is quite recent.

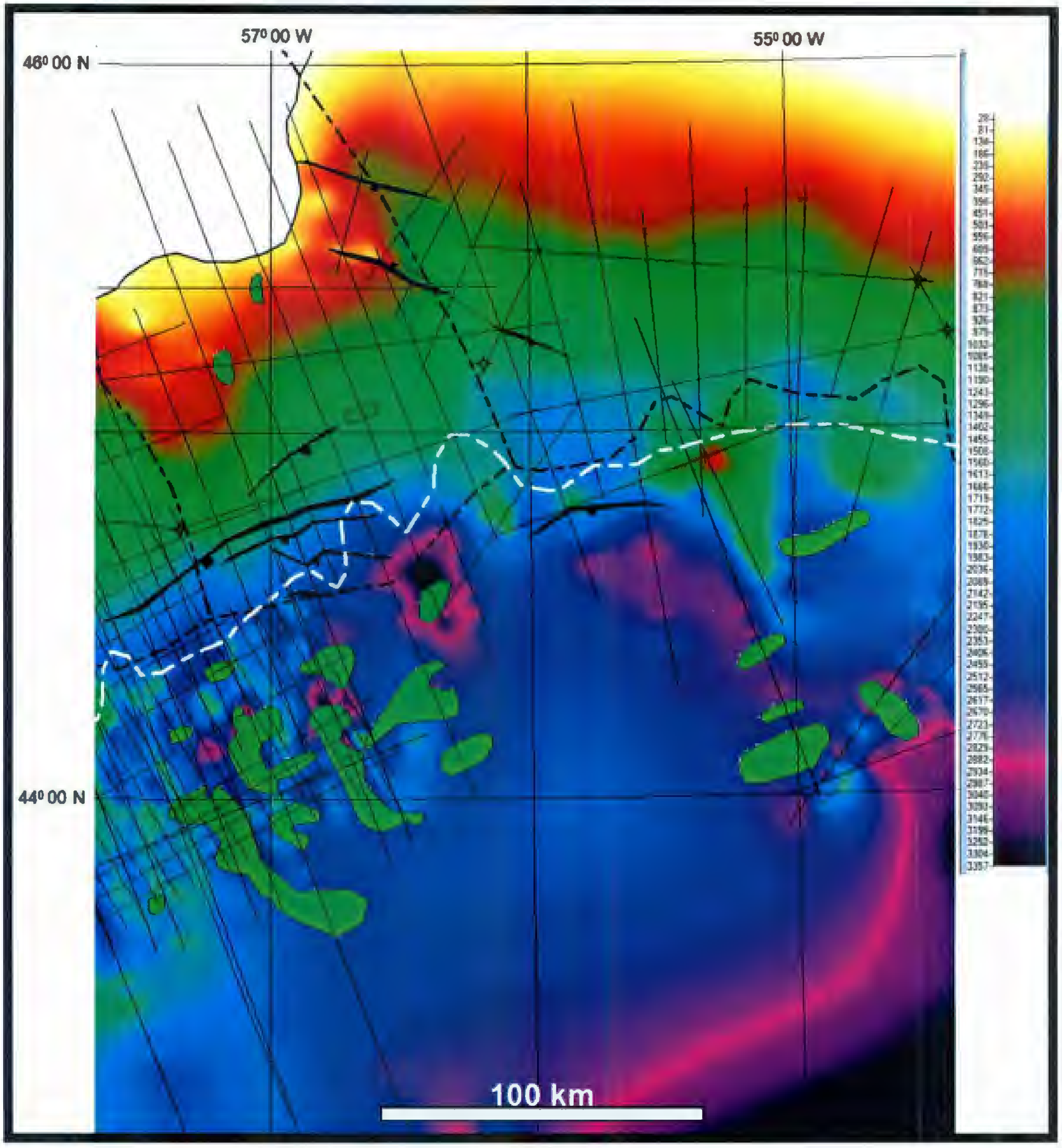

Figure 4.16

Tertiary Isopach Map. Thickness in m is shown on colour bar, and the outlines of the shelf edge and Laurentian Channel are shown as dashed black lines. The white dashed line indicates where the MMU merges with the Base Tertiary Unconformity (BTU).

4.3 Structural Analysis

Figure 4.17 is a composite map showing the faults that were picked at the Pre-rift, Breakup Unconformity, Avalon Unconformity and Base Tertiary Unconformity horizons. The faults are colour coded to indicate the horizon at which they were picked. Based strictly on orientation we can divide these faults into three groups.

1. ESE to SE trending faults

These faults are deeply rooted and associated with the Late Triassic – Early Jurassic rifting. They (mostly) run parallel and sub-parallel to the CC fault / hinge zone which is effectively the basin bounding fault of the Laurentian Basin. Although initially created by oblique extension they have been re-activated throughout the basin's evolution by:

a) movement along the CC fault caused by rifting of the Grand Banks basins during the Late Jurassic - Early Cretaceous; and

b) shear stress projected, primarily, into the NW quadrant of the study area from the NFZ, which continues into modern times.

The fact that these faults penetrate the shallow section (as indicated by the overlapping of the "blue" faults in the figure) supports the deduction that the faults have been reactivated by late movement along the CC or NFZ fault systems, or some combination of the two.

2. East–West trending faults

There are two major east west faults shown that are associated with a large ridge that is interpreted to extend almost entirely across the basin near the 45^{th}

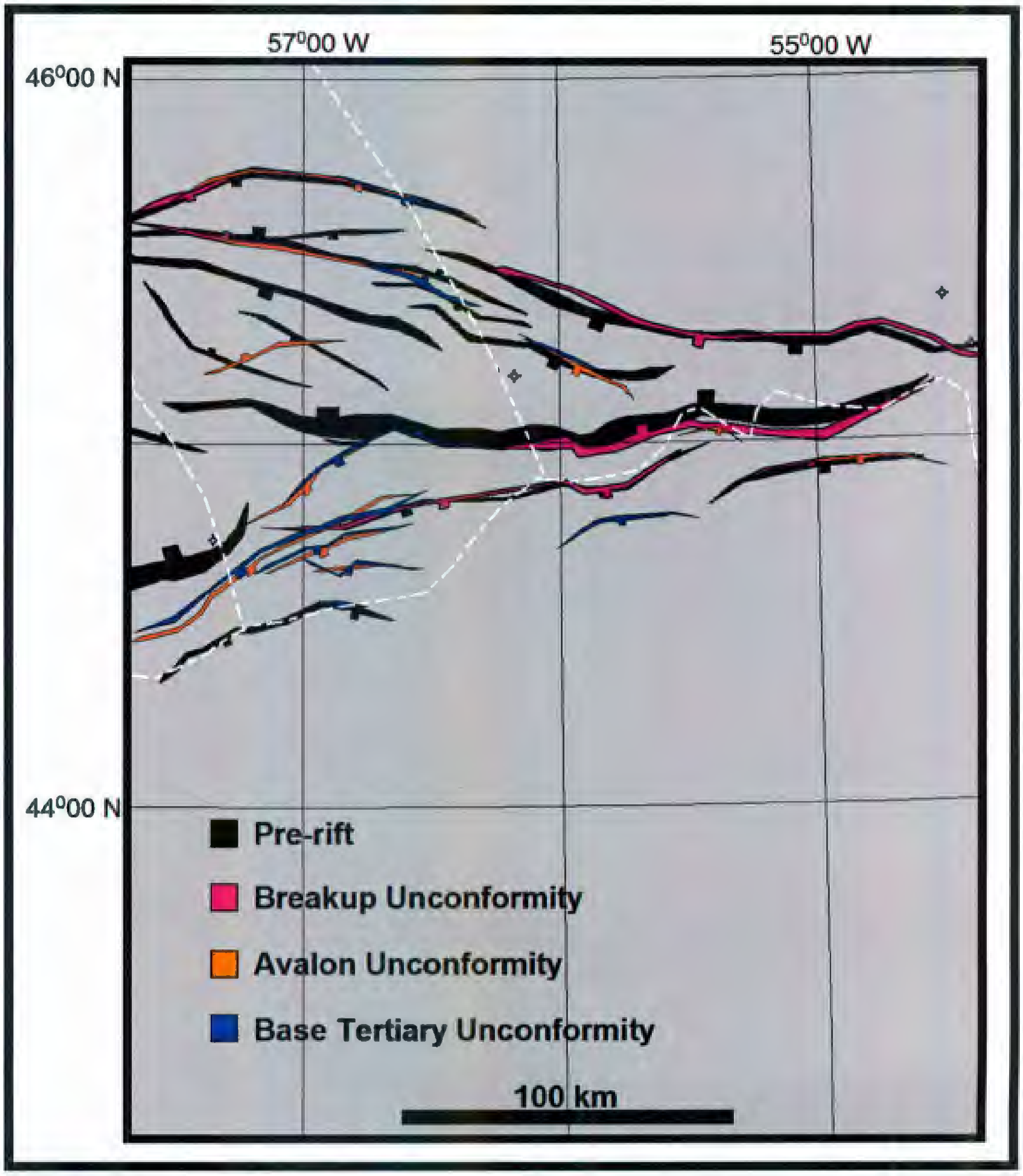

Figure 4.17
Map showing faults at Pre-rift, Breakup Unc., Avalon Unc., and Base Tertiary Unconformity. Faults are colour coded indicating the horizon at which they were picked. The outline of the shelf edge and Laurentian Channel are shown as white dashed lines.

parallel. As this ridge is not well imaged on all lines it is possible that it is in fact a series of ridges which may be cut by the SE and ESE trending faults. The east – west alignment of this ridge may be a reflection of a pre-existing zone of weakness within the Meguma Zone which affected fault patterns during the initial Mesozoic rifting. Alternatively, it may be related to shear stress projected into the basin as the Canso Ridge pressed into the basin from the west as a result of left lateral movement along the CC fault during the Late Triassic – Early Jurassic opening of the Fundy Basin.

3. WSW – SW trending faults

These faults, which are observed predominantly at the Base Tertiary and Avalon Unconformity levels in Figure 4.17, run approximately parallel to the modern shelf edge. They are interpreted to be gravitationally driven by sediment loading during the Tertiary. A few of these faults extend all the way into the Triassic and may have resulted from loading on pre-existing zones of weakness. In other cases they are seen to terminate in the Jurassic or Cretaceous sequences (Figures 4.4B, 4.5, 4.12 and 4.18).

4. 4 Petroleum System

With its very limited drilling, and with the detailed results of the Bandol #1 well yet confidential, the presence of a significant petroleum system has yet to be proven for the Laurentian Basin. However, given that commercial hydrocarbons have been discovered within similar age rocks in the Jeanne d'Arc Basin 550 km to the northeast and within the Sable Sub-basin 200 km to southwest, it can be said that, at the least, the regional setting is favourable for oil and gas exploration. In considering regional analogues, the Sable Sub-basin which is part of the same Scotian Basin depocentre as the Laurentian Basin will provide a better comparison than the Jeanne d'Arc Basin, which is located on the opposite side of the Avalon Uplift and has resulted from a failed rift. MacLean and Wade (1992) carried out a probabilistic analysis of the Laurentian Basin petroleum potential based on a variety of play concepts they had identified and concluded that, at an average expectation, the basin contained 8-9 tcf of recoverable gas and 600-700 million barrels of oil. This analysis was based on 300 structural leads lying above 7000 m depth, which is judged to be the approximate base of the hydrocarbon window for the area (Maclean and Wade, 1992). In this study no attempt has been made to replicate the detailed quantitative analysis provided by Maclean and Wade but the work completed does allow for some general statements on the presence of a petroleum system and the pointing out of some play concepts and leads. Figure 4.18 is a seismo – geological dip section of the western side of the Laurentian Basin. The MacLean and Wade (1992) stratigraphic chart has been inserted to identify the zones of potential reservoir and source rock.

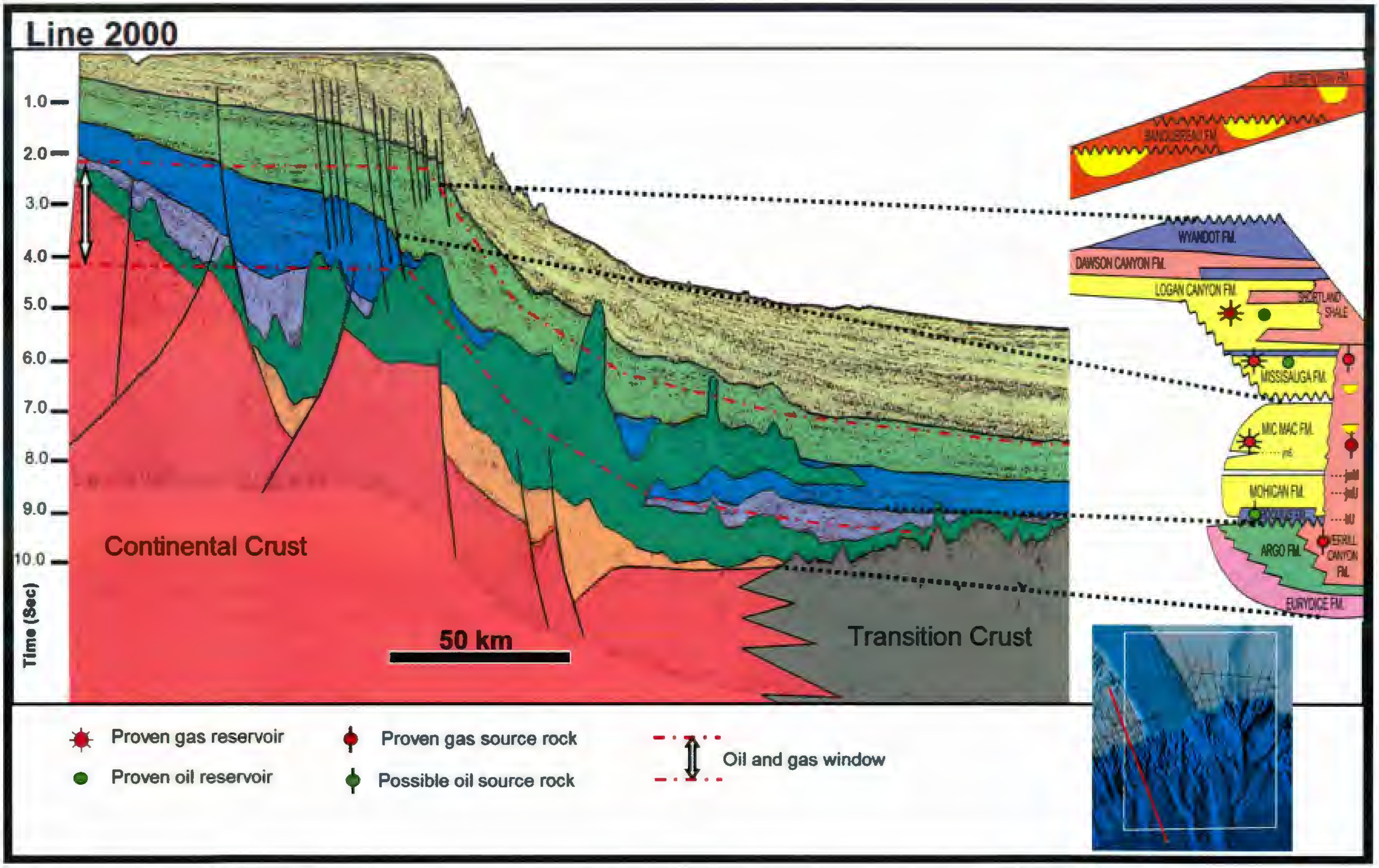

Figure 4.18
Seismic line showing the main stratigraphic intervals of the Laurentian Basin, with zones of potential reservoir and source rock and current hydrocarbon window. The two major fault systems (rift related and gravitationally driven) are also evident in this section. Stratigraphic chart modified after Maclean and Wade (1992), reservoir and source rock zones from, Sinclair (1988), Mukhopadhyay (1989, 1990); MacLean and Wade (1992). Hydrocarbon window estimated from depths provided in Nantais (1983) and MacLean and Wade (1992). Seismic line courtesy of GX Technology.

Considering the Scotian Shelf analogue, good quality sandstone reservoirs can be expected throughout the Jurassic and Cretaceous section particularly within the Mic Mac and Mississauga formations. Although the presence of the Jurassic carbonate bank edge is not proven in the Laurentian Basin this play cannot be completely discounted, especially given the ambiguity of the seismic imaging below the Avalon Unconformity.

The proven source rock for the Sable area discoveries is the Mid Jurassic to Early Cretaceous Verrill Canyon Shale (Powell, 1982; Mukhopadhyay, 1989, 1990; MacLean and Wade, 1992) which is the distal equivalent of the sandstones and limestones of the Mississauga and Mic Mac Formations. Although the Verrill Canyon is recognized as a predominantly gas prone source rock, Mukhopadhyay (1989, 1990, quoted in MacLean and Wade, 1992) reports that localized differences do occur in the nature of the organic matter and its maturity, and that the most oil prone source rock of this sequence occurs within pro-delta facies of the Mississauga – Verrill Canyon Formation. The evaporitic dolostones of the Iroquois Formation were also identified as a potential oil source rock by Sinclair (1988) and are noted as such in Figures 4.1 and 4.18. MacLean and Wade (1992) point out that although gas and condensate are the most common hydrocarbons found on the Scotian Shelf, small accumulations of light gravity oil have been encountered in four structures. The Mississauga and Mic Mac formations are the most important gas reservoirs on the Scotian Shelf but the oil discoveries have been concentrated in the upper Mississauga and Logan Canyon formations.

Although an important natural gas basin has been established on the western flank of the Laurentian Basin the same cannot be said for the adjacent South Whale Basin to the east. Fourteen wells were drilled in the South Whale Basin from 1966 to 1973, with one deep water well drilled in 1987 – all of which were dry. A more recent well drilled by Husky in 2005 was also dry. Although good quality Mic Mac and Mississauga sandstones have been encountered in a number of South Whale Basin wells, and there have been shows of oil and gas, no significant hydrocarbon discoveries have yet been made in the basin. The reasons for the lack of exploration success can be debated. However, a case can be made that the initial drilling efforts were too narrowly focused on salt dome drape and flank plays – which may not have had the right timing for this basin. An additional concern is that a definitive high quality oil or gas source rock has not been proven for the basin. The failure to prove a source rock can be at least partially explained by the fact that wells drilled over salt domes encountered a very restricted stratigraphic section which is not representative of the basin as a whole. Another concern is that a significant portion of the Jurassic section, that may have contained source rock, was removed by erosion during the emergence of the Avalon Uplift. However, significant amounts of Jurassic shale should have been preserved in the more distal environments and within deep grabens. Even if all Jurassic source rocks were removed by the Avalon Uplift the Cretaceous

Verrill Canyon shales, which postdate the Avalon Uplift, should be present along the outer margins of the South Whale and Laurentian Basins. The approximate oil and gas window on the Scotian Shelf, which begins at roughly 2200 m burial and ends at 5-6 km (Nantais, 1983; MacLean and Wade, 1992) is outlined in Figure 4.18 by dashed red lines. Assuming a similar geothermal regime for the Laurentian Basin Mesozoic section it would appear that a large area containing Triassic, Jurassic and Cretaceous successions remains within the hydrocarbon thermal window today.

In the absence of well cuttings or core through a source rock interval it is entirely reasonable to use regional trends to predict the presence of a source rock within a basin. However, we can also look to seismic data for variety of acoustic anomalies such as bright spots, dim spots, flat spots and gas chimneys that can provide evidence of an active petroleum system in a basin. Figure 4.19 shows gas chimneys on seismic lines located near the eastern and western extremities of the study area. In both cases the gas appears to be rising from the Jurassic section to the surface, and to be charging the near surface sediments with gas. Figure 4.19A also shows a Carboniferous section to be present beneath the Mesozoic section, and it is known that active petroleum systems are present in a number of Atlantic Canada Carboniferous basins. However, vitrinite reflectance analysis by Avery (1987) indicates that the Carboniferous section in Hermine E-94 is overmature, while the Cretaceous section directly above it is just entering

A

B

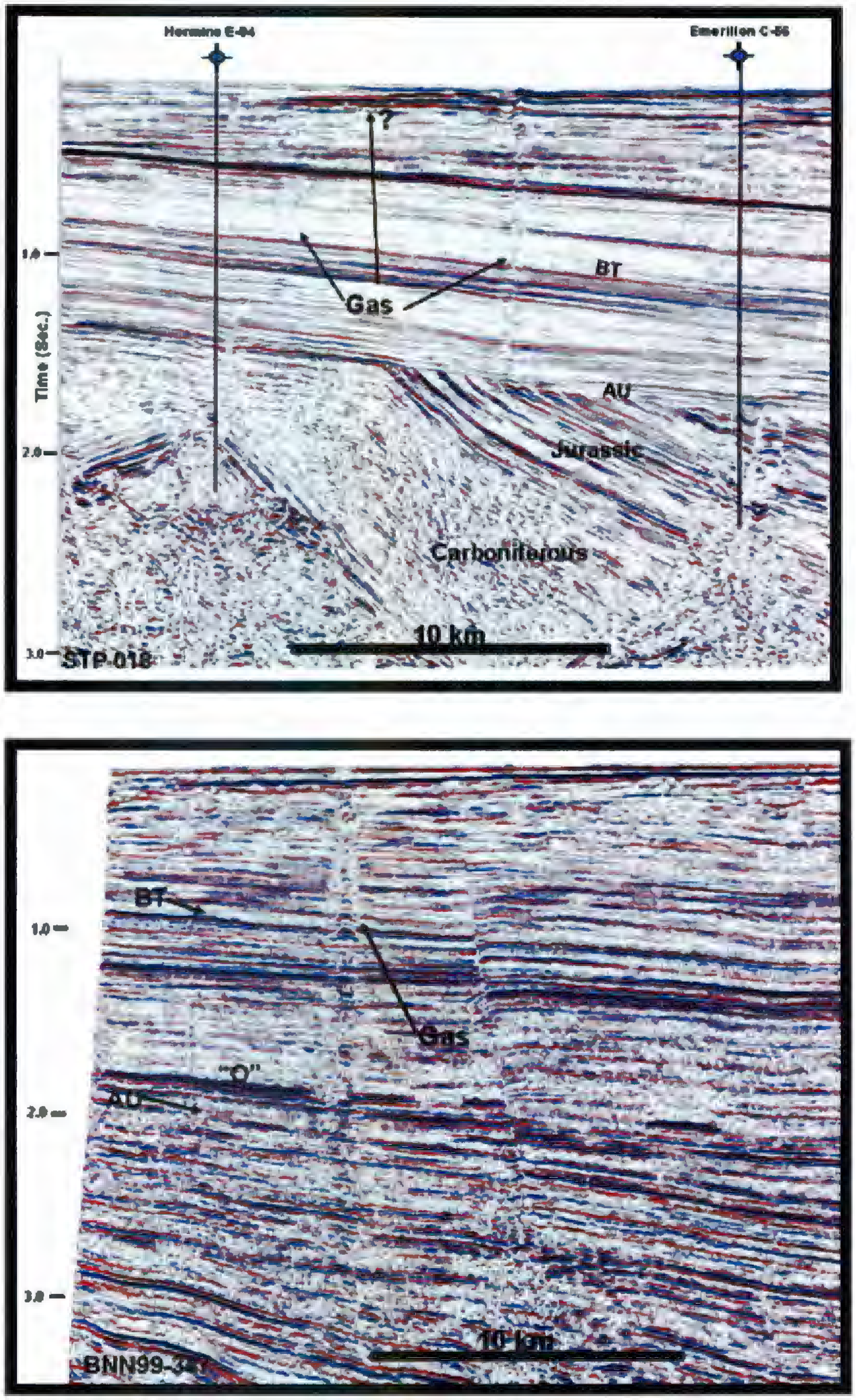

Figure 4.19

Seismic lines showing gas chimneys in the Laurentian Basin. Line STP 18 is located on the eastern margin of the study area and line BNN99 347 is located near the western margin of the study area. Acronyms: BT (Base Tertiary), AU (Avalon Unc.) and "O" ("O" Mkr.). Line STP 018 courtesy of the GSC and line BNN99 347 courtesy of GSI.

the marginally mature phase (MacLean and Wade, 1992). Given that the top Carboniferous at Hermine lies under only 1550 m of sediment, the fact that it is over mature indicates that it was exposed to much higher temperatures than the Cretaceous section above it. This implies that these Carboniferous rocks were either buried much more deeply than they are now or were affected by a thermal anomaly at some time prior to the deposition of the overlying Cretaceous section. Certainly there is a sharp increase in sonic velocity of the Carboniferous sandstones sitting below the AU (Figure 3.7) as compared to the Eider sands located directly above it. The dramatic increase in sandstone velocities supports a "step up" in compressional history as one crosses the AU. Additionally, it is clear that a great amount of erosion occurred during the AU hiatus in this part of the basin. However, given that there are many other areas in Atlantic Canada where the Carboniferous is not overmature there remains some possibility that its over maturity at Hemine E-94 is caused by proximity to a pre-Cretaceous thermal anomaly associated with the CC fault. There is even a subtle hint of gas emanating from the Carboniferous to the right of but very near, the Hermine E-94 wellbore in Figure 4.19A. Nevertheless, the best candidate for source rock in this basin remains the Verrill Canyon Formation, which should be preserved in significant thicknesses, especially along the outer part of the shelf and slope. An additional point that comes directly from the mapping of the Pre-Rift horizon, is that during the synrift phase stagnant lakes may have developed behind the large ridges mapped, that favoured the growth of lacustrine algae and hence the development of a potential continental lacustrine oil source rock. In Figure 4.18

we see a thick synrift sequence (coloured purple) directly above the Argo Salt and below the Break-up Unconformity. It is not known if this sequence has source rock or reservoir potential in the study area, and it is not noted in the existing stratigraphic charts for the Atlantic Canada Mesozoic basins. However, the sequence was discussed in a recent abstract and presentation by Brown et al (2007) where they have proposed calling it the Heracles Formation.

Assuming that there is significant mature source rock in the basin, it is clear from released well data that reservoir rocks are present and the existence of large gas and possible oil accumulations is a matter of migration paths, timing and trap integrity. Figures 4.19 to 4.21 present some examples of hydrocarbon leads and play possibilites noted in this study. In Figure 4.20 moving from right to left we see some interesting amplitude changes within the Jurassic section as we cross faults. In the centre of the line there is well defined rollover against dip likely caused by salt withdrawal below or drape over Pre-Rift ridges, which affects both the Jurassic and Cretaceous sections. This feature would have had greater trapping potential prior to the seaward tilting of the basin during the Tertiary but still maintains significant rollover on this line. Moving further to the left we see pinchouts and terminations against the basin margin within the Triassic and Jurassic section, as well as some rollover and faulting within the Cretaceous section. A concern with the leads on this part of the section is that the fault above the ridge may run to surface and have thereby breached any traps at this

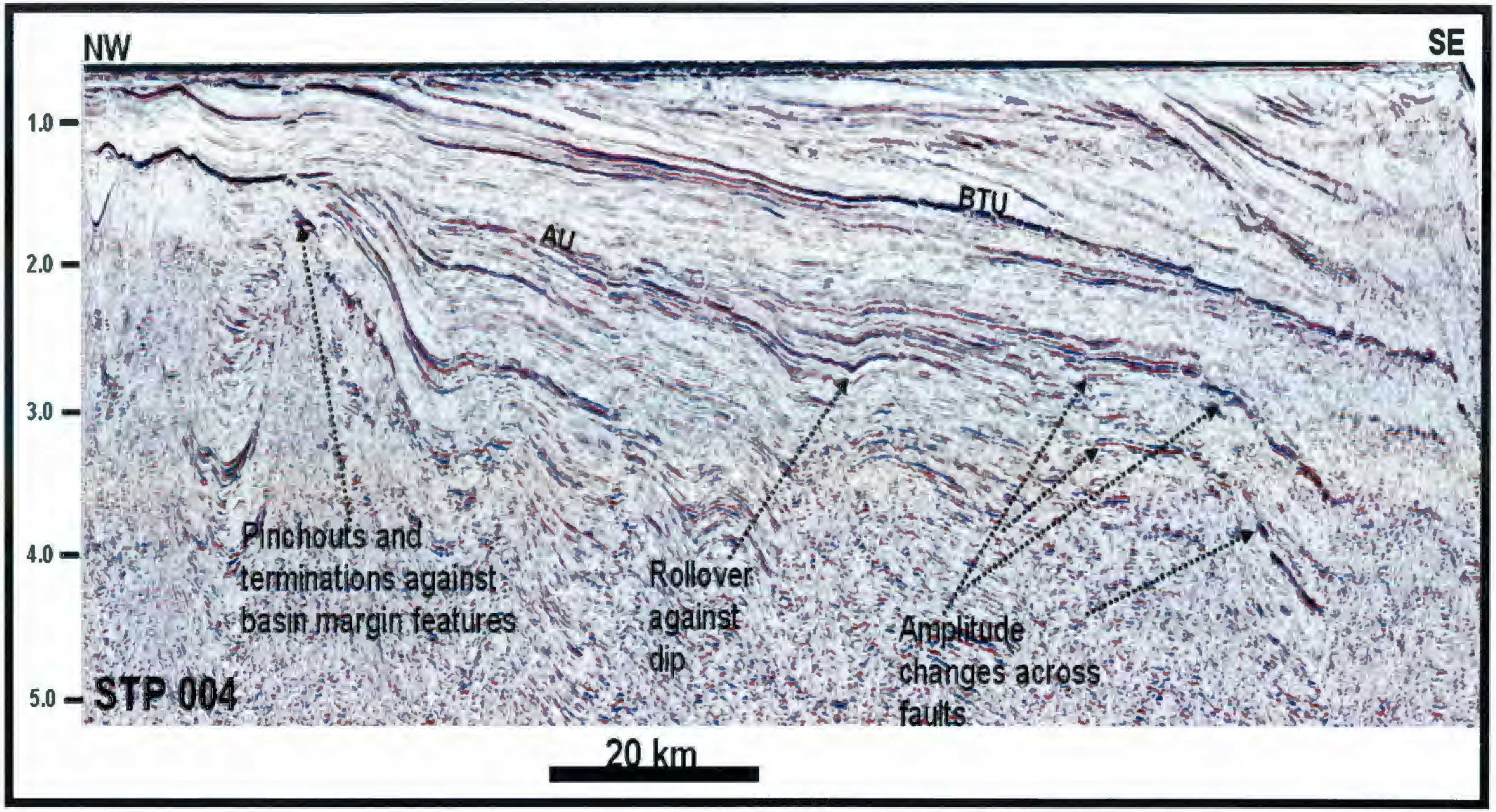

Figure 4.20
Seismic line STP 004 showing play concepts and leads. Acronyms: BTU (Base Tertiary Unc.), AU (Avalon Unc.) Line STP 004 courtesy of the GSC.

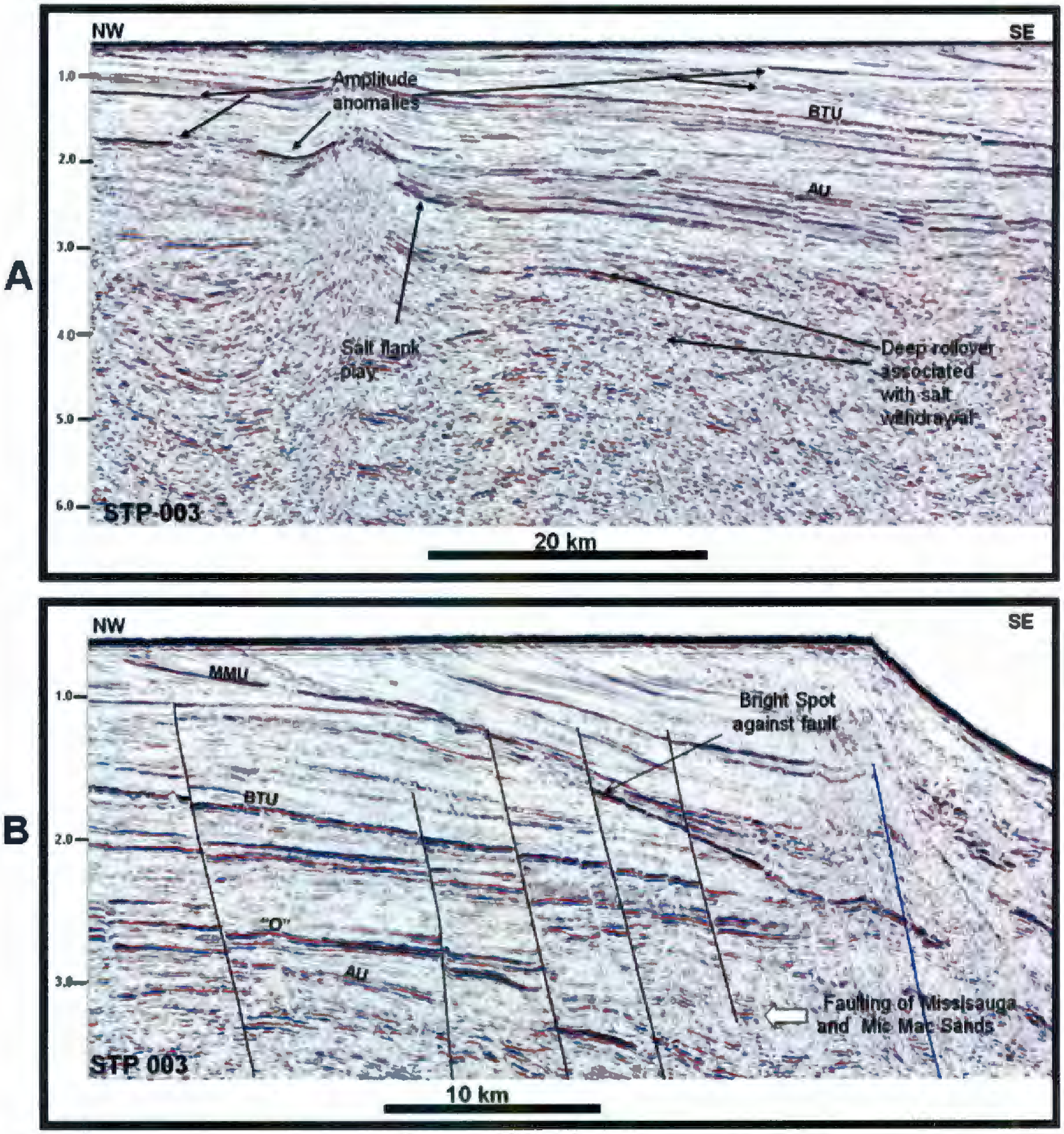

Figure 4.21

Selected portions of line STP 003 showing play concepts and leads. Acronyms: MMU (Mid Miocene Unc.), BTU (Base Tertiary Unc.), "O" ("O" Mkr.) and AU (Avalon Unc.). Seismic line courtesy of the GSC.

location. Nevertheless, it can be expected that when a passive margin basin tilts seaward as is the case for the Laurentian Basin, previously existing structural traps are likely to spill their contents updip, and fields may be concentrated along linear strike trends where pinchouts or other "blockages" occur. Figure 4.21A shows additional plays including a large deep Jurassic rollover associated with salt withdrawal, with anomalous reflection amplitude at the top of the feature. We also see a salt flank play with some rollover above the salt and various amplitude anomalies within the Cretaceous and Tertiary. Figure 4.21B shows a number of examples of normal faults affecting the Jurassic, Cretaceous and Tertiary sections. A similar style of faulting has been a successful play in the Sable Sub-basin when the reservoir and overlying sealing zones close against the faults.

Figure 4.22 is a grayscale version of line STP 028 showing a stratigrqaphic play (pinchout) below the Avalon Unconformity near the basin margin. Interestingly, there is a dimming of the reflectors which could be caused by gas within Jurassic carbonates or within higher velocity sands that are overlain by shale. A possible flat spot is noted, although there is a time variation of approximately 50 ms across the feature. Caution is also required in interpreting this as a flat spot as the interbed multiple between the BTU and the seabed arrives at approximately this time. Nevertheless, when anomalous characteristics such as dimming and cross-cutting events coincide with a stratigraphic pinchout within a potential reservoir zone, it is worthy of notice.

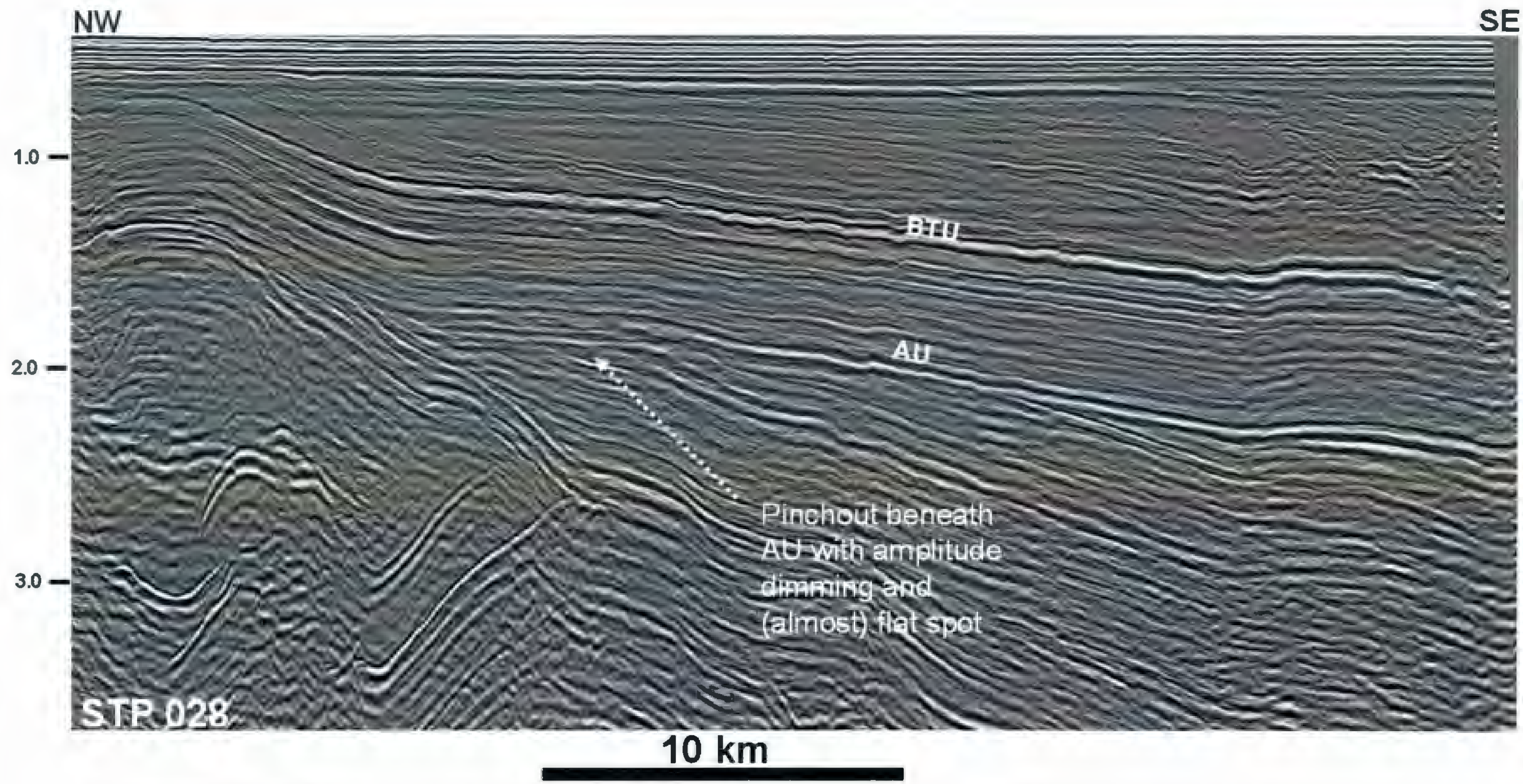

Figure 4.22

Seismic line STP 028 showing stratigraphic play against basin margin. Note dimming of reflectors and a possible flat spot. Acronyms BTU (Base Tertiary Unc.) and AU (Avalon Unc.) Seismic line courtesy of the GSC.

4.5 Evidence of Recent Tectonism

Figure 4.23 is a map taken from the Natural Resources Canada website showing the locations and magnitudes of earthquakes in or near Canada between 1627 and 2007. Given that the technological capability and the geographical coverage of detectors has evolved significantly over this period, there is little doubt that significant earthquakes in more distal regions may have gone undetected in earlier days. Nevertheless, the map represents a considerable body of data and indicates some tectonic hotspots and trends.

The 1929 Grand Banks earthquake, lying in the north central part of the study area, is clearly anomalous in that it is the only known earthquake greater than magnitude 7 located east of Quebec. It also appears to be sitting at a juncture of two trends: one running southeast along the Newfoundland Fracture Zone; and, the other running to the northeast towards the Avalon Peninsula of Newfoundland. Figure 4.24 shows the GSC's regional aeromagnetic data with an insert containing the first derivative of the Fugro high resolution data. Although the map shows a complex magnetic signature, NE trending lineaments can be seen in addition to those associated with the CC fault (discussed in Chapter 2). These lineaments reflect the older Appalachian structural fabric, which was truncated by the CC fault with the arrival of the Meguma zone. A prominent "double lineament" in the NE quadrant of the study area shows up on seismic data as two fairly subtle breaks in continuity of the Carboniferous section. This feature has been identified by MacLean and Wade (1992) as correlating with

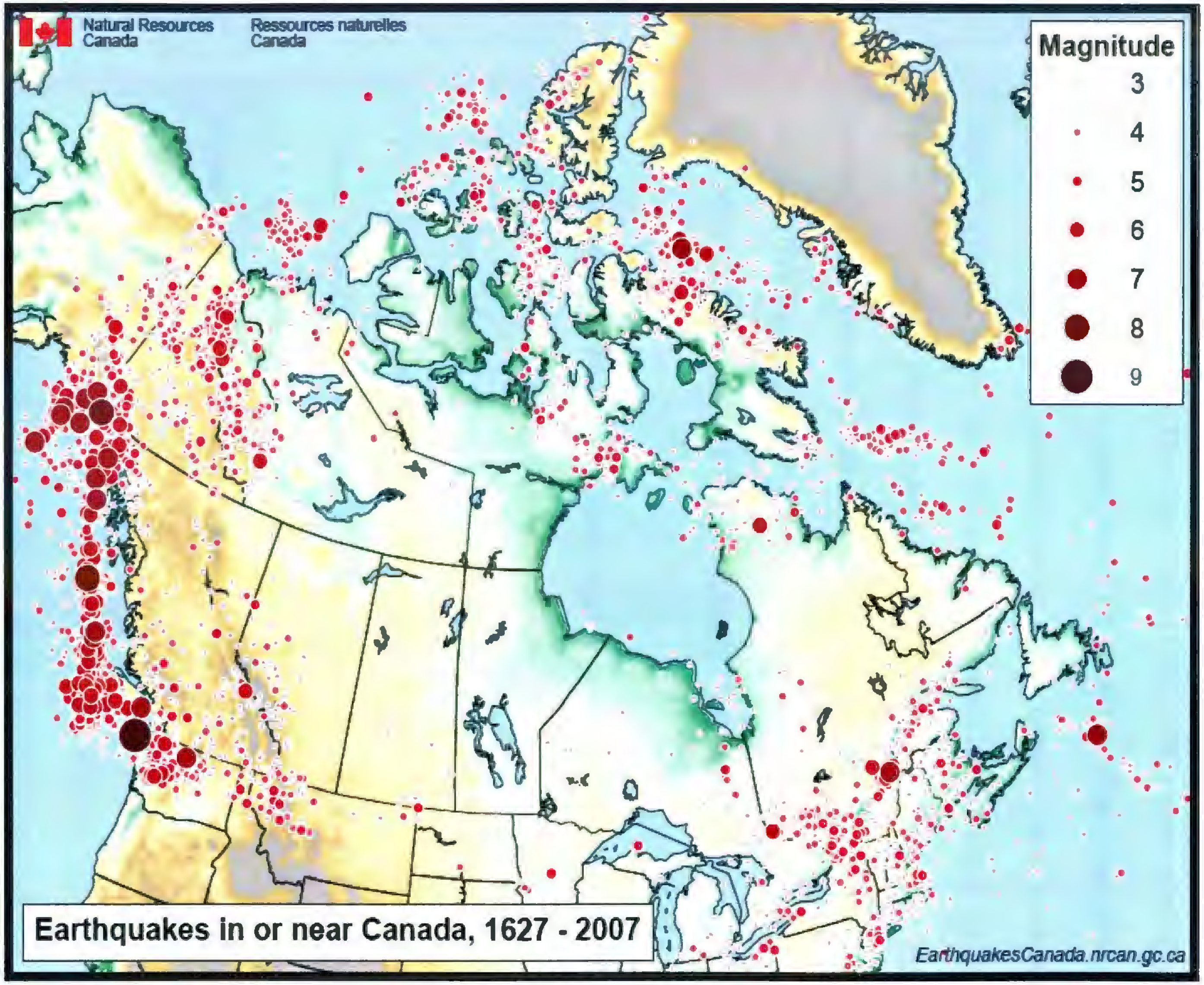

Figure 4.23

Map showing historic earthquake locations in or near Canada from 1627 to 2007 and magnitudes. Source: Natural Resources Canada website: http://earthquakescanada.nrcan.gc.ca/histor/caneqmap-eng.php early Mesozoic (201MY: Papezik and Hodych, 1980) quartz normative tholeiite dykes on the Avalon Peninsula, and likely related to the early rifting of Pangea. We recall from Chapter One that Bent (1994, 1995) concluded that the 1929 earthquake involved an original event on a NW trending plane followed by two later subevents on a NE trending plane. These observations, combined with the quake trends shown in Figure 4.22, are consistent with zones of weakness along the NFZ, perhaps coupling with sub-parallel zones of weakness along the CC system, with secondary stress being released along the older Appalachian trends. A NW trending shear stress regime is also consistent with the fault and ridge pattern observed in the Pre-Rift horizon (Figure 4.7).

There is also a series of short wavelength lineaments radiating in a southeasterly direction from a point on the eastern shoulder of the Laurentian Channel (Figure 4.24). Seismic line STP 025 (indicated by a white dotted line in Figure 4.24) crosses this trend and shows that the short wavelength lineaments correlate with a series of faults that break the surface in this area (Figure 4.25). This series of small faults disrupting the surface on line STP 025 appear to be the secondary effects of a more deeply rooted event associated with the basin bounding CC fault system. The fact that they radiate to the northwest within the shallow section implicates the NFZ as the source of stress. The longer wavelength magnetic response, which represents the deeper basement features, is parallel to the CC fault. And so it would appear that the NFZ is introducing NW directed shear

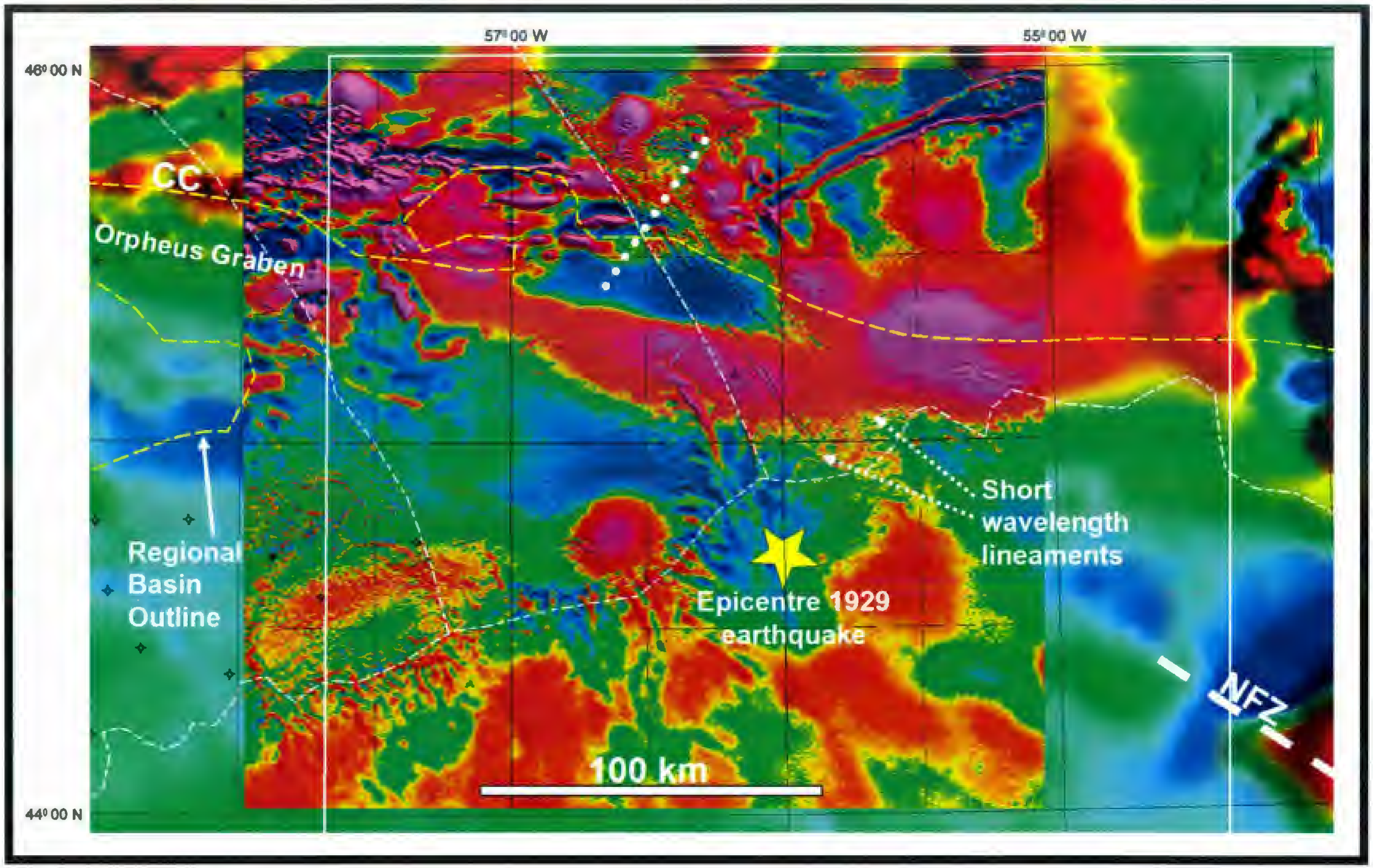

Figure 4.24

High resolution aeromagnetic map (first vertical derivative) inserted in regional total field magnetic map. Regional basin outline based on 4000 m depth to basement contour from the GSC mapping is shown as a dashed yellow line and the shelf edge and Laurentian Channel are shown as dashed white lines. The location of seismic line STP 025 (Figure 4.25) is shown as a white dotted line. Newfoundland Fracture Zone (NFZ) shown as heavy dashed white line. For colour legends see Figure 3.12. Regional magnetic map courtesy of the GSC and high resolution magnetic map courtesy of Fugro .

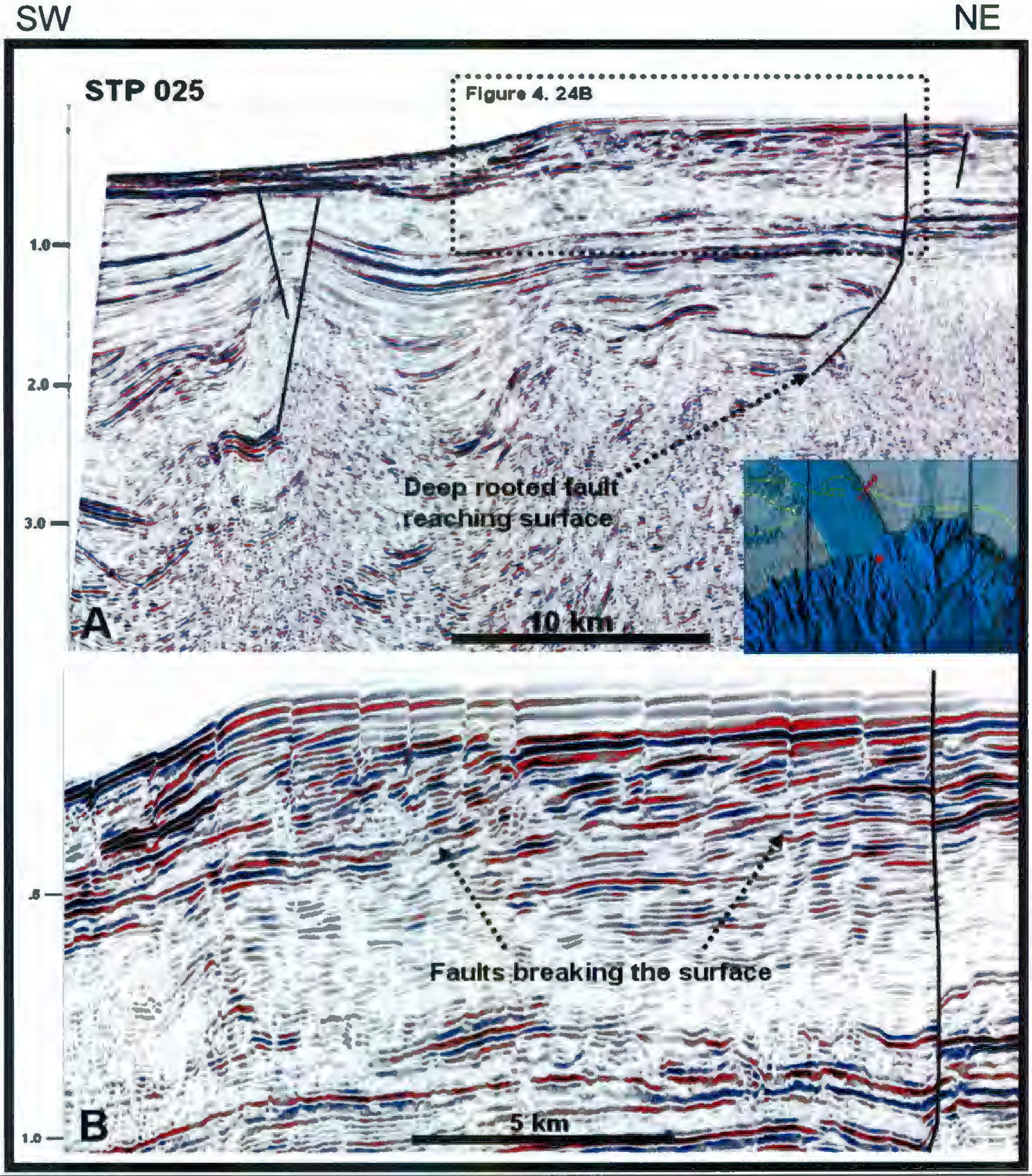

Figure 4.25

Seismic line STP 025 is showing deep rooted faults approaching and reaching the surface along the northern margin of the basin and shallow secondary faults breaking the surface. Seismic line courtesy of the GSC.

stress into the area that is being translated into WNW stress along the CC fault, except in the shallowest section where it is manifested as NW trending faults. Figure 4.26 shows a seismic line (STP 023) running close to the epicentre of the 1929 earthquake. The hypocentre lies at a depth of 20 km (Piper et al 1987; Bent, 1995), which is well below the seven seconds recorded on the section. Although the sedimentary section is highly disturbed by both salt tectonics and nearby slumping there is no obvious fault reaching the surface at this location. This may be explained by a non-vertical fault that reaches the surface somewhere else, but indeed no such fault has been mapped in the offshelf area in this study. In fact, the only place that faults are observed to reach the surface is along the basin margin to the north, and in particular towards the northwestern corner of the study area. As noted previously, a possible explanation for these observations is that in the more basinal areas, where the Argo salt is thick, it acts as a detachment between the movements of basement and the overlying sediments. But this is not the case at the basin margin where NW directed stress from the NFZ is re-directed along the CC fault resulting in uplift of ridges and compressional folding of Mesozoic and Cenozoic sediments, along with the shallow NW trending faults noted above. When slip occurs along the NFZ or its imbricates, as in the 1929 quake, secondary events are triggered along existing zones of weakness which include the CC fault and NE trending Appalachian faults.

Recognizing that faults along the northern margin of the basin can be very recent

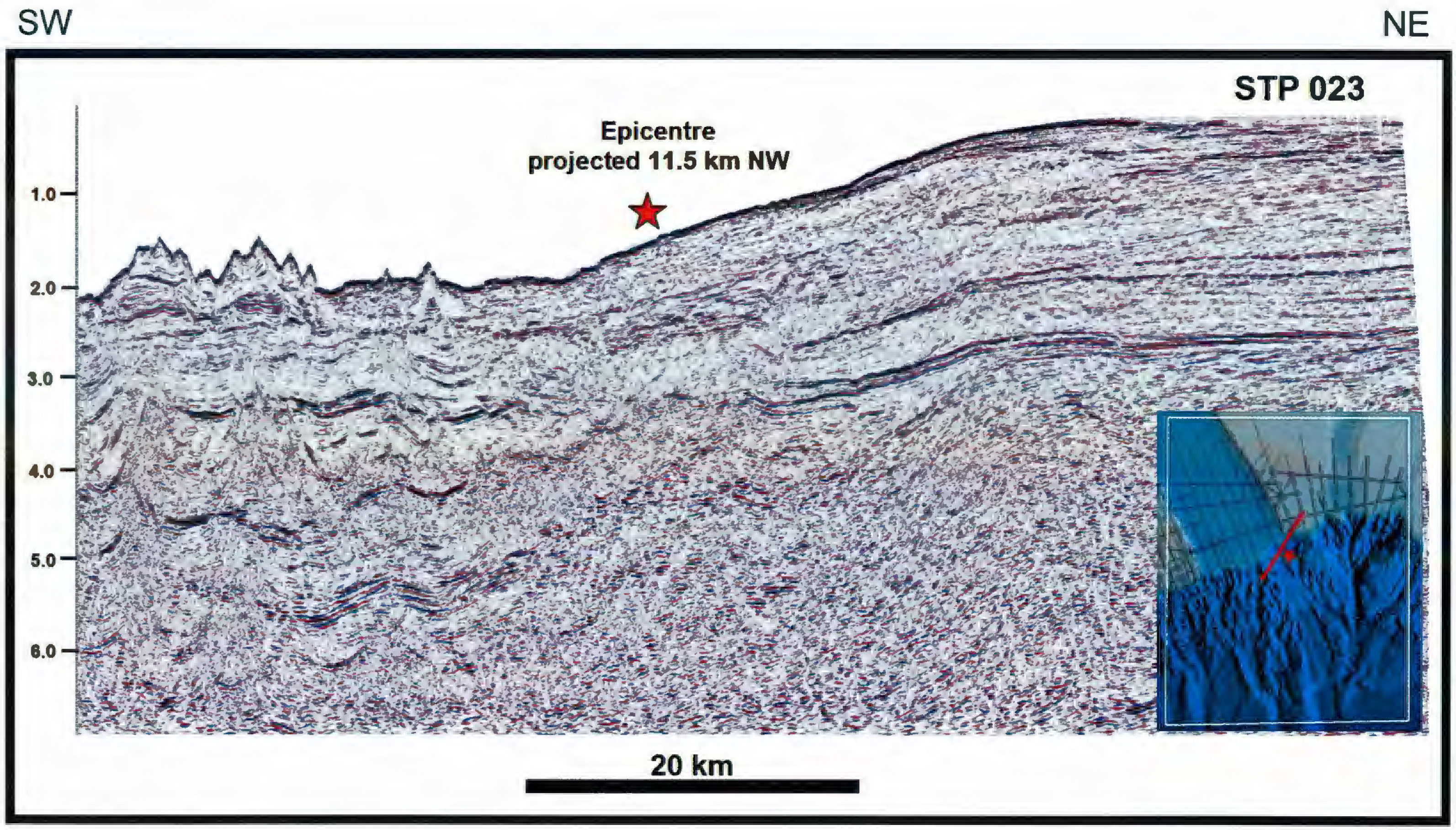

Figure 4.26
Seismic line STP 023, located near the epicentre of the 1929 earthquake. Epicentre at 20 km depth, well below the 7 second recording time of the seismic section. Seismic line courtesy of the GSC. Time scale in seconds.

and reach the surface, is an important factor that must be taken into consideration when evaluating individual hydrocarbon prospects in this part of the basin.

Chapter 5

Summary, Conclusions and Recommendations

5.1 Summary and Conclusions

The Laurentian Basin has undergone complex geological evolution during the Mesozoic and Cenozoic due to it being located at the transform boundary between the Scotian and Newfoundland continental margins. Exploration of the basin has been curtailed by moratoria stemming from international and provincial boundaries that cross the basin. Additionally, a large proportion of the basin is situated in the deep waters of the continental slope which has only become the focus of active exploration by the industry in relatively recent times. Interest in mapping the deep water geology has also achieved recent currency with governments interested in deciphering the structure of the continental margin with regard to the seaward extension of territorial claims.

This study uses donated and public domain multichannel reflection seismic, supplemented by potential field data and well data to produce maps and cross-sections of the basin. Building on the work of previous researchers, conclusions were drawn and ideas proposed regarding the tectonic and structural framework of the Laurentian Basin and its petroleum system. Laurentian Basin is an area where little published literature exists, and where improved understanding of the geology can increase the chances of success in petroleum exploration.

Since the Laurentian Basin is not clearly defined by geographic or geological features a rectangular block was carved out to include the Dauntless D-35 well to the west and the Emerillon C-56 well to the east, with the northern and southern boundaries roughly defined by the limits of seismic coverage. This 87,000 km^2 rectangle, which is shown on many of the maps herein for geographic reference, is referred to interchangeably as the "study area" or the "Laurentian Basin" throughout the text. Although approximately 17,000 km of regional seismic data were reviewed in the study, it was the 3072 km acquired by the GSC between 1984 and 1987 that best covered the basin and constituted the core dataset in terms of interpreting seismic sequences, tectonic trends and in generating seismic time structure and depth maps. Additionally, approximately 3600 km of data provided by geophysical contractors crossed into the study area, mostly in its southwest corner. The industry seismic, which included some newer data recorded to longer intervals, proved to be critical in investigating the deeper crustal architecture.

In the simplest sense the basin can be divided into two zones:

1. An area lying north of a roughly east west trending hinge line (Figure 4.7). The hinge is traced by a series of down to the basin faults that coincide with the Cobequid-Chedabucto fault system (MacLean and Wade, 1992). North of the hinge we have a thin Mesozoic section over a well imaged Carboniferous sequence. The Mesozoic is in turn overlain by a Cenozoic wedge that thickens basinward from a zero edge.

2. The Mesozoic section south of the hinge is a deep complexly structured basin that has been formed by extensional tectonics during the rifting of the Scotian – Grand Banks margin. To varying degrees during its development the Mesozoic – Cenozoic section in this area has been deformed by localized compressional strike slip movement, oblique extension and salt tectonism. Although there are occasional hints as to what lies below the Mesozoic section south of the hinge line, the seismic imaging at that level is highly ambiguous, and it cannot be definitively stated that the Carboniferous section is present south of the hinge line.

The basement, interpreted to mean the base of sedimentary section, is not a good reflector anywhere in the basin. The Base of Windsor Salt is the oldest correlatable horizon in the basin, and although it is a strong reflector in a few areas above the hinge line, it is very likely to be underlain by Tournaisian sediments, as is common in many of the Atlantic Canada Carboniferous basins including the adjacent Sydney Basin (Langdon and Hall 1994; Pascucci et al, 2000; Enachescu 2006a and b). In terms of investigating the basin's structural evolution the mapping of the Pre-Rift horizon was judged to be the critical first step, but this proved to be no easy task because of the very tenuous nature of this reflector south of the hinge line. As outlined in section 4.1 an intense iterative process was brought to bear with generous allotments of interpolation and extrapolation to produce the map shown in Figure 4.7. Figure 5.1 is a 3D representation of this map, with an overlay of the regional basin outline (yellow line corresponding to 4 km depth to basement contour) from previous work by the

GSC. Although the mapping is highly interpretive in places, due to the already mentioned data challenges, we do see some of the basin's major features. Moving from north to south on the map, we see that the CC Fault across which the basin "hinges" to the south is not a simple continuous fault, but a series of en echelon faults, with a step-down ridge into the basin that was also mapped by MacLean and Wade (1992). Moving basinward we come to a large ridge or, more likely, a series of en echelon ridges running roughly east-west. At the western end of this ridge system we observe the possible beginnings of another ridge or perhaps an offset along a transfer fault can be interpreted. Transfer faults cutting across the general structural trends can be expected in an extensional environment, but are not always easy to recognize on seismic data. Such was the case in this mapping effort, and although transfer faults are likely to be present, none were readily correlatable on the seismic data and as such are not integrated into the mapping.

Moving further seaward the basement drops down sharply, at a point roughly coincident with the modern shelf edge. Less detail is seen in the deeper water area because of the presence of complex salt features within the Mesozoic – Cenozoic section which combines with decreased seismic coverage to make an interpretation of the Pre-Rift section even more tenuous. Although there are likely a number of synrift basement features in the deeper water section as well, they

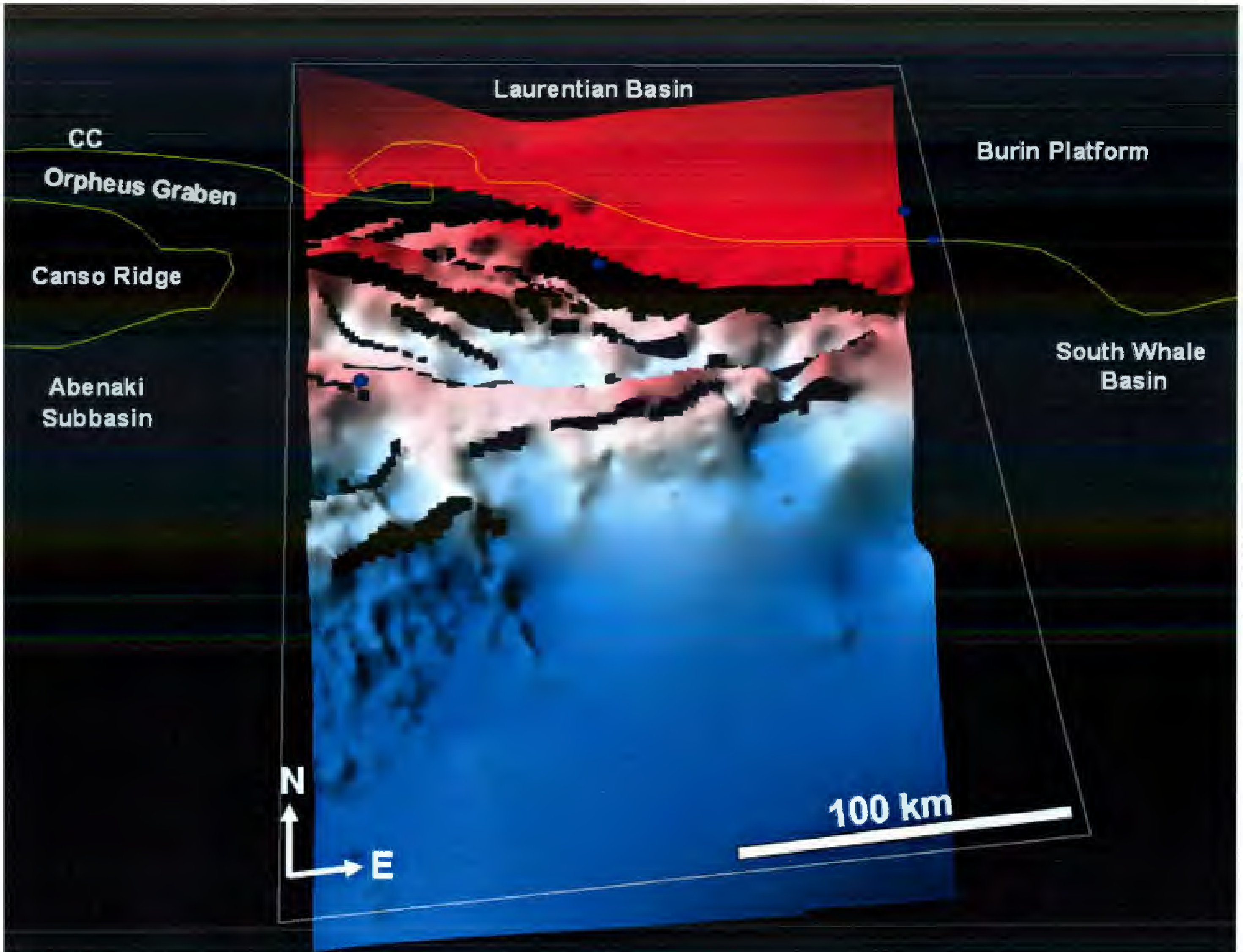

Figure 5.1

3D image of pre-rift section. Dark areas within the figure represent faults. Blue dots show well locations. The yellow outline represents the regional basin outline as defined by the 4 km contour on the GSC's regional depth to basement map. This contour lies near the Mesozoic hinge line on the said GSC map.

do no show up on the map as the Pre-Rift horizon correlations in this area are heavily interpolated beneath the salt. As seen in Figure 4.4, imaging in the deep water part of the basin improves considerably as one moves seaward of the halokinetic disturbed zone and the Pre-Rift horizon merges with what is interpreted to be transitional crust. The interpretation of this seismic character as transitional crust is consistent with that of Louden et al. (2005) and with the fact that transitional crust was encountered in ODP drilling on the Grand Banks and Iberian margins (Sibuet et al., 2007). Autochthonous salt appears to onlap the transitional crust for the full 75 km to the end of the line.

Although the major effort in this project was to map the Pre-Rift horizon, maps were also prepared for the Break-up Unconformity (Pleinsbachian), the Avalon Unconformity (Late Jurassic to Early Cretaceous), the Base Tertiary Unconformity and two erosional surfaces within the Tertiary, tentatively identified as the Late Oligocene Unconformity and the Mid-Miocene Unconformity by correlation to the Vail et al (1977,1984) and Vail and Mitchum (1979) sea level chart. Additionally, a brief discussion of the basin's petroleum system was provided and evidence of recent tectonism was presented. A list of additional observations and conclusions are presented below.

1. The structural patterns within the Pre-Rift section (en echelon ridges and faults trending ESE and east-west) are consistent with an oblique (SE trending) extensional system constrained by a roughly east-west running basin boundary, represented by the Cobequid – Chedabucto fault system.

2. Moving basinward across the hinge line we observe a deep graben behind a large basement ridge that has been mapped as running approximately east-west across the study area. This ridge, which is not well imaged and may in fact be a series of en echelon ridges, is bounded by normal faults. The east-west trend of these faults, which is at odds with the ESE to SE trends of the more landward faults may be explained by:
   a) rifting along a pre-existing zone of weakness within the Meguma terrane; or
   b) east-west shearing stress projected into the basin as the Canso Ridge pressed into the basin from the west with the Late Triassic – Early Jurassic opening of the Fundy Basin.

3. A series of NE to ENE trending faults are observed to (variably) extend from the Tertiary section into the, Cretaceous, Jurassic or Triassic sequences. These faults which run roughly parallel to the modern shelf edge are interpreted to be gravitationally driven features that have resulted from sedimentary loading during the Tertiary.
4. No thrust faults were observed on the seismic data but there were numerous steeply dipping faults, consistent with strike slip movement.
5. Very few faults extended above the Break-up Unconformity in the study area. Where they did they were primarily associated with the buildup of NW directed shear stress against the CC fault from the NFZ. These faults are located mostly in the northwest sector of the study area. Other shallow

cutting faults were the gravitationally induced faults (mentioned above), located mostly near the shelf edge. The Break-up Unconformity map (Figure 4.9) also shows how salt piercements in the northwest corner of the basin have been elongated along faults in a SE direction. This is interpreted as further evidence of shear stress being projected into the basin along the NW – SE trending Newfoundland Fracture Zone.

6. Additional shallow cutting faults constrained to the youngest Tertiary – Quaternary(?) section were observed trending in a northwest direction on the eastern side of the Laurentian Channel. These faults, which correlate very well with NW trending short wavelength magnetic lineaments, are postulated to have been created by NW directed stress from the NFZ reaching the shallow sediments along faults near the basin boundary. The NFZ is not expressed on seismic data as an unambiguous correlatable feature (at least within the study area). What we do see are secondary effects in the form of sub-parallel faults and ridge features, and compressional features where stress from the NFZ meets the CC fault system.
7. No clear fault can be seen at the epicentre of the 1929 earthquake. However, the hypocentre was located at 20 km depth, well below the seven second recording time on the available lines near it. We do see large slump and canyon features in this area and all across the slope portion of study area. A weakly traceable magnetic anomaly running sub-parallel to the NFZ (named lineament BA in Figure 2.3) projects into the

study area near the epicentre, which may represent an imbricate of the NFZ that is affecting the area.

8. An explanation as to why the NFZ and its imbricates are not easily seen on the seismic data in the Laurentian Basin and environs is that movement along this system originates within the basement which is detached from the overlying sediments by the Argo salt over large areas. However, we do see effects (shallow cutting faults, compressional features) where the shear stress from the NFZ meets the basin bounding CC fault system.
9. The 1929 earthquake may have been caused by one of the imbricates of the NFZ.
10. The locations of "instantaneous" cable breaks in the 1929 turbidite event indicate a source area for the flow that extends over about 33,000 km^2.
11. Assuming correct identification of the ages of major erosional events in the Tertiary, most of the off-shelf Tertiary sediments were deposited after the mid-Miocene.
12. Being located directly on trend with the Scotian Shelf with similar age sediments, the Laurentian Basin is likely to have a similar, gas prone, hydrocarbon system. Direct hydrocarbon indicators such as gas chimneys and amplitude anomalies terminating against faults are common in the Laurentian Basin.

13. Assuming a similar thermal regime to the Scotian Shelf, a significant portion of the Cretaceous, Jurassic and Triassic sediments of the Laurentian Basin are within the thermal hydrocarbon window today.
14. The massive amount of salt (Figure 4.18) that is preserved in the basin despite being exposed to repeated erosional events, suggests that the diapiric region observed today was part of a large basinal low that preserved the salt through these events. Even the large ridge interpreted in Figure 4.18 that appears to be covered by salt, and was likely to be contained within a broad basinal low in comparison to the height of the rift shoulder to the north and the spreading ridge to the south.
15. Significant seaward tilting of the basin occurred during the Jurassic and Tertiary which would have disrupted existing structurally trapped hydrocarbon pools, causing them to drain landward. Stratigraphic traps should have remained intact, and structural traps that had sufficient vertical closure would still present viable drill targets. Where hydrocarbons have been spilled updip fields may be found along linear strike trends at basin “blockages”. Shallow cutting faults near the basin’s landward boundary may have drained some of the (potential) hydrocarbon pools in this part of the basin. The presence of shallow cutting faults should be considered in assessing geological risk and prioritizing hydrocarbon prospects.
16. Seismic data acquired in this area need to be recorded to at least 12 seconds to ensure imaging the deepest parts of the basin (off-shelf).

17. Although not an integral part of the study, it is noted that the ECMA which can be easily followed up the Atlantic margin becomes disrupted as one approaches the study area, and is cut by a NNW trending transfer fault approximately 135 km west of the study area's western boundary. Where the faded remnant of the ECMA crosses a seismic line in this area it is clearly associated with continental crust rifting and not with the transition to oceanic crust.
18. The high resolution magnetic map shows a "conical" shaped anomaly near the shelf edge, near the centre of the study area, that is suggestive of a volcano or intrusive body. One seismic line runs through the anomaly, but does not show a feature that looks like an obvious volcano. However, the imaging is poor at that location and the pre-rift horizon is interpreted to be very close to the seven second recording time. Several other similar but less well defined magnetic anomalies are observed in the same area.
19. Finally, the conclusions and postulations regarding the tectonic evolution of the basin are summarized below:
    a. In the Late Triassic rifting begins across the region. The opening of the Fundy Basin moves a large Scotian Shelf block eastward along the southern margin of the Orpheus Graben by left lateral movement. The Canso Ridge (Figures 2.2 and 5.1) presses into the Laurentian Basin from the west introducing localized compressional and shearing forces.

b. With the start of Scotian Shelf seafloor spreading in the Pleinsbachian, uplift occurs with an associated Break-up Unconformity. Given that extremely thick salt sections survived this event it would appear that a broad area between the rift shoulder and the spreading ridge remained below sea level and allowed the preservation of the Argo Salt.

c. Also, with the start of seafloor spreading in the Pleinsbachian, right lateral strike slip movement from the NFZ becomes significant in the Laurentian Basin and combines with gravitational forces from the seaward tilting of the margin to produce a general, right lateral oblique slip setting for the basin.

d. As the Jurassic proceeds, and the basin enters the passive margin stage, thermal cooling leads to differential basin subsidence, manifested as a seaward tilting of the basin. Although tectonism within the basin has diminished significantly in this post-rift phase right lateral shear stress from the NFZ continues to affect the basin to a significant degree, and persists in some measure to modern times. A portion of the NW directed shear stress from the NFZ is translated into roughly E-W directed stress along the CC fault. As the basin tilts seaward the Argo Salt is mobilized into diapirs by differential loading from the north and also begins to flow basinward, penetrating the overlying Jurassic section.

e. In the Late Jurassic – Early Cretaceous the Avalon Uplift leads to severe erosion of the Jurassic section on the eastern side of the basin. Salt movements continue throughout this period. In areas uplifted sufficiently by salt domes all of the Jurassic section and some of the Argo is removed. The westward tilting of the basin by the Avalon Uplift affects the direction of sediment transport so that it attains a significant NE to SW component. This results in a considerable amount of sediment being moved westward from the Southern Grand Banks and Laurentian Basin into the Scotian Shelf basins. East to west running rivers from the Grand Banks to the Scotian Shelf would likely follow the CC fault and it's imbricates. Some indications of channeling into the Pre-Rift basement by the Avalon Unconformity are seen above the hinge line on seismic data.

f. General subsidence occurs during the later Cretaceous. The effects of the NFZ on faulting in the basin are restricted to the area where it meets the northern basin-bounding CC fault. The start of seafloor spreading between the Grand Banks and Iberia contributes to right lateral movement on the CC Fault. Evidence of this movement can be seen in the deposition of the Chaswood Formation onshore Nova Scotia.

g. At the end of the Cretaceous, the North Atlantic basins are eroded by combination of Mega-tsunamis from the KT asteroid impact and a lowering of sea level, creating a widespread unconformity that provides a highly correlatable seismic marker across the entire NW Atlantic region. The Base Tertiary Unconformity is the most coherent seismic marker in the region and allows direct correlations between the Scotian Shelf and Slope, Laurentian Basin and Grand Banks basins.

h. As the Tertiary Period progresses the basin tilts seaward again and the hinterland rises providing an abundance of sediment that progrades seaward across the shelf. Several dramatic Tertiary erosional surfaces can be mapped within the study area relating to eustatic sea level changes and the development of the paleo St. Lawrence River.

i. The deepest erosion within the Tertiary channels lies very close to where the NFZ magnetic lineament projects into the basin and may be related to a focusing of the paleo – St. Lawrence River along faults related to the NFZ.

j. At present, shear stress from the NFZ continues to project into the Laurentian Basin as evidenced by shallow cutting faults running parallel and sub-parallel to the NFZ and resulting in occasional powerful earthquakes.

5.2 Recommendations for Future Work

5.2.1 Acquisition, re-processing and integration of new data

- ***Integration of additional seismic data:*** Other than the southwest corner of the study area which had a relatively dense seismic grid, this study was based on a fairly coarse grid of dip lines (12 km separation) and a few strike lines (20-30 km separation). In recent years significant amounts of new data have been acquired by the companies operating in the area, some of which are now available in hardcopy from the C-NLOPB or will become available soon. These data can at some time be integrated with the data used here for a more detailed mapping project to benefit research and exploration in the area.
- ***Acquisition of new seismic data:*** With regard to the placement of future seismic lines, one must take into consideration the locations of the new data that have already been acquired by the operators. As these data are released, seismic basemaps and hardcopy sections can be obtained from the C-NLOPB. However, as can be seen in Figure 3.1 there is a large data gap in the middle of the study area. It would also be very helpful to have additional infill strike lines on the shelfal portion of the basin to better tie some of the features seen on the dip lines. Three dimensional seismic data are needed to properly map the complex structuring in the NW part of the study area. New data extending into the deep water areas should be recorded to at least 12 seconds to properly image the basement. By

recording the data to 15 - 20 seconds one can also image the Moho and thereby investigate how deep crustal dynamics impacts the evolution of the overlying sedimentary basins. In general it will be important to find a way (more powerful energy sources perhaps) to get more energy below the Avalon Unconformity to better image the Jurassic and Triassic sequences.

- ***Data Reprocessing:*** Significant improvement was made to the older GSC data by the Arcis reprocessing which focused on pre-stack time migration and multiple removal. In attempting to image below the highly complex salt section pre-stack depth migration can be very helpful, as was demonstrated by the GX Technology data made available for this study. GX processed the data by depth migration and then converted back to time for integration with the existing grid. Reprocessing the seismic data by pre-stack depth migration and use of inverse wave equation migration algorithms are recommended for future work.
- ***High Resolution Aeromagnetic Data:*** Given the effectiveness of magnetic data in identifying basement highs and fault traces, it would be useful to acquire additional high resolution aeromagnetic data to supplement the data donated by Fugro. These data are particularly useful in the shallow water areas where the basement features are closer to the magnetometer during acquisition.

5.2.2 Lithostratigraphic Correlations

- ***Laurentian Basin well results:*** The Bandol #1 well (drilled on the shelf in French territory) results will become publicly available in 2011 and a validation of the interpreted seismic horizons with geological tops will then be possible, using the seismic profile crossing the well location. Also, the ConocoPhillips partnership which holds licences for large tracts in the basin spudded the *East Wolverine G-37* exploratory well in a deep water portion of the basin on November 24, 2009. The results will be publicly available in 2012 and will facilitate tying the deep water geology to that of the shelfal area.

5.2.3 Seismic data attribute studies

- ***Direct hydrocarbon indicators:*** DHIs can significantly lower the exploration risk. A number of potential DHIs were identified in this study and may warrant further analysis by modern processing techniques such as true amplitude processing, inversion, amplitude versus offset (AVO), and Lambda-Mu-Ro analysis.

5.2.4 Dynamic and kinematic modeling

- The hypothesis of movement of the CC Fault concomitant with the opening, deepening and mild inversion of the Laurentian Basin can be tested by dynamic and kinematic modeling.

- As Figure 4.18 shows there is a remarkable amount of salt interpreted to be preserved in the basin. In fact, although no structural - stratigraphic balancing or restoration has been attempted in this study, a cursory inspection of Figure 4.18 gives the impression that there is too much allochtonous salt present to balance the section. This suggests the possibility that the salt buildups observed have resulted from allochthonus flow along strike as well as along dip. This question can be investigated by 3D kinematic modeling.
- The hypothesis presented in Section 2.1 regarding a possible cause of break-up unconformities by flexural bulge can be investigated by dynamic and kinematic modeling.

References

Allen, F., 1992, St. Pierre et Miquelon Historical Review, Internal Report to Newfoundland and Labrador Department of Energy.

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V., 1980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: Science, v. 208, p. 1095–1108, doi: 10.1126/science.208.4448.1095.

Amoco Canada Petroleum Company Ltd. and Imperial Oil Ltd. 1973, Regional Geology of the Grand Banks, Bulletin of Canadian Petroleum Geology, Vol. 21.

Atlantic Geoscience Society, 2001, The Last Billion Years, A Geological History of the Maritime Provinces of Canada, Nimbus Publishing, p. 96.

Atlantic Geoscience Society, 2005, Elements of the APPALACHIAN OROGEN in Atlantic Canada, available online at: http://www.ualberta.ca/~jwaldron/nsfieldtrip/Introduction.htm

Auzende, J.M., Olivet, J.L., and Bonnin, J., 1970, La marge du Grand Banc et la fracture de Terre-Neuve; Comptes Rendus de l'Academe des Sciences, Paris, Series D, v. 271, p. 1063-1066.

Avery, M.P. 1987, Vitrinite reflectance (Ro) of dispersed organics from Elf Hermine E-94, Geological Survey of Canada, Open File report 1804, 15p.

Barss, M.S., Bujak, J.P., and Williams, G.L., 1979, Palynological zonation and correlation of sixty-seven wells, eastern Canada, Geological Survey of Canada, Paper 78-24, 118p.

Bell, J.S. and Howie, R.D., 1990. Paleozoic geology; Chapter 4 in Geology of the Continental Margins of Eastern Canada, M.J. Keen and G.L. Williams (ed.); Geological Survey of Canada, Geology of Canada, no.2, p. 141-165.

Bent, A.L., 1994, Seismograms for historic Canadian earthquakes: The 18 November 1929 Grand Banks earthquake, Geological Survey of Canada, Open File Report No. 2563(1994), 36 pp.

Bent, A. L., 1995, A Complex Double Couple Source Mechanism for the Ms 7.2 1929 Grand Banks Earthquake, Bulletin of the Seismological Society of America, Vol. 85, No. 4, pp. 1003-1020.

Brown, D.E., Dehler, S.A., Louden, K., and Wu, Y., 2007, The Early Jurassic Heracles Sequence, Scotian Basin, Canada: Recognition of Latest Stage Synrift Tectonism and Correspondence to Structures Offshore Morocco, (abs.), Moroccan Association of Petroleum Geologists International Conference and Exhibition, October 28 – 31, 2007, Marrakech, Morocco. Available online at: http://www.searchanddiscovery.net/documents/2008/08006morocco_abs/abstracts/brown.pdf

Dehler, S.A. and Keen, C.E. 2001, Magnetic signature of a volcanic to non-volcanic margin transition off Atlantic Canada, Eos Trans. AGU, 82(47), Fall Meet. Suppl., Abstract T52A-0910 (American Geophysical Union Fall Annual Meeting, December 2001, San Francisco, CA)

Dewey, J.W. 1977, Status Review, Pilgrim, Mass., Seismology, Boston Edison Company, Pilgrim Station, Unit 2, Plymouth County, Massachusetts, NRC Docket No. 50-471. United States Geological Survey, Office for Earthquake Studies, Reston, Virginia, April 7, 1 p., United States Nuclear Regulatory Commission, Public Document Room, Docket 50-471 p. 201.

Dewey, J. W. and Gordon, D.W., 1984, Map showing recomputed hypocenters of earthquakes in the eastern and central United States and adjacent Canada, 1925-1980, United States Department of the Interior, U.S. Geological Survey, Miscellaneous Field Studies, Pamphlet, 39 pp., plus Map MF - 1699, approximate scale 1:2,500,000.

Doeven, P.H., 1983, Cretaceous nannofossil stratigraphy and paleoecology of the Canadian Atlantic Margin, Geological Survey of Canada, Bulletin 356, 70p.

Doxsee, W.W. 1948, The Grand Banks Earthquake of November 18, 1929, Publications of the Dominion Observatory, Canada Department of Mines and Technical Surveys, Ottawa, Ontario, Vol. 7, No. 7, pp. 323-335.

Enachescu, M.E., 1987, Tectonic and structural framework of the Northeast Newfoundland continental margin, Sedimentary basins and basin-forming mechanisms, (Eds) Beaumont, Christopher and Tankard, Anthony J. Basins of Eastern Canada and worldwide analogues, CSPG Memoir 12, Atlantic Geoscience Society Special Publication, vol. 5, p. 117-146.

Enachescu, M.E., 1992, Enigmatic basins offshore Newfoundland, Canadian Journal of Exploration Geophysics, vol. 28, no. 1, p. 44-61.

Enachescu, M.E., 2006a, Call for Bids NL06-1, Parcels 1, 2 and 3, Regional Setting and Petroleum Geology Evaluation, available online at: http://www.nr.gov.nl.ca/mines&en/call_for_bids/nl06_1.pdf

Enachescu, M.E., 2006b, Call for Bids NL06-2, Parcels 1 to 3, Regional Setting and Petroleum Geology Evaluation, Government of Newfoundland and Labrador Department of Natural Resources, Available online at: http://www.nr.gov.nl.ca/mines&en/call_for_bids/cfb_nl06-2_%20enachescu_report.pdf

Enachescu, M.E, S. Kearsey, V. Hardy, J-C. Sibuet, J. Hogg, S. Srivastava, A. Fagan, T. Thompson and R. Ferguson, 2005, Evolution and Petroleum Potential of Orphan Basin, Offshore Newfoundland, and its Relation to the Movement and Rotation of Flemish Cap Based on Plate Kinematics of the North Atlantic, Gulf Cost Society of Sedimentary and Petroleum Mineralogists (GCSSEPM) Perkins Conference, Petroleum Systems of Divergent Continental Margin Basins, paper on CD-Rom, 25 figs, 1 table, p. 75-131.

Ericson, D.B., Ewing, M. and Heezen, B.C., 1952, Turbidity Currents and Sediments in North Atlantic. Bulletin of the American Association of Petroleum Geologists, Vol 36, No. 102 3, March, p. 489-511.

Fruth, L. S., Jr., 1965, The 1929 Grand Banks turbidite and the sediments of the Sohm Abyssal Plain, Unpublished M.Sc. thesis, Columbia University, New York City, New York, May 15, 157 p.; with Appendices A, B and C, 367 p.

Geological Survey of Canada, 1988a, Gravity anomaly map of the Continental Margin of Eastern Canada; Geological Survey of Canada, map 1708A, scale 1:5,000,000, available online at: http://apps1.gdr.nrcan.gc.ca/mirage/db_results_e.php

Geological Survey of Canada, 1988b, Magnetic anomaly map of the continental margin of eastern Canada; Geological Survey of Canada, map 1709A, scale 1:5,000,000, available on line at: http://apps1.gdr.nrcan.gc.ca/mirage/db_results_e.php

Given, M.M., 1977, Mesozoic and early Cenozoic geology of offshore Nova Scotia, Bulletin of Canadian Petroleum Geology, v.25, p. 63-91.

Grant, A.C (comp.), 1988, Depth to basement of the Continental Margin of Eastern Canada; Geological Survey of Canada, Map 1707A, scale 1:5,000,000. Available online at: http://apps1.gdr.nrcan.gc.ca/mirage/db_results_e.php

Grant, A.C. and McAlpine, K.D. 1990, The Continental margin around Newfoundland, In Geology of the Continental Margins of Eastern Canada, M.J. Keen and G.L. Williams (eds.), Geological Survey of Canada, Geology of Canada, no. 2: 239-292.

Gradstein, F.M., Ogg, J.G., Smith, A.G., et al, 2004, A Geologic Time Scale; Cambridge University Press, Available online at: http://www.stratigraphy.org/chus.pdf

Hasegawa, H.S. and Kanamori H., 1987, Source Mechanism of the Magnitude 7.2 Grand Banks Earthquake of November 1929: Double Couple or Submarine Landslide? Bulletin of the Seismological Society of America, Vol. 77, No. 6, pp. 1984-2004.

Hasegawa, H.S. and Herrmann, R.B., 1989, A Comparison of the Source Mechanisms of the 1975 Laurentian Channel Earthquake and the Tsunamigenic 1929 Grand Banks Event. In Søren Gregersen and Peter W. Basham, Editors, Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound, NATO Scientific Affairs Division, ASI Series, Series C, Mathematical and Physical Sciences, Vol. 266, Kluwer Academic Publications, pp. 547-562.

Haworth, R.T., 1975, The Development of Atlantic Canada as a result of continental collision – evidence from offshore gravity and magnetic data; in Canada's Continental Margins and Offshore Petroleum Exploration, ed. C.J. Yorath, E.R. Parker, and D.J. Glass: Canadian Society of Petroleum Geologists, Memoir 4, p. 59-77.

Heezen, B.C. and Ewing M., 1952, Turbidity current and submarine slumps and the 1929 Grand Banks earthquake. American Journal of Science, December, Vol. 250, No. 12, pp. 849-873.

Heezen, B.C., Ericson D.B. and Ewing, M., 1954, Further Evidence for a Turbidity Current Following the 1929 Grand Banks Earthquake, Deep-Sea Research, Vol. 1, pp. 193- 202.

Heezen, B.C. and Drake C.L, 1964, Grand Banks slump, American Association of Petroleum Geologists Bulletin, Vol. 48, No. 2, pp. 221-225.

Jansa, L.F., Wade, J.A., 1975a, Paleogeography and Sedimentation in the Mesozoic and Cenozoic, Southeastern Canada Canada's Continental Margins and Offshore Petroleum Exploration, Canadian Society of Petroleum Geologists, Memoir 4.

Jansa, L.F. and Wade, J.A., 1975b, Geology of the Continental Margin off Nova Scotia and Newfoundland, in Offshore Geology of Eastern Canada, Volume 2, Regional Geology Edition, ed. W.J.M. van der Linden and J.A. Wade; Geological Survey of Canada, Paper 74-30, v.2. p. 51-106.

Keppie, J.D., 1982, The Minas Geofracture, in P. St. Julien and J. Beland, eds., Major Structural Zones and Faults of the Northern Appalachians, Geological Association of Canada Special Paper 24. p. 263-280.

Kidston, A.G., Brown, D.E., Altheim, B., and Smith, B.M., 2002, Hydrocarbon Potential of the deep-water Scotian Slope, Canada-Nova Scotia Offshore Petroleum Board report, October 2002, Version 1.0.

King, L.H., 1970, Surficial geology of the Halifax-Sable Island map area, Marine Sciences Branch, Dept. of Energy , Mines and Resources, Ottawa, Marine Science Paper, 16p.

Kuenen, P. H., 1952, Estimated Size of the Grand Banks Turbidity Current, American Journal of Science, Vol. 250, No. 12, December, p. 874-884.

Kullenberg, B., 1954, Remarks on the Grand Banks Turbidity Current, Deep-Sea Research, Vol. 1, pp. 203-210.

Langdon, G.S. and Hall, J., 1994, Devonian–Carboniferous tectonic and basin deformation in the Cabot Strait area, Eastern Canada. American Association of Petroleum Geologists Bulletin, 78: p. 1748–1774.

Louden, K., Lau, H., Funck, T., and Wu, Y. 2005, Large-scale structural variations across the eastern Canadian continental margins: documenting the rift-to-drift transition, in: P.J. Post et al., eds., Petroleum Systems of Divergent Continental Margin Basins, GCSSEPM 25th Annual Bob F. Perkins Research Conference, pp. 56-74, CD-ROM, ISSN 1544-2462.

MacLean, B. C., and J. A. Wade, 1992, Petroleum geology of the continental margin south of the islands of St. Pierre and Miquelon, offshore eastern Canada, Bulletin of Canadian Petroleum Geology, v. 40, p. 222–253.

McGiver, N.L., 1972, Mesozoic and Cenozoic stratigraphy of the Nova Scotia Shelf, Canadian Journal of Earth Sciences, v.9,p.54-70.

McWhae, J.R.H., 1981, Structure and spreading history of the northwestern Atlantic region from the Scotian Shelf to Baffin Bay; Canadian Society of Petroleum Geologists Memoir 7, p.299-332.

Mukhopadhyay, P.K., 1989, Cretaceous organic facies and oil occurrence, Scotian Shelf, Geological Survey of Canada, Open File 2282, 49p.

Mukhopadhyay, P.K., 1990, Evaluation of organic facies of the Verrill Canyon Formation, Sable Sub-basin, Scotian Shelf, Geological Survey of Canada, Open File 2435, 36p.

Murty, T.S. and Wigen, S.O., 1976, Tsunami behavior on the Atlantic coast of Canada and some similarities to the Peru coast. Proc. IUGG Symp. Tsunamis and Tsunami Res., Jan. 29–Feb. 1, 1974, Wellington, N.Z. R. Soc. N. Z. Bull., 15, 51–60.

Nantais, P.T., 1983, A reappraisal of the regional hydrocarbon potential of the Scotian Shelf, Geological Survey of Canada, Open File 1175, 83p.

Negut, D., Enachescu, M.E., Jauer, C., Besoiu, E., Fagan, P., 2007, Rediscovering an Offshore Treasure Trove: Reprocessing Old 2D Data Offshore East Coast of Canada, presentation to the 2007 CSEG conference, Calgary Alberta.

Northcor Energy Ltd., 1985, Final report to the Canada Oil and Gas Lands Administration, on 1983 and 1984 geophysical surveys in the South Whale Basin, Program Number 8624 N10 2E, Filed with the Canada Newfoundland and Labrador Offshore Petroleum Board.

Pascucci, V., Gibling, M.R. and Williamson, M.A., 2000, Late Paleozoic to Cenozoic history of the offshore Sydney Basin, Atlantic Canada, Canadian Journal of Earth Sciences, v. 37, p. 1143-1165.

Papezik, V.S. and Hodych, J.P. 1980, Early Mesozoic diabase dikes of the Avalon Peninsula, Newfoundland: Petrochemistry, mineralogy and origin, Canadian Journal of Earth Sciences. V. 17, p.1417-1430.

Pe-Piper, G. and Piper, D.J.W., 2004, The effects of strike-slip motion along the Cobequid-Chedabucto SW Grand Banks fault system on the Cretaceous-Tertiary evolution of Atlantic Canada, Canadian Journal of Earth Sciences, 41, 799-808.

Petro-Canada et al, 1984, Bonnet P-23 Well History Report: Canada Oil and Gas Lands Administration, Department of Energy Mines and Resources, Ottawa, Canada, 138p.

Piper, D.J.W and Aksu, A.E., 1987, The source and origin of the 1929 Grand Banks turbidity current inferred from sediment budgets, Journal Geo-Marine Letters Publisher Springer Berlin / Heidelberg ISSN 0276-0460 (Print) 1432-1157 (Online) Issue Volume 7, Number 4 / December, 1987 DOI 10.1007/BF02242769 Pages 177-182 Subject Collection Earth and Environmental Science Springer Link Date Wednesday, November 16, 2005.

Piper, D.J.W., Shor, A.N., Farre, J.A., O'Connell, S., and Jacobi R., 1985, Sediment slides and turbidity currents on the Laurentian Fan: Sidescan sonar investigations near the epicenter of the 1929 Grand Banks earthquake, Geology, v 13, no 8, p. 538-541.

Piper, D.J.W., Shor, A.N., Hughes Clarke, J.E., 1988, In: Clifton, H.E. (Ed.), The 1929 Grand Banks Earthquake, Slump, and Turbidity Current, Spec. Pap.-Geol. Soc. Am. 229, 77– 92.

Powell, T.G., 1982, Petroleum Geochemistry of the Verrill Canyon Formation; a source for the Scotian Shelf hydrocarbons, Bulletin of Canadian Petroleum Geology, v. 30, p. 167-169.

Powell, T.G., 1982, Petroleum Geochemistry of the Verrill Canyon Formation, a source for the Scotian Shelf hydrocarbons, Bulletin of Canadian Petroleum Geology, v. 30, p. 167-179.

Rabinowitz, P.D., 1974, The boundary between oceanic and continental crust in the western North Atlantic, in Geology of the Continental Margins, ed. C.A. Burk and C.L. Drake, Springer Verlag, New York, p.67-84.

Ruffman, A., 1996, Tsunami Runup Mapping As An Emergency Preparedness Planning Tool: The 1929 Tsunami In St. Lawrence, Newfoundland Volume 1, Geomarine Associates Ltd; prepared for the Office of the Senior Scientific Advisor Emergency Preparedness Canada Produced within the Canadian Framework for the International Decade for Natural Disaster Reduction, available online at: http://dsp-psd.pwgsc.gc.ca/Collection/D82-41-1-1996E.pdf

Ruffman, A., 2005, Comment On: Tsunamis And Tsunami-Like Waves Of The Eastern United States By Patricia A. Lockridge, Lowell S. Whiteside And James F. Lander With Respect To The November 18, 1929 Earthquake And Its Tsunami, Science of Tsunami Hazards, Vol. 23, No. 3 p52. available online at: http://www.sthjournal.org/233/ruff.pdf

Sen Gupta, S., 1964, Grand Banks Earthquake of 1929 and the 'Instantaneous' Cable Failures. Nature, Vol. 204, No. 4959, p. 674-675.

Shepard, F.P. 1954, High-Velocity Turbidity Currents, A Discussion. In E.C. Bullard, editor, A Discussion on the Floor of the Atlantic Ocean. February 28, 1953, London, England, Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences, Vol. 222, No. 1150, March 18, p. 323-326.

Sheridan, R.E., 1989, The Atlantic Passive Margin, in Bally, A.W. and Palmer, A.R., eds., The Geology of North America – An Overview; Boulder Colorado, Geological Society of America, The Geology of North America, v. A.

Sherwin, D.F. 1973. Scotian Shelf and Grand Banks. In: McCrossan, R.G. (Ed.), Future Petroleum Provinces of Canada - Their Geology and Potential, Can. Soc. Petrol. Geol., Mem. 1, pp. 519-559.

Sibuet, J-C., Srivastava, S. and Manatschal, G., 2007, Exhumed mantle-forming transitional crust in the Newfoundland-Iberia rift and associated magnetic anomalies, J. Geophys. Res. 112 (2007) doi:10.1029/2005JB003856.
Available online at: http://www.ifremer.fr/docelec/doc/2007/publication-3015.pdf

Sinclair, I.K., 1988, Evolution of Mesozoic-Cenozoic sedimentary basins in the Grand Banks area of Newfoundland and comparison with Falvey's (1974) rift model, Bulletin of Canadian Petroleum Geology, v. 36; no. 3; p. 255-273.

Swift, J.H., and Williams, J.A., 1980, Petroleum source rocks, Grand Banks area; in Facts and Principles of World Petroleum Occurrence, ed. A.D. Miall, Canadian Society of Petroleum Geologists Memoir 6, p. 567-588.

Tankard, A.J. and Welsink, H.J. 1989, Mesozoic extension and styles of basin formation in Atlantic Canada. *In*: Tankard, A.J. & Balkwill, H.R. (eds), Extensional Tectonics and Stratigraphy of the North Atlantic Margins, American Association of Petroleum Geologists, Memoirs, 46, 175–195.

Vail, P.R., Mitchum, R.M., Jr., and Thompson, S . III., 1977, Global cycles of relative changes of sea level; in Seismic Stratigraphy – Applications to Hydrocarbon Exploration, ed. C.E. Payton, AAPG Memoir 26, p. 83-97.

Vail, P.R. and Mitchum, R.M., Jr., 1979, Global Cycles of relative changes of sea levels from seismic stratigraphy; in Geological and Geophysical Investigations of Continental Margins, ed., J.S. Watkins, L. Montadert and P.W. Dickerson, AAPG, Memoir 29, p469-472.

Vail, P.R, Hardenbol, J., and Todd, R.G., 1984, Jurassic unconformities, chronostratigraphy and sea level changes from seismic stratigraphy and biostratigraphy: in inter-regional unconformities and hydrocarbon accumulation, ed J.S. Schlee, AAPG Memoir 36, p. 129-144.

Wade, J.A. and B.C. MacLean, 1990, The geology of the southeastern margin of Canada, Chapter 5 in Geology of the Continental Margin of Eastern Canada, M.J. Keen and G.L. Williams (ed.); Geological Survey of Canada.

Welsink, H.J., Dwyer, J.D. and Knight, R.J., 1989, Tectono-stratigraphy of the passive margin off Nova Scotia: Extensional Tectonics and Stratigraphy of the North Atlantic Margin, Tankard, A.J. and Balkwill, H.R. (Eds.), AAPG, Memoir 46, p.215-231.

Williams, H., 1978, Tectonic lithofacies map of the Appalachian Orogen, Memorial University of Newfoundland, Map no. 1.

Williams, H., 1984, Miogeoclines and Suspect Terranes of the Caledonian-Appalachian Orogen: Tectonic Patterns in the North Atlantic Region, Canadian Journal of Earth Science, Vol. 21, p. 887-901.

Williams, G.L., Ascoli, P., Barss, M.S., Bujak, J.P., Davies, E.H., Fensome, R.A. and Williamson, M.A. 1990, Biostratigraphy and related studies: Offshore eastern Canada. Chapter 3 in M.J. Keen and G.L. Williams (eds.), Geology of the Continental Margin off Eastern Canada, Geological Survey of Canada, Geology of Canada, no. 2, p. 89-137 (also Geological Society of America, The Geology of North America, v. I-1).

Williams, H. 1995, Summary and overview; Chapter 11 in Geology of the Appalachian-Caledonian Orogen in Canada and Greenland, H. Williams (ed.); Geological Survey of Canada, Geology of Canada, no. 6, p. 843-890 (also Geological Society of America, The Geology of North America, v. F-1).

Withjack, M.W., Schlische, R.W. and Olsen, P.E., 1998, Diachronous rifting, drifting, and inversion on the passive margin of central eastern North A.merica: an analog for other passive margins, AAPG Bulletin, V. 82, No. 5A, May (Part A), P. 817–835.

Additional sources of information:

GSC Basins website:
http://basin.gsca.nrcan.gc.ca/index_e.php?PHPSESSID=c8bea3e9a0ccb18f79b49c53138a110

Canada-Newfoundland and Labrador Offshore Petroleum Board website:
http://www.cnlopb.nl.ca/

Louisiana State University Website:
www.geol.lsu.edu/Faculty/Juan/PhysicalGeology_F2004/images/liquefaction

National Ocean Industries Association website:
http://www.noia.org/website/article.asp?id=123

Newfoundland and Labrador Department of Natural Resources website:
http://www.nr.gov.nl.ca/nr/

Nova Scotia Department of Energy website:
http://www.gov.ns.ca/energy/

Jenson, J. and R. Hooper, 2006, Laurentian - A Jurassic basin with High Expectations, Presentation to NOIA Conference, St John's, Newfoundland: available on NOIA website archives: www.noianet.com

Appendix A

NEWFOUNDLAND AND LABRADOR PETROLEUM INDUSTRY REPORTS RELATING TO STUDY AREA

The following list of reports was provided by the C-NLOPB, as overlapping to some degree with the study area.

Program Number	Name of Program	
8620-A004-001E	1964	NORTH AND SOUTH GRAND BANKS
8620-A004-003E	1965	NORTH AND SOUTH GRAND BANKS
8620-A004-004E	1967	NORTH AND SOUTH GRAND BANKS
8620-A004-006E	1973	NORTH AND SOUTH GRAND BANKS
8620-C004-003E	1971	GREEN BANKS
8620-E004-001E	1970	GREEN BANK AND AVALON BLOCKS
8620-G005-001P	1971	OFFS. NEWFOUNDLAND-GRAND BANKS-SCOTIAN SHELF
8620-G005-004P	1972	OFFSHORE NEWFOUNDLAND-SCOTIAN SHELF
8620-H006-004E	1982	SOUTH WHALE BASIN
8620-J001-001E	1972	LAURENTIAN CONE,ORPHAN BASIN
8620-J001-002E	1973	NORTH AND SOUTH LABRADOR, ORPHAN
8620-M003-007E	1968	GRAND BANKS, SABLE IS, GEORGES BANK, BAY FUNDY
8620-S014-010E	1983	SOUTH WHALE BASIN-GRAND BANKS
8620-T007-007E	1973	CABOT STRAIT
8624-A004-003E	1968	NORTH AND SOUTH GRAND BANKS
8624-A004-006E	1970	SOUTH GRAND BANKS
8624-A004-011E	1972	NORTH AND SOUTH GRAND BANKS
8624-A004-017E	1974	NORTH AND SOUTH GRAND BANKS
8624-A025-001E	1981	SOUTH WHALE BASIN
8624-A025-002E	1981	SOUTH WHALE BASIN
8624-B011-007E	1984	EAST BANQUEREAU
8624-D001-002P	1970	SCOTIAN SHELF,GRAND BANKS
8624-D001-003P	1971	SCOTIAN SHELF,GRAND BANKS
8624-D001-004P	1972	SCOTIAN SHELF,GRAND BANKS
8624-E004-001E	1967	AVALON, GREEN BANK, BALLARD BANK
8624-E004-003E	1969	GREEN BANK
8624-E004-004E	1971	GREEN BANK
8624-E004-005E	1973	GREEN BANK
8624-G005-003P	1982	SOUTH WHALE BASIN TO FLEMISH PASS
8624-H006-003E	1981	SOUTH WHALE BASIN
8624-H007-013E	1981	SOUTH WHALE BASIN AREA
8624-N010-001E	1983	SOUTH WHALE BASIN
8624-N010-002E	1984	SOUTH WHALE BASIN
8624-P011-001E	1971	WHALE SUB BASIN
8624-P011-002E	1975	OFFSHORE LABRADOR,GRAND BANKS
8624-P028-007E	1981	LAURENTIAN CONE
8624-P028-023E	1981	SOUTH WHALE BASIN

8624-P028-024E	1981	LAURENTIAN CONE
8624-P028-032E	1982	EMERILLON AREA-GRAND BANKS
8624-P028-066E	1983	SOUTH WHALE BASIN
8624-P028-078E	1985	SOUTH WHALE BASIN
8624-P028-081E	1985	SOUTH GRAND BANKS
8624-S006-007E	1971	AVALON BASIN
8624-T007-004^{E}	1969	CABOT STRAIT
8624-T007-006^{E}	1970	CABOT STRAIT
8624-T007-009E	1974	GREEN BANK AREA
8624-T007-014E	1976	GREEN BANK
8624-T007-018E	1977	GREEN BANK
8624-T021-005E	1981	GREEN BANK
8624-T021-009E	1983	GREEN BANKS, SOUTHERN GRAND BANKS
8924-G033-001E	1998	2-D SEISMIC SOUTH NEWFOUNDLAND
8924-G033-002E	2001	2-D SOUTH NEWFOUNDLAND

NOVA SCOTIA PETROLEUM INDUSTRY REPORTS RELATING TO STUDY AREA

The following list of reports was provided by the C-NSOPB, as overlapping to some degree with the study area.

Program Number			
NS24-G001-001E	Other Jurisdiction		GULF CANADA
8624-W013-005P	Not Public		WESTERN GEOPHYSICAL
8624-P028-072E	PETRO-CANADA	1985	SCOTIAN SHELF
8624-B011-008E	BOW VALLEY	1984	SCOTIAN SHELF
8620-J008-007E	ICG RESOURCES	1983	SCOTIAN SHELF
8620-S014-006E	SOQUIP	1983	SCOTIAN SHELF/SCOTIAN
8624-B011-004E	BOW VALLEY	1983	SCOTIAN SHELF
8624-B011-005E	BOW VALLEY	1983	SCOTIAN SHELF
8624-N005-002E	NORCEN ENERGY	1983	SCOTIAN SHELF
8624-W013-001P	WESTERN GEOPHYSICAL	1983	SCOTIAN SHELF and SLOPE
8624-C055-003E	CANTERRA ENERGY	1982	SCOTIAN SHELF
8624-N005-001E	NORCEN ENERGY	1982	SCOTIAN SHELF
8624-P028-029E	PETRO-CANADA	1982	SCOTIAN SHELF
8624-P028-046E	PETRO-CANADA	1982	SCOTIAN SHELF
8624-S006-032E	SHELL CANADA	1982	SCOTIAN SHELF
8624-S006-033E	SHELL CANADA	1982	SCOTIAN SHELF/SCOTIAN SLOPE
8624-M003-041E	MOBIL OIL CANADA	1981	SCOTIAN SHELF/SCOTIAN SLOPE
8624-S006-028E,31E	SHELL CANADA	1981	SCOTIAN SHELF/SCOTIAN SLOPE
8620-J001-002E	Other Jurisdiction IMPERIAL OIL	1973	
8624-S006-012E	SHELL CANADA	1973	SCOTIAN SHELF/SCOTIAN SLOPE
8620-J001-001E	Other Jurisdiction IMPERIAL OIL	1972	
8620-S024-001P	SEISCAN EXPLORATION	1972	SCOTIAN SHELF/SCOTIAN SLOPE/GRAND BANKS/E NFLD SHELF/LABRADOR SHELF
8624-C020-001E	CANADIAN SUPERIOR	1972	SCOTIAN SHELF
8620-C004-002E	CHEVRON	1971	SCOTIAN SHELF
8620-C020-001E	CANADIAN SUPERIOR	1971	SCOTIAN SHELF/SCOTIAN SLOPE
8624-M003-002E	MOBIL OIL CANADA	1970	SCOTIAN SHELF
8624-P028-036E	PETRO-CANADA		BANQUEREAU
8624-P028-068E	PETRO-CANADA		BANQUEREAU