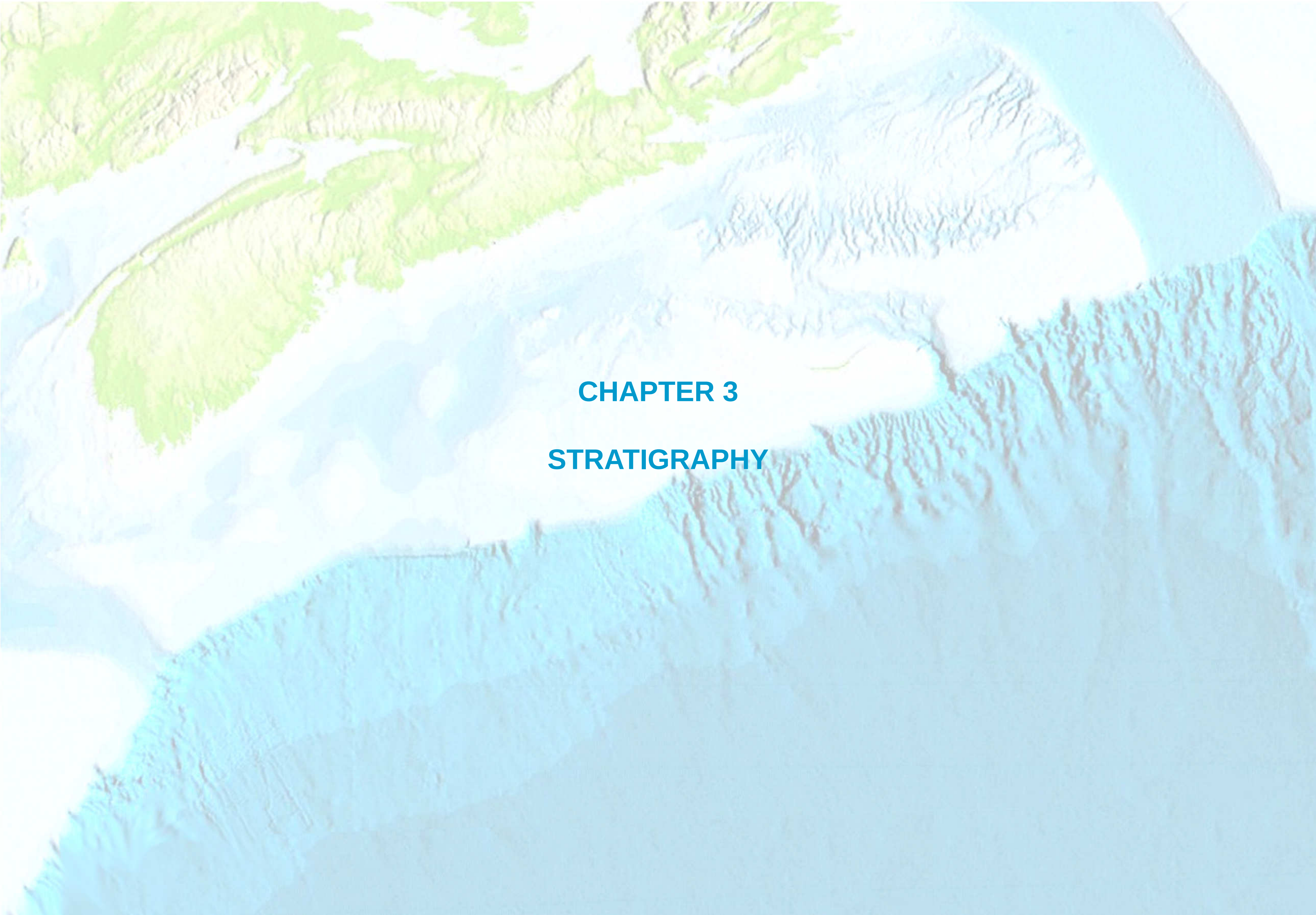


CHAPTER 3

STRATIGRAPHY

INTRODUCTION

Objectives

The objective of Chapter 3 is to update the Mesozoic-Cenozoic stratigraphic framework of the Sable Sub-basin in order to refine the current understanding of the petroleum system in the area.

Results of the study are:

- A lithostratigraphic update of Sable Sub-basin based on facies and lithological interpretation, for eight relevant stratigraphic surfaces delimited by nine key seismic horizons;
- A second order stratigraphic breakdown for each well studied illustrating the major stratigraphic sequences (PL. 3.3.1 to PL.3.3.5; Appendix 1.4);
- An updated stratigraphic and lithostratigraphic chart for the Sable Sub-basin (PL 3.2.1 and 3.3.5) adapted from the Scotian Margin stratigraphic chart;
- A chronostratigraphic and lithostratigraphic interpretation of 3 key seismic transects;
- A set of GDE maps for each key intervals (PL. 6.3.4 to 6.3.15).

Well Database and Methodology

The well database consists of ten key wells (Table 1) distributed over Sable Sub-basin from shelf to deep water (Figure 1). These wells were used for refining the lithostratigraphy and sequence stratigraphy of the area.

The composite geological well logs are presented in Appendix 1.4. They display (1) a suite of logs (GR, NPHI curve, RHOB); (2) a lithological column; (3) biostratigraphic surfaces; (4) formation tops; (5) sequence stratigraphic breakdown and (6) depositional environments.

- *Well lithology and petrophysics*

Lithological, petrological and petrophysical interpretations were obtained from PFA 2011 data set (OETR, 2011) and used as such. Such information includes qualitative log interpretations, mud reports, geological mud logs, existing composite well logs, and master logs.

For each well, lithologies were obtained from final well reports cross checked with electrofacies analysis. The qualitative lithological interpretation presented in composite logs is determined by statistical electrofacies determination through cluster analysis. The resulting lithologies (clastics and carbonates) are computed from log responses calibrated on cutting descriptions and master logs.

- *Biostratigraphy in wells*

No new quantitative biostratigraphic analyses have been performed on key wells for the current study. Biostratigraphy from the 2011 PFA study and subsequent published work (Weston et al., 2012) were enough to conduct the current work.

- *Stratigraphic sequence breakdown and depositional environment in wells*

The stratigraphic sequence breakdown was determined in 2011 except on Banquereau C21, Thebaud I93 and Venture B52. For these three wells, the stratigraphic breakdown was performed by correlation with nearby wells (Figure 1; PL. 3.3.1 and 3.3.2).

Up to five, second order stratigraphic sequences, with average duration of 3-15 Ma, are defined from Middle Jurassic to late Oligocene. Obtained second order sequences are propagated at the Sable Sub-basin scale through seismic mapping and well correlations.

- *Well correlations*

In order to provide a broad picture of the Sable petroleum system, two parallel transects were completed on the shelf and slope, and a dip wheeler section (shelf to slope) was updated from the 2011 PFA.

Content

Chapter 3 includes:

- A lithologic and stratigraphic overview of Sable Sub-basin supported by an updated Stratigraphic Chart of the area (Figure 2). This overview establishes the stratigraphic framework that will be used in the current study;
- Two well correlation panels that illustrate the vertical and lateral variation of sedimentary facies and depositional environments through time (PL. 3.3.1 to 3.3.4);
- One lithostratigraphic section in time that shows the impact of geological events on sequence thickness and the spatial distribution of depositional sequences (PL. 3.3.5).

Stratigraphic framework results will be used in Chapter 6 for :

- Three key seismic transects interpreted in terms of seismic stratigraphy (PL. 6.1.1 to 6.1.3) showing the 2D geometry of the full sedimentary system and successive depositional sequences in response to geological events;
- A set of GDE maps for each key interval (PL. 6.3.4 to 6.3.15).

Well ID	Company	Year	Latitude	Longitude	RT	WD	TD	Well Classification	Formation at TD	TD Geological age	Study
Alma F67	Shell Pex et al	1984	43°36'17.98"	60°39'56.75"	24	68	5054	Gas Well	Mic_Mac/L. Missisauga	Tithonian	PFA 2011
Annapolis G24	Marathon Cda	2002	43°23'22.94"	59°48'29.19"	35.5	1711	6182	Gas Well	Verrill Canyon /M.Missisauga	Hauterivian	PFA 2011
Balvenie B79	Imperial Oil	2003	43°08'01.29"	60°10'56.84"	25	1803	4750	Gas Show	Logan Canyon /Shortland Shale	Mid Albian	PFA 2011
Banquereau C21	Petrocan	1982	44°10'07.52"	58°34'00.24'	27	83	4991	Gas Well	Verrill Canyon /M. Missisauga	Valanginian	Current Study
Chebucto K90	Bow Valley	1984	43°39'44.73"	59°42'51.52"	22.8	86	5235	Gas Well	Verrill Canyon /M. Missisauga	Hauterivian	PFA 2011
Crimson F81	Marathon Cda	2004	43°20'22.29"	59°42'57.03"	21.4	2092	6676	Gas Show	Verrill Canyon /M. Missisauga	Valanginian	PFA 2011
Glenelg J48	Shell Petrocan	1983	43°37'38.57"	60°06'24.84"	24	87	5148	Gas Well	Mic_Mac/L. Missisauga	Berriasian/tithonian	PFA 2011
Tantallon M41	Shell/PCI et al	1986	43°50'55.96"	58°22'23.99"	24	1516	5602	Gas Show	Verrill Canyon /M. Missisauga	Valanginian	PFA 2011
Thebaud I93	Mobil et al	1985	43°52'44.54"	60°13'50.94"	37	31	5166	Gas Well	Mic_Mac/L. Missisauga	Tithonian	Current Study
Venture B52	Mobil et al	1983	44°01'12.88"	59°38'07.76"	34	19.5	5960	Gas Well	Mic_Mac/L. Missisauga	Tithonian	Current Study

*Table 1: Selected wells for the stratigraphic framework study: 7 key wells (from the 2011 PFA**)** and 3 additional wells from the current study.*

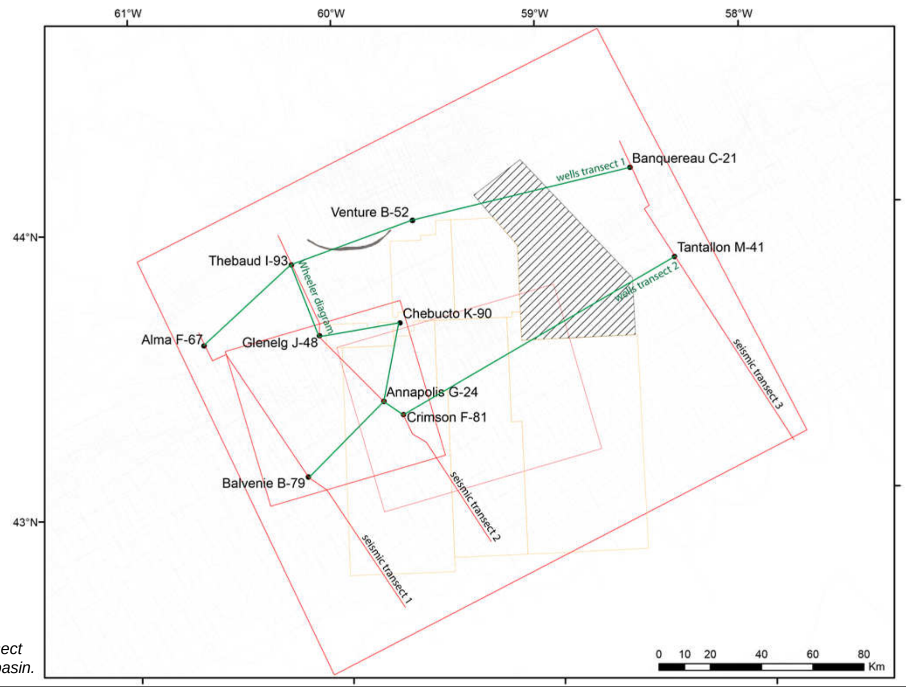
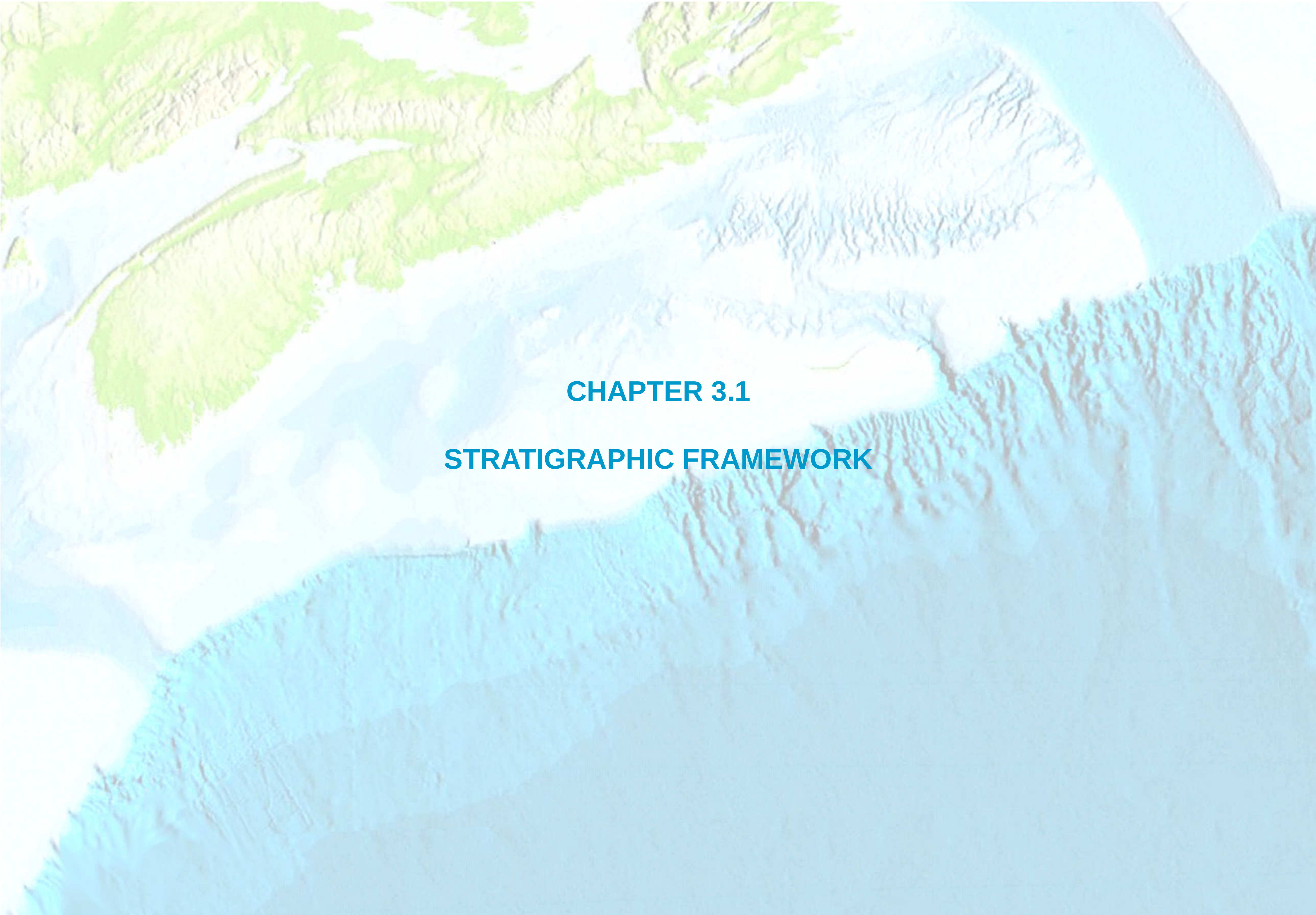
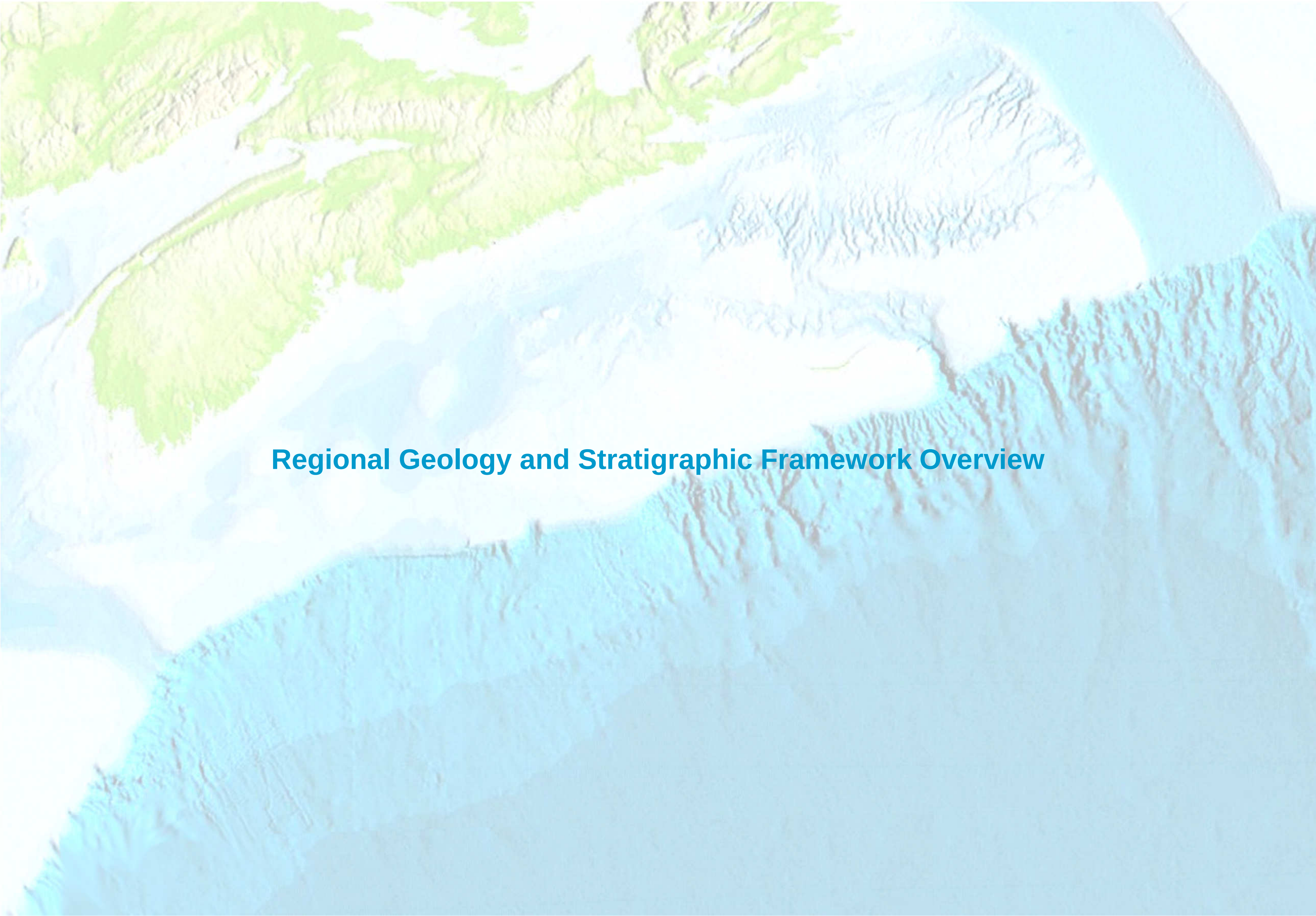


Figure 1: Wells and correlation transect location across the Shelburne Sub-basin.



CHAPTER 3.1

STRATIGRAPHIC FRAMEWORK



Regional Geology and Stratigraphic Framework Overview

Regional Geology and Stratigraphic Framework Overview

The Sable Sub-basin corresponds to the central slope of the Scotian Margin and has been the main focus of offshore oil and gas exploration in Nova Scotia, with several commercial discoveries since the 1970s leading to the development of the Sable Offshore Energy Project in the late 1990s early 2000s (http://www.cnsopb.ns.ca/offshore-activity/offshore-projects/sable-offshore-energy-project). The Sub-basin is bounded landward by the Abenaki Sub-basin and to the west by LaHave Platform; it expands offshore over Missisauga and Alma Ridges (PL. 2.1.18). The Sable Sub-basin ~~It~~ may correspond to the thickest post-rift sediment accumulation of the entire margin, with a total average thickness exceeding 14 km (Kendell et al., 2016).

The sedimentary record of the Sub-basin spans the last 250 million years with continuous sedimentation from the initial opening of the Atlantic Ocean to the recent post-glacial period (Figures 2 to 4). The Sub-basin was fed by clastic sediments from a large drainage system over the northeastern Canadian Shield corresponding to the proto St. Lawrence estuary. The exact size of the drainage system and organisation of related tributaries are not yet well understood, although recent work has revealed a complex history of shift in drainage areas in response to the Avalon uplift (Tsikouras et al., 2011; Li et al., 2012; Strathdee, 2012).

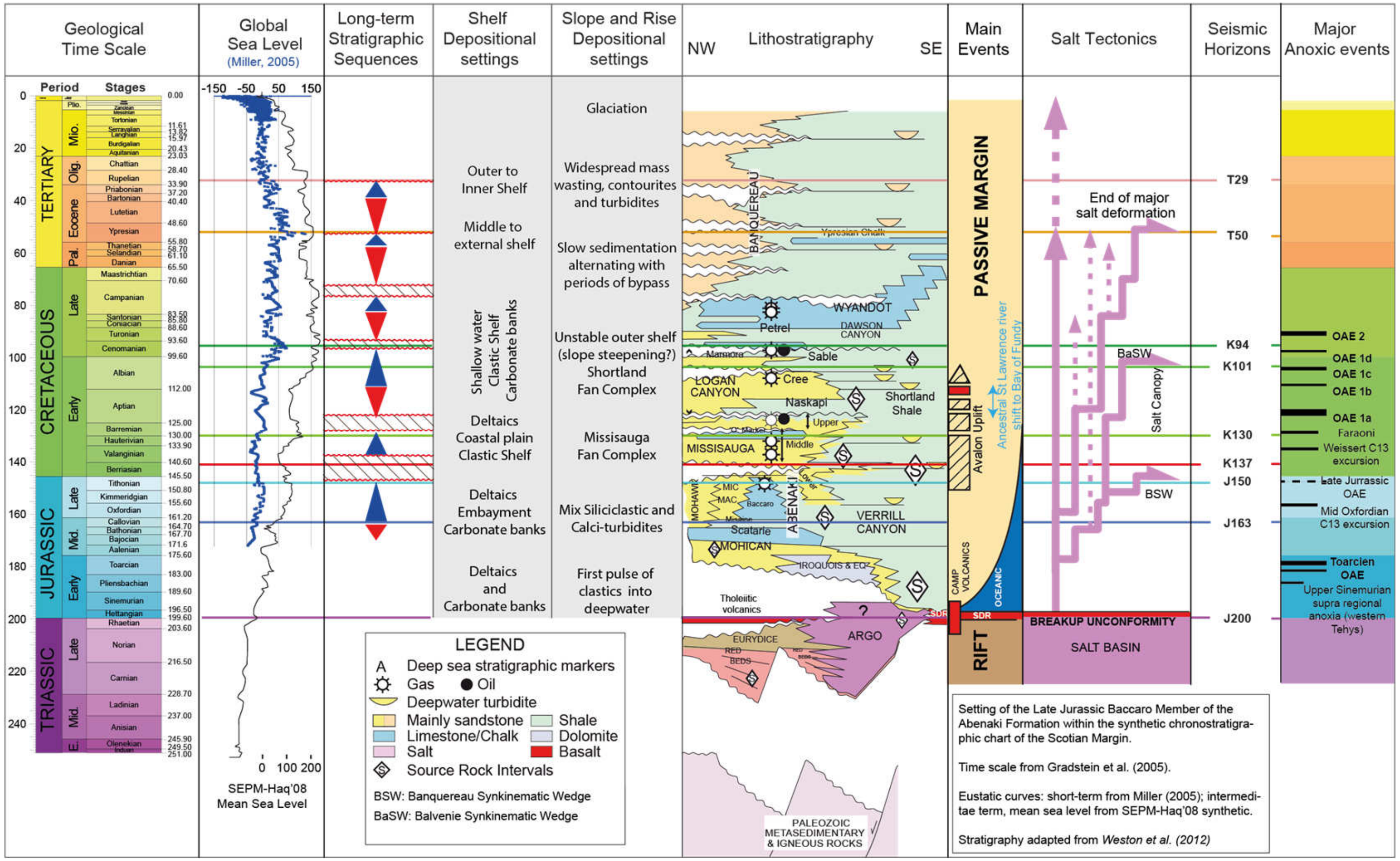
PRE-RIFT

The Scotian Basin developed after the breakup of Pangea when North America rifted and separated from the African continent (see Chapter 2). It consists of a series of alternating horsts and grabens, or platforms and depocenters, namely the LaHave Platform, Abenaki Sub-basin, Missisauga Ridge, Migrant Ridge, Venture Ridge, Alma Ridge and Sable Sub-basin.

The boundaries of these platforms and basins may have been defined by regularly-spaced oceanic fracture zones that extended landward onto continental crust (Welsink et al., 1989). A northeast trending basement hinge zone is also present along the margin, defining the landward limit of maximum tectonic extension and an abrupt seaward increase in basement depth due to thermal subsidence. Together, these basement elements exerted a strong control on sediment distribution in the region for more than 250 million years (PL. 2.1.1 to 2.1.12; Chapter 2).

SYN-RIFT

Red beds and evaporites were the dominant deposits during the late pre-rift phase (Wade and MacLean, 1990) (Figure 2). Rifting began in the middle-early Late Triassic Period, about 250 – 225 Ma. At that time, Nova Scotia was located in a near equatorial position adjacent to Morocco, with most of its older Paleozoic rocks having direct Moroccan affinities (Schenk et al., 1980). A series of narrow, interconnected rift basins were created during the rifting phase and were filled with fluvial and lacustrine red bed sediments, as well as volcanic rocks. By the Rhaetian – Hettangian transition (Triassic – Jurassic), the North American and African plates had moved northward, with the Nova Scotia – Moroccan region in an arid subequatorial climate zone. Renewed Late Triassic rifting further to the north and east in the Grand Banks / Iberia region led to the first incursions of marine waters from the eastern Tethys paleo-ocean into the interconnected syn-rift basins. Restricted shallow marine conditions were established with some mixed clastic - carbonate sedimentation (Eurydice Formation; PL. 3.1.5 Figure 8). Due to the hot and dry climate, the shallow seas were repeatedly evaporated, resulting in the precipitation of extensive salt and minor anhydrite deposits that were as much as 2.0 km thick in the central parts of the rift system (Argo Formation; Figures 2 to 4).



It has been suggested that Triassic sediment deposition started in the Scotian Basin before any other basin along the Eastern Canadian Margin (Wade and MacLean, 1990). The distribution of red beds, Euridice and Argo Fms varies from Sub-basin to Sub-basin, with some recording considerable amount of syn-rift red beds (Wade and MacLean, 1990). The syn-rift record offshore from Alma Ridge is not well known as it is often poorly imaged due to the impact of the salt on seismic data.

Grabens formed during the rifting acted as loci for clastic deposition for newly established fluvial drainage systems (Figure 5). Renewed tectonism in the central rift basin during the Early Jurassic (Hettangian) is recorded by the complex faulting and erosion of Late Triassic and Early Jurassic sediments and older rocks. This phase of the rifting process resulted in the formation of a Breakup Unconformity (J200), which coincided with the final separation of the North America and Africa continents, the creation of true oceanic crust through volcanism, and opening of the proto-Atlantic Ocean (see Chapter 2). As a result of the Breakup Unconformity (J200), the heavily faulted, complex terrane of grabens and basement highs along the Scotian Margin underwent a significant degree of peneplanation.

Figure 2: Detailed Stratigraphic Chart incorporating all sedimentary and geological events as well as major anoxic events. (Modified and updated from PFA 2011).

EARLY POST-RIFT

Marine transgression after the Breakup Unconformity (**J200 maker**) led to the development of a shallow and restricted sea within which thin sequences of carbonate and clastic sediments accumulated. By the late Early Jurassic, tidally influenced dolomites and clastics formed in localized areas under slightly restricted marine conditions (**Iroquois Formation**). In the meantime, a thick succession of coarse grained clastic sediments and shales from fluvial sources was deposited on the margins (**Mohican Formation**). Clastic sediments infilled grabens and basement highs were buried by the early Middle Jurassic (Wade and MacLean, 1990) (Figure 3 and 4). The deep water portion of the basin was infilled with marine mud.

The Atlantic Ocean became broader and deeper by the Middle Jurassic, with water depth exceeding 1000m. Prominent carbonate banks developed and persisted until the Late Jurassic – Early Cretaceous (Figures 3 and 4). Growth of the carbonate banks alternated with Upper Jurassic and Lower Cretaceous deltaic successions. The thick carbonate banks formed during the Jurassic correspond to the **Abenaki Formation** (Figures 3 and 4) which can be Subdivided into 3 members:

- **Scatarie Member:** consists of a carbonate succession that was established along the basin hinge zone and prograded out into deeper water where marls and clastic muds were deposited;
- **Misaine Member**: consists of a shale dominated interval formed at a time were carbonates and clastic sediments on the shelf were blanketed by transgressive marine shales;
- **Baccaro Member:** correspond to a late-Middle to Late Jurassic interval. The succession corresponds to carbonate reef, bank and platform environments formed along the basin hinge line on the LaHave Platform.

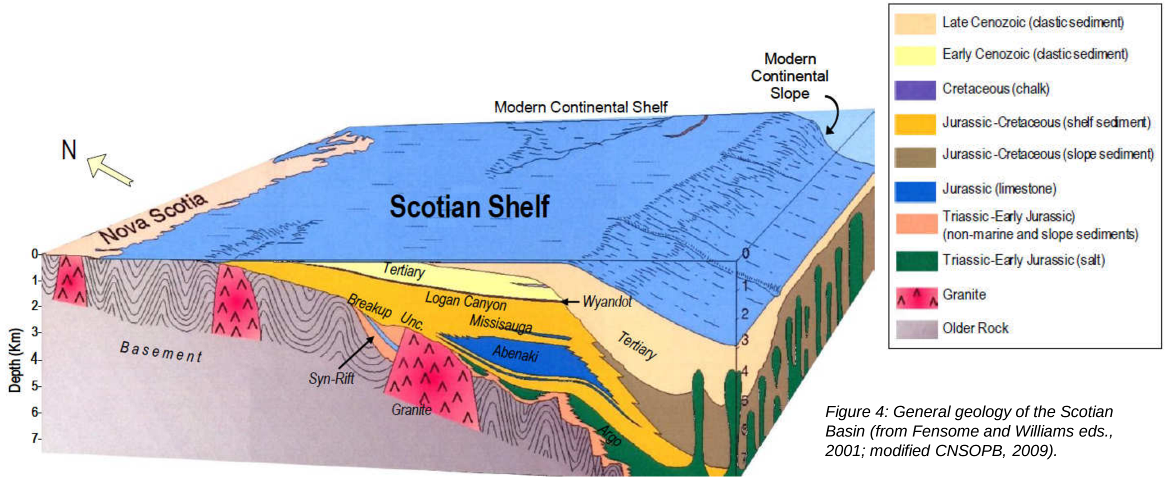


Figure 4: General geology of the Scotian Basin (from Fensome and Williams eds., 2001; modified CNSOPB, 2009).

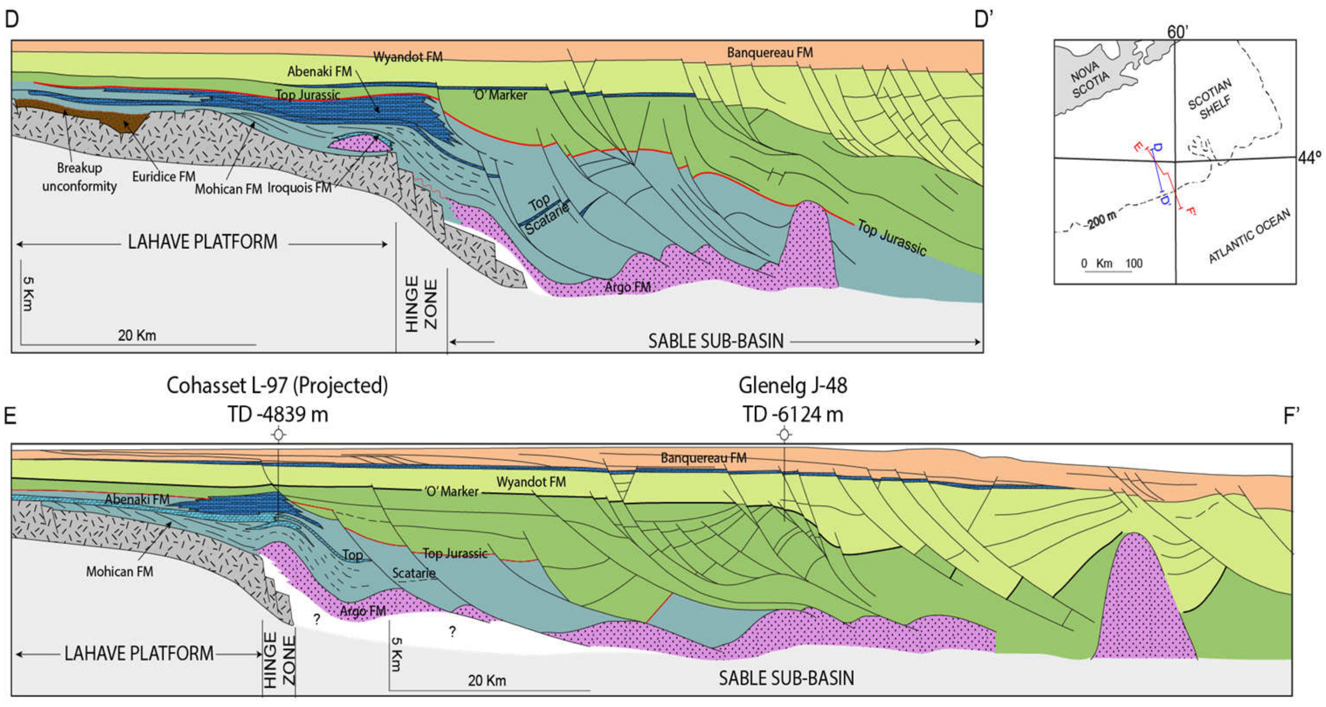


Figure 3: Geological cross-sections showing stratigraphic relationships from the LaHave Platform to the Sable Sub-basin (modified from Wade and MacLean, 1990).

LATE POST RIFT

The **Late Jurassic (Oxfordian – Tithonian)** sees the establishment of large clastic sedimentary systems, for instance the Sable Delta complex in the Huron and Laurentian Sub-basins, and slightly later in the Sable Sub-basin (Figures 3 to 5). These sediments were primarily sourced from the adjacent Silurian to Permian sediments that covered the entire Atlantic Provinces and parts of New England (Pe-Piper & Piper, 2004; Pe-Piper & MacKay, 2006) (Figures 5 and 6). This first phase of delta progradation produced the **Mic Mac Formation and equivalent**. This Formation is characterized by sandy fluvial channels and sandy delta front cyclically interfingering with prodelta and marine shales of the **Verrill Canyon Formation and equivalent**.

During the **Middle Jurassic and Cretaceous** the sediment load on the shelf edge and slopes accentuated the subsidence and also mobilized the salt, creating a complex slope morphology (e.g. Kidson et al., 2002; Shimeld, 2004) analogous to other basins with mobile salt substrates (e.g. the Gulf of Mexico). Shelf and slope deformations are associated with the development of seaward-dipping growth faults (Figure 3; see also Chapter 2). This time interval also coincides with the beginning of a regional uplift called the Avalon uplift associated to one or more significant thermal anomalies as evidence by the widespread igneous rocks and dikes spread in Nova Scotia and Newfoundland, as well as the Newfoundland seamounts east of the Grand Banks (Wade and MacLean, 1990; Bowman et al., 2012; Pe-Piper et al., 2015). This uplift phase resulted in an increase of sediment supply leading to the development of significant deltas along the coast.

Around the **Late Hauterivian – Late Cenomanian** time, the uplift induced a rerouting of the Laurentian Channel to the south through the Bay of Fundy which led to a massive input of sediment into the Shelburne Sub-basin and a decrease of clastic input into the Sable Sub-basin (Li et al., 2012; Stradhee, 2012; Figures 5 and 6). The overall increase in sediment load during the Late Jurassic and Early Cretaceous accentuated salt mobility leading to the formation of diapirs, pillows, canopies and related salt features (see Chapter 2 PL. 2.1.13 to 2.1.21). During periods of low sea level, rivers incised the exposed outer shelf sediments and formed shelf-edge delta complexes (Cummings 2004; Cummings and Arnott, 2005). Such deltas supplied turbidity currents and mass transport deposits to the slope, generating potential reservoirs in canyons and intra-slope and salt mini basins (CNSOPB, 2012; Deptuck et al., 2014; Kendell et al., 2016).

During the **Early Cretaceous,** the ancestral St. Lawrence River was well established (Figures 6). Increases of clastic sediment supply into the Scotian Basin overwhelmed and buried the carbonate reefs and banks. A series of thick sand-rich deltaic strand plain**s**, carbonate shoals and shallow marine shelf successions dominated sedimentation throughout the Early Cretaceous (**Missisauga Formation and equivalent**; Figures 3 and 4). The **Sable Delta** prograded rapidly southwest into the Laurentian, Huron and Sable Sub-basins and over the Banquereau Platform (Figures 4 and 6). Along the LaHave Platform, small local rivers draining from the mainland of southwest Nova Scotia (Figure 6) provided modest amounts of sands and shales to this region.

In the **late Early Cretaceous,** a major marine transgression called the **Aptian MFS** was followed by drastic decreases of deltaic sedimentation which was replaced by thick marine shales corresponding to the **Naskapi Member of the Logan Canyon Formation** (Figure 2). Transgressive shales were periodically interrupted by influxes of coarse clastic sediment in the **Albian-Cenomanian** (**Cree and Marmora Members of the Logan Canyon Formation**; Wade and MacLean, 1990). The sand was deposited along a broad coastal plain and shallow shelf. During the Late Cretaceous the margin underwent structural readjustments following the end of the Avalon uplift. The margin was then characterized by a significant relative sea level rise related to basin subsidence. The proto St. Lawrence River returned to its former location but with its main outlet northward of Sable Sub-basin (Figure 6).

During the **Turonian- Santonian,** sediment supply decreased from the lower relief hinterland and the sand was replaced by deeper water marine shales and limestones corresponding to the **Dawson Canyon Formation** (Figure 2). During this period, the Scotian Basin recorded marine marls and chalks of the **Wyandot Formation** (Figures 2, 3 and 4).

Banquereau Formation formed during the Tertiary and corresponds to marine mudstones and sandstones. Several major unconformities related to relative sea level falls occurred throughout the **Tertiary**. The St. Lawrence outlet migrated northward to its current location and built up a large turbidite system (Figure 6). During the **Quaternary** several hundred meters of glacio-marine sediments were deposited across the Scotian Basin with the main ice stream located within the St. Lawrence channel.

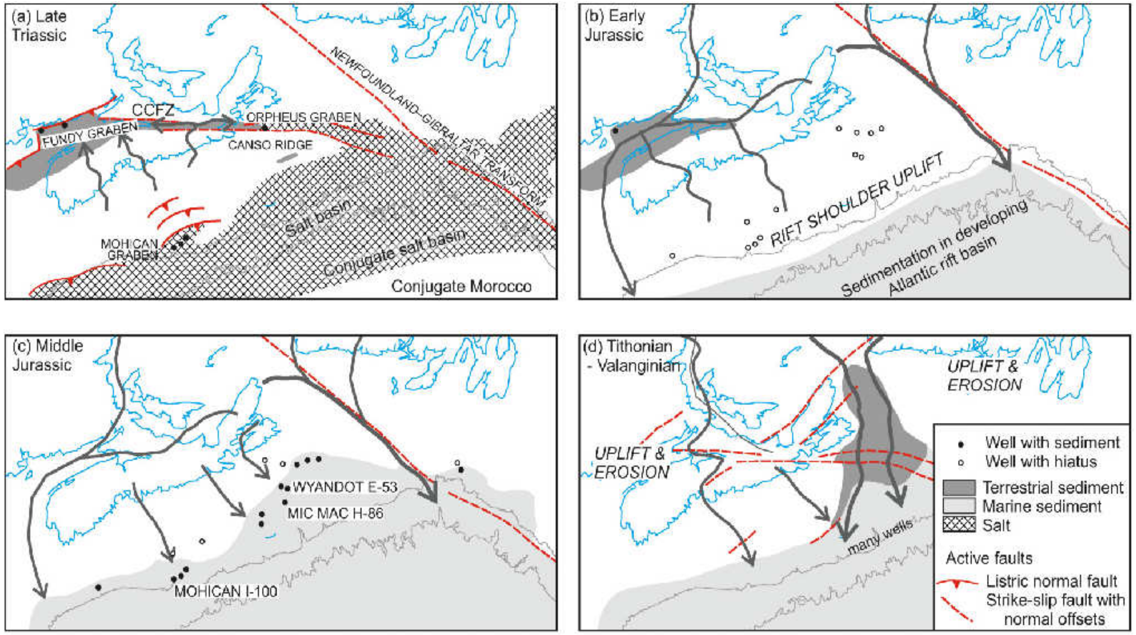
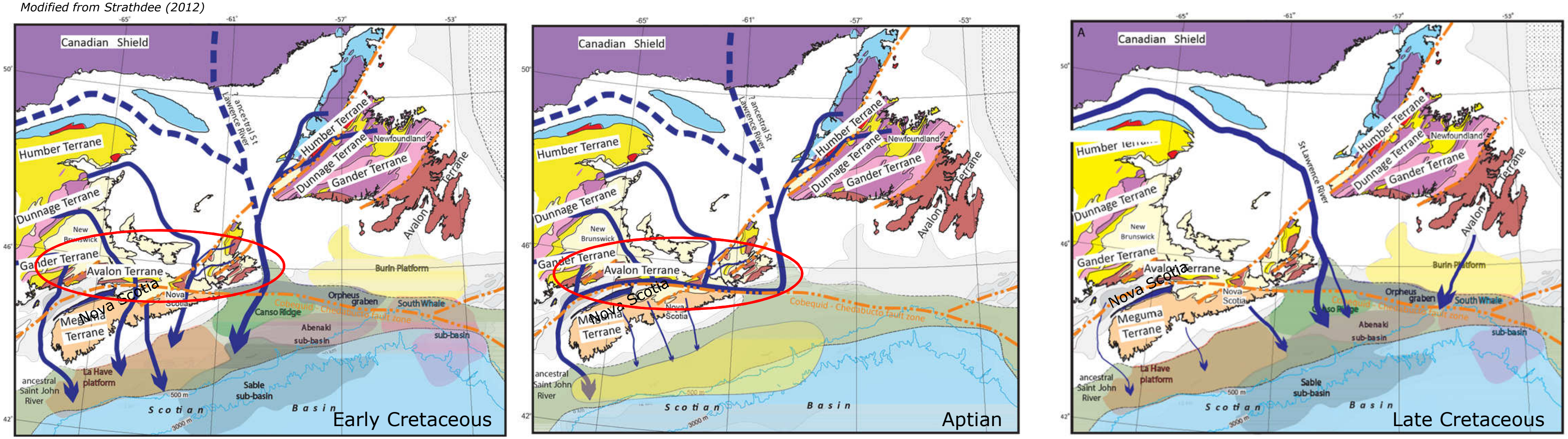


Figure 5: Map showing the structural and geomorphic evolution of the Scotian Basin and its hinterland from late Triassic to early Cretaceous: (a) late Triassic; (b) early Jurassic; (c) middle Jurassic; (d) Tithonian–Valanginian. (From Li et al., 2012).

Figure 6: Map showing proposed paleogeography of Atlantic Canada during the early Cretaceous (from Strathdee, 2012). During the early Cretaceous, sources are broadly distributed across the margin. During the late Hauterivian – Late Cenomanian interval, the main river systems are blocked by uplift south of the Cobequid-Chedabucto fault zone and related volcanism and therefore rerouted to the Bay of Fundy. (For further information, see Pe-Piper et al., 2011; Tsikouras et al., 2011).

Modified from Strathdee (2012)



Detailed Stratigraphic Framework

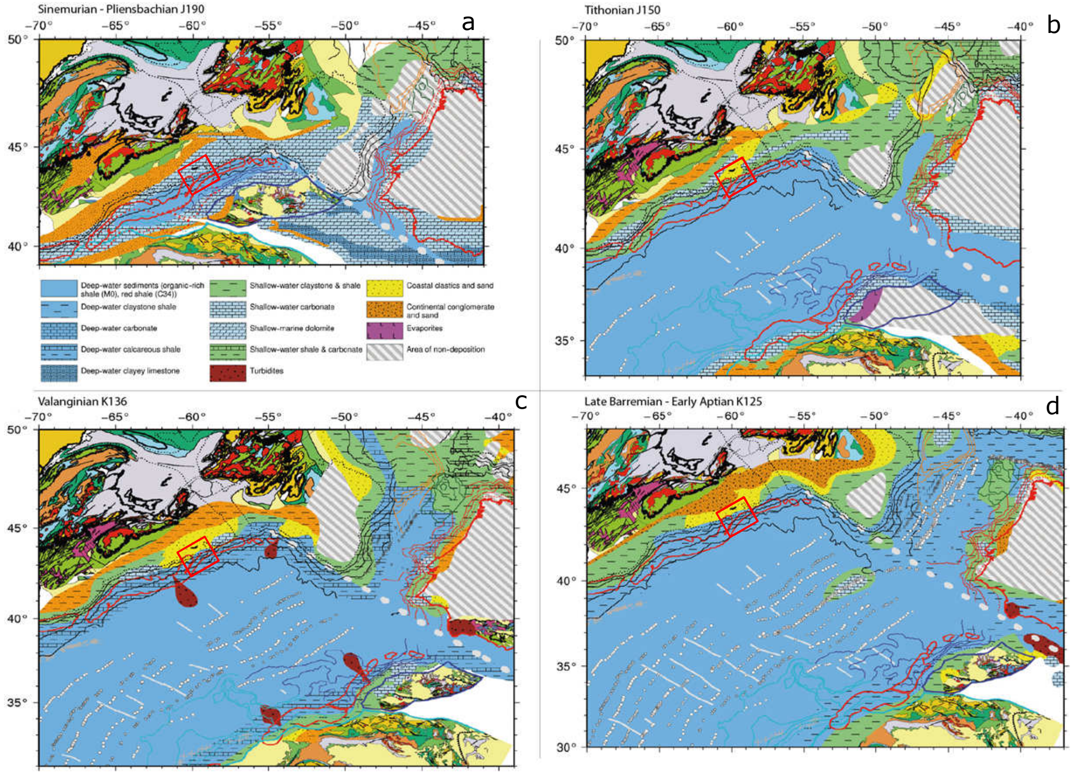


Figure 7: Paleogeography of the eastern Canadian margin from Early Jurassic to Middle Cretaceous (Sibuet et al., 2012). Study area is indicated by the red box.

Generalized Stratigraphy of the Scotian Basin

The Scotian Basin contains Mesozoic-Cenozoic sedimentary rocks up to 15km thick in places, which were deposited during the rifting of Pangea and the opening of the North Atlantic (Figure 7).

The earliest basin infill occurred during the Triassic rifting, and consists of red continental clastic sediments and evaporites (**Euridice and Argo Formation**; Figure 8).

During the **Early Jurassic**, rift basins were gradually infilled by clastic and carbonate sediments (Figure 7a). Fully marine conditions developed by **Mid Jurassic**, leading to a set of alluvial plains, deltaic and carbonate environments (Figure 7b).

Consecutive to the **Avalon Uplift**, the **Early Cretaceous** was dominated by deltaic progradation and shelf clastic deposits (Figure 7c).

Late Cretaceous / Early Tertiary sedimentary deposits were dominated by transgressive shale, sporadic influxes of deltaic sands, limestone, and chalk sequences (Figure 7d).

Relative sea level fluctuations during the Paleogene and Neogene created a mix of marine sandstones and shales interbedded with coarse clastics and marine carbonates (chalks). These sedimentary successions are overlaid by unconsolidated glacial till, glacio-marine and marine sediments that were deposited during the Quaternary.

Table 2: Well markers and biostratigraphic surfaces.

Stratigraphic Marker	Stratigraphic surface	Stage	Equivalent Formation	Alma F67	Annapolis G24	Balvenie B79	Banquereau C21	Chebucto K90	Crimson F81	Glenelg J48	Tantallon M41	Thebaud I93	Venture B52
T29	Unconformity	Rupelian	Banquereau		2513	3113			3037		2526		
T50	Unconformity	Ypresian	Dawson Canyon Petrel Wyandot Ypresian chalk		3354	3444	1209	1640	3485	1515	3109		949
K94	Unconformity	Cenomanian			3491	3825	1909	1910	3655	1774	3263	1309	1500
K101	Unconformity	Albian	Logan Canyon Shortland Shale Naskapi Roseway	1908	3852	4204	2389	2640	3990	2300	3704	1746	1907
Mid Alb unc	Unconformity	Albian		2170	4002				4296				
Alb/Apt mfs	MFS	Albian/Aptian		2323	4274			3318	4548	3218	4122		
Intra Aptian mfs	MFS	Aptian		2675	4470			3557	4722	3386			
Apt/Barr unc	Unconformity	Aptian/ Barremian		3168	4563			3689	4772	3480	4400		
K130	MFS	Hauterivian	Missisauga/Verilll Canyon	3730	5285		4175	4853	5928	4061	4738	3311	3564
Hauterivian unc.	Unconformity	Hauterivian								4150	5143		
K137	Unconformity	Valanginian		4448						4715		4118	4468
J150	MFS	Tithonian	Abenaki MicMac	4985								4591	5235

BASEMENT AND PRESERVED CARBONIFEROUS - EARLY TRIASSIC DEPOSITS

The basement is composed of granite complex and metamorphic rocks (gneiss and schist). Seismic data reveals tilted blocks and associated troughs infilled with Early Triassic salt and undefined sedimentary deposits (Figure 8). Onshore, these sediments outcrop on the western rim of the Scotian Shield mainly along the Bay of Fundy (Fensome and William, 2001). Eastward from Halifax, the geological map indicates limited outcrops of Carboniferous age rock. In the current study, no wells have reached the basement or syn-rift deposits (Table 2).

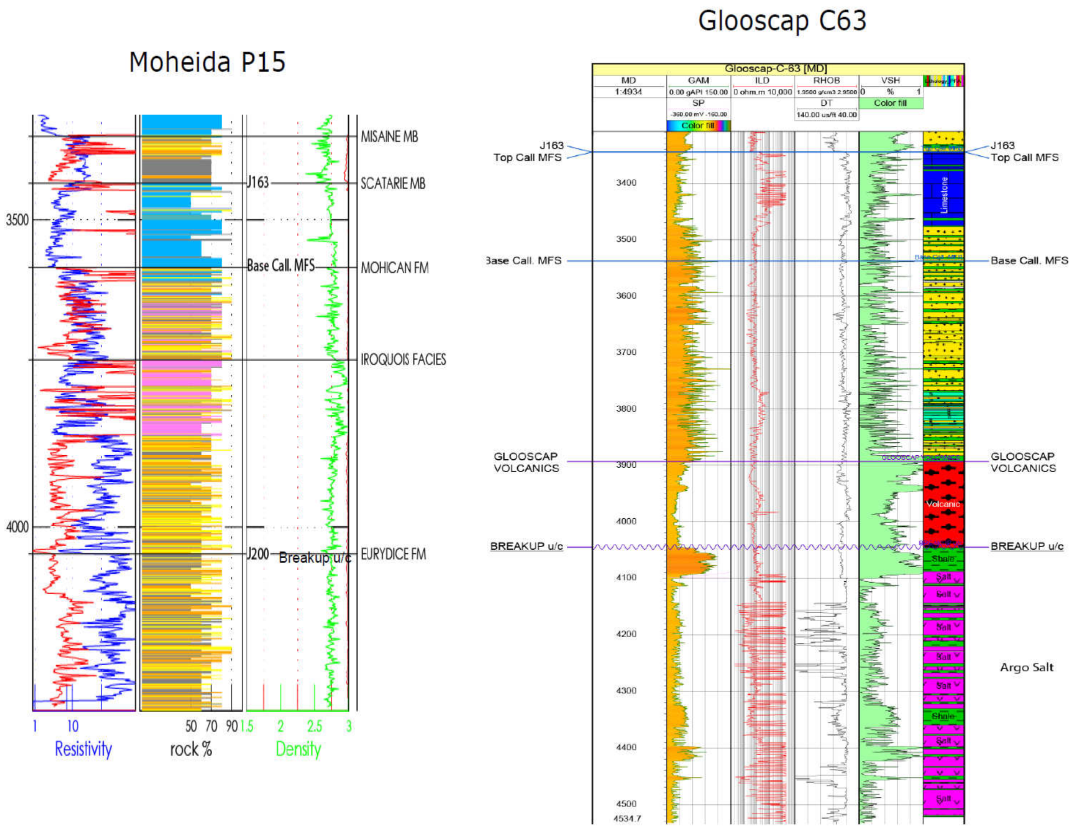
TRIASSIC

Formations: Eurydice and Argo Salt Equivalent (Figure 8)

Glooscap C-63 and Moheida P-15 have recorded pre breakup sedimentation, i.e. the Eurydice and Argo Fms and are among the few wells that have sampled syn-rift sediment offshore.

The **Eurydice Formation** corresponds to the oldest synrift sequence linked to the Atlantic opening. The Formation corresponds to a thick series of Late Triassic red sandstones, siltstones and shales (Figure 8). The Euridice Formation is a sedimentary succession widespread across the margin. The thickest area known to date is found in the Orpheus and Naskapi Grabens where seismic data indicate a total thickness over 3,000 m (Wade and MacLean, 1990).

Figure 8: Late Triassic to mid Jurrassic litholog interpretation.
A: Moheida P15 (after Fensome, modified); B: Glooscap C63.



The **Argo Formation** is coeval or overlies the Eurydice Formation (Figure 8). The Argo Formation consists of massive beds of pale orange salt interbedded with thin red shale units. The distribution of salt along the Scotian Margin coincides with major basement trends and suggests that the basins morphologies are shaped by inherited structural networks and the continental – oceanic crust boundary (Figure 9 and 10).

Total salt thickness prior to breakup is estimated to be at least 2,000 m (Wade and MacLean, 1990). Shortly after the rifting along most of the margin, the salt flowed extensively due to Subsequent sediment loads and possible reactivation of rift-related faults. Salt pillows, diapirs and canopies are common along the margin from Georges Bank north to western Grand Banks (see Chapter 1 for more details).

Figure 9: Structural sketch map of the study area showing the main crustal elements and autochthonous salt basins (Argo Salt).

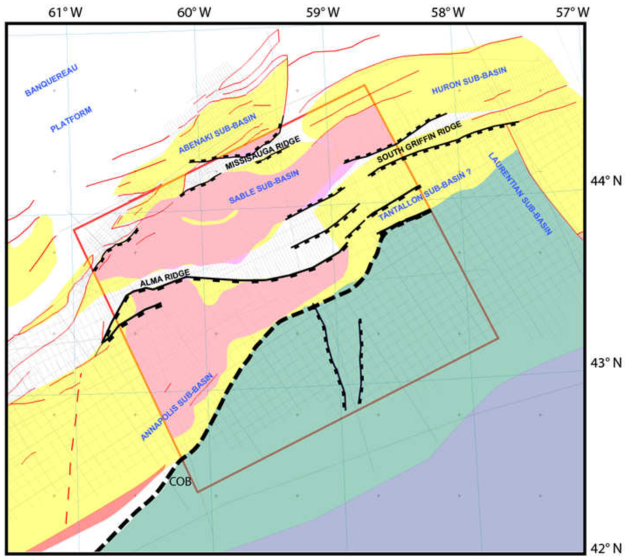
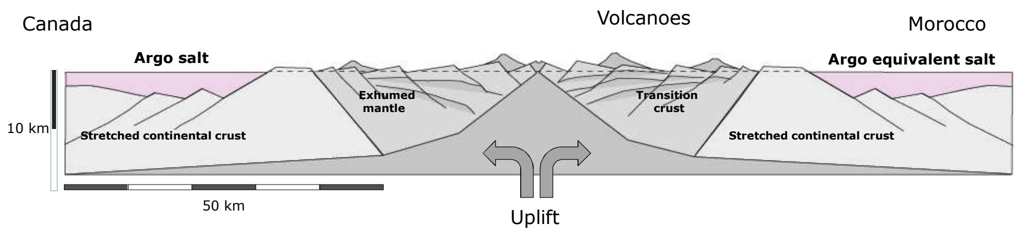


Figure 10: Cross-section sketch of Scotian Margin and its Moroccan conjugate at J200.



BREAKUP UNCONFORMITY - J200

The J200 Breakup Unconformity (BU) is dated to the Early Jurassic (200 Ma; Figure 11) and separates the synrift and post rift sequences. The unconformity corresponds to the opening of the North Atlantic Ocean and is traced from the Shelburne Sub-basin up to the Laurentian Sub-basin. Seismically, the unconformity is characterized by a strong reflection, which can be mapped regionally.

EARLY TO MIDDLE JURASSIC J200 – J163

The Early to Middle Jurassic stage corresponds to the development of large river systems with deltaic environments along the shore combined with large carbonate rims and platforms on the shelf (**Iroquois Fm**) (Figures 5, 11 and 12). The Sable Sub-basin records its first pulses of clastic sediments during the late Early Jurassic forming the first turbidite deposits offshore. This sequence corresponds to the **Mohican Fm** or offshore equivalent Fm (Given, 1977; Deptuck et al., 2014).

Toward the middle Jurassic, clastic input decreases and carbonate platform extends, sporadically cut by deltas developed at river mouth complexes (Figures 13). In Sable Sub-basin, a wide carbonate platform developed along the outer hinge zone (Figure 3) and corresponds to the northward extension of the **Abenaki carbonate bank**. The lower part of the **Abenaki Fm** corresponds to the **Scatarie Mbr.** (Figure 14 to 17). The **Scatarie Mbr.** correspond to a carbonate dominated formation widely developed across the margin and predominantly composed of oolitic limestone (Wade and MacLean, 1990). The Scatarie Mbr. is restricted to the shelf part of the margin, while the basin is dominated by marine shale deposits overlaying a Mohican turbidite system (Figure 13). The Scatarie Mbr. is drowned by transgressive marine shales corresponding to the **Misaine Mbr.**, the transgression that reaches its maximum with the **Callovian mfs (J163)**.

Identification

- Formation/Member equivalents: **Iroquois Fm.** (carbonate platform), **Mohican Fm**. (clastic sands), **Scatarie Mbr.** (carbonate platform), **Misaine Mbr.** (marine shale)
- Number of exploration wells that reached the Early to Middle Jurassic: None of the wells used in the current study have encountered these formations. For wells that have reached the cited formations, see the 2011 PFA (http://energy.novascotia.ca/oil-and-gas/offshore/play-fairway-analysis);
- Regional top sequence/seismic horizon: **J163 (Top Scatarie; Callovian MFS)**;
- Age: **Hettangian – Callovian**.

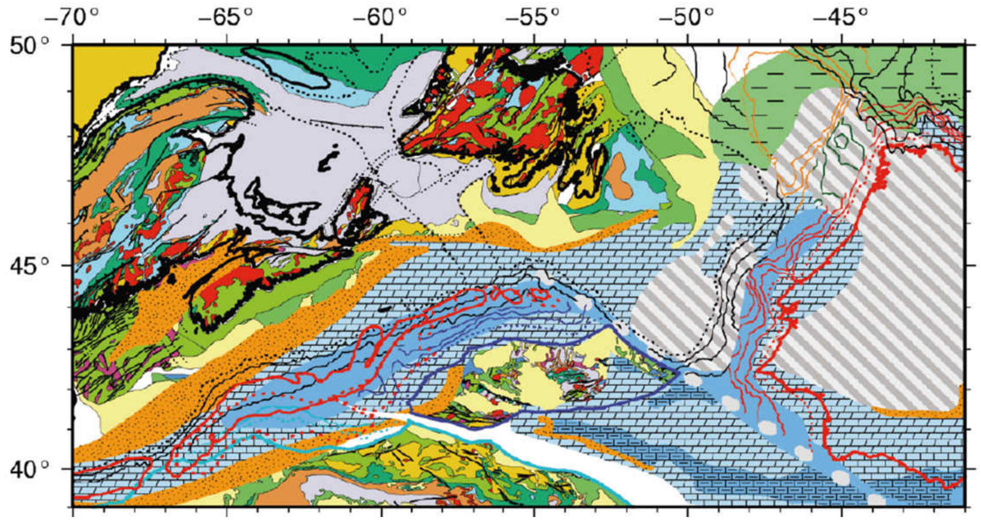


Figure 12: Sinemurian/Pliensbachian limit (190 Ma) Mohican – Iroquois Fm

Figure 11: Gross depositional environment map at J200 (Hettangian). The J200 period is the transition from rifting to drifting.

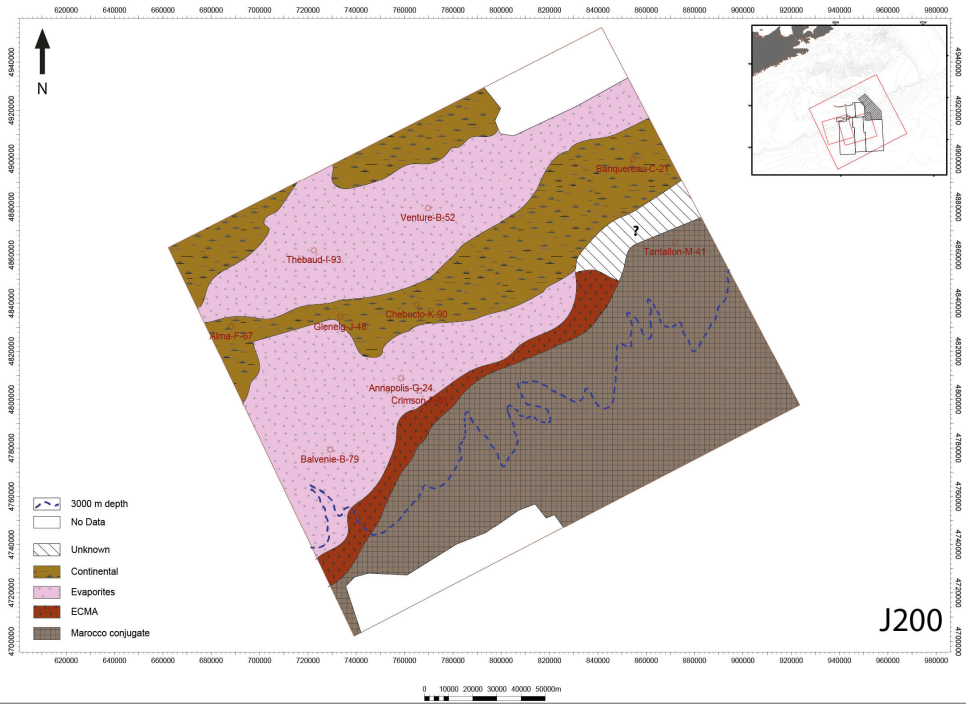
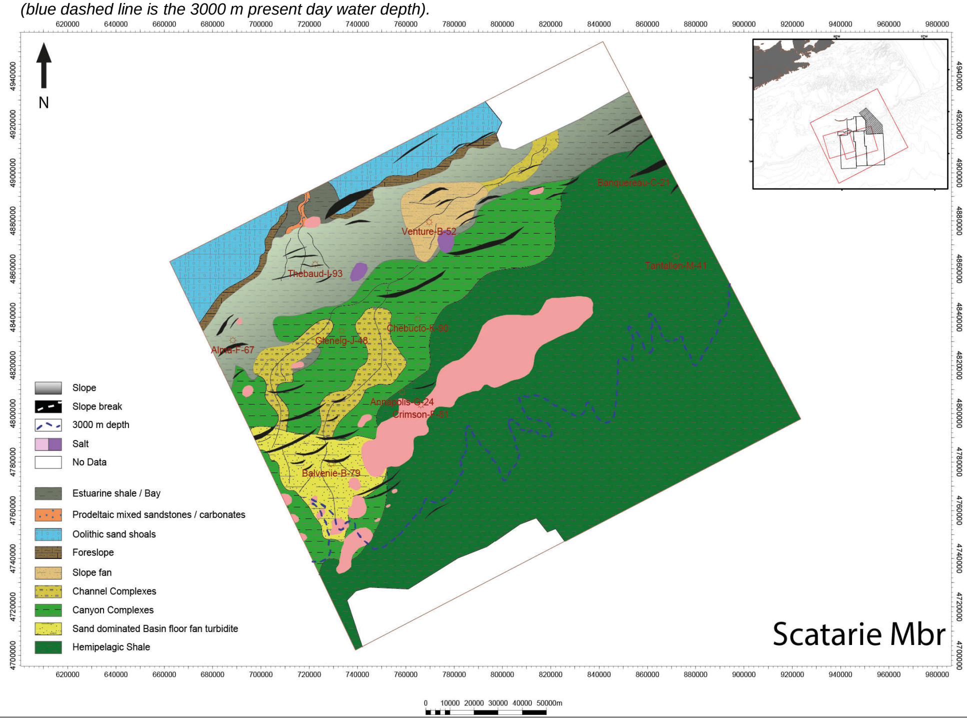


Figure 13: Gross depositional environment map for the Scatarie Mbr. This period is marked by the development of a thick oolitic limestone sequence combined with marine shale deposits overlaying a Mohican turbidite system (blue dashed line is the 3000 m present day water depth).



Description

Along Sable Sub-basin, Early to Middle Jurassic formations overlie the Breakup Unconformity, separating post-rift sediments from the Argo salt and Eurydice Fms (Figures 8, 11 and 13). Iroquois and Mohican Formations cover the timespan between the Hettangian and Bajocian (Figure 2). The Iroquois Fm is a transgressive formation consisting primarily of dolomite deposited under slightly restricted marine conditions. Iroquois Formation is coeval with the lower part of the Mohican Formation due to coexisting carbonate rims and deltaic formations (Wade and MacLean, 1990). Mohican and Iroquois Fms are difficult to trace in Sable Sub-basin because of their depth. Nonetheless, thickness map for the early to mid Jurassic interval (J200 – J163) shows very thick sequences in the basin, up to 2.5 km (Annex 2.4).

The Iroquois and Mohican Fms are topped by **Scatarie Mbr** on the shelf and **Verrill Canyon Fm** on the distal part. The **Scatarie Mbr**. is the lower member of the Abenaki Formation (Figure 14) and has the most extensive coverage compared to the other members. The Scatarie Mbr. covers the **Bajocian – Callovian** interval. Proximal facies are predominantly shallow water and oolitic limestones for Scatarie Mbr, interrupted by the transgressive Misaine shale (Figure 15 and 16). In the study area, carbonate formations related to Scatarie Mbr. are located in the northwestern corner (Figure 13). Offshore sedimentation is predominantly marine shale until the Callovian.

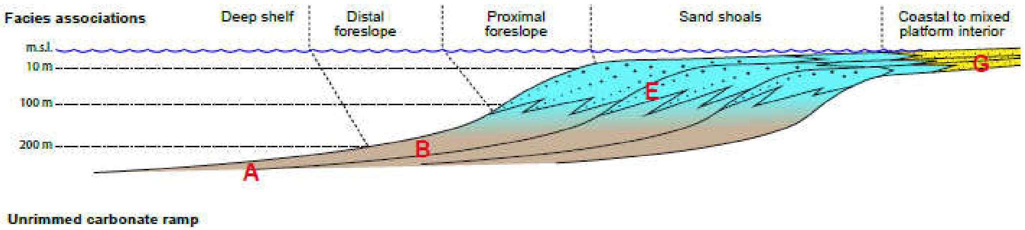


Figure 15: Typical depositional profiles for the Scatarie Mbr. identified from sedimentary facies. A: Laminated shales, siltstone to very fine sandstones, pelagic forams, Radiolarian tests, ammonites; B: Same as A plus hexactinellids, hithistids, tubiphytes; E: Oolites, oncolites, skeletal grains; G: Sandstones mixed with shells, coral debris and oolites.

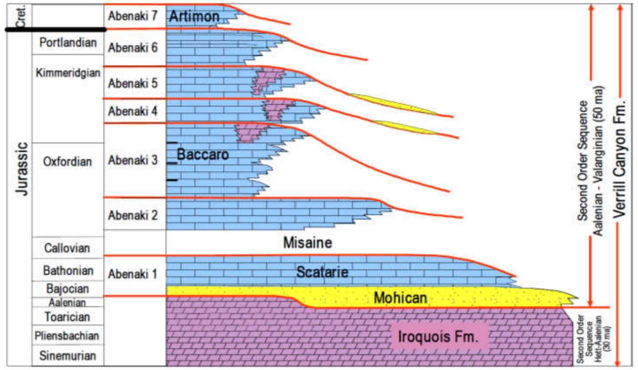


Figure 14: Subdivision of the Abenaki Formation and their respective onshore-offshore extension

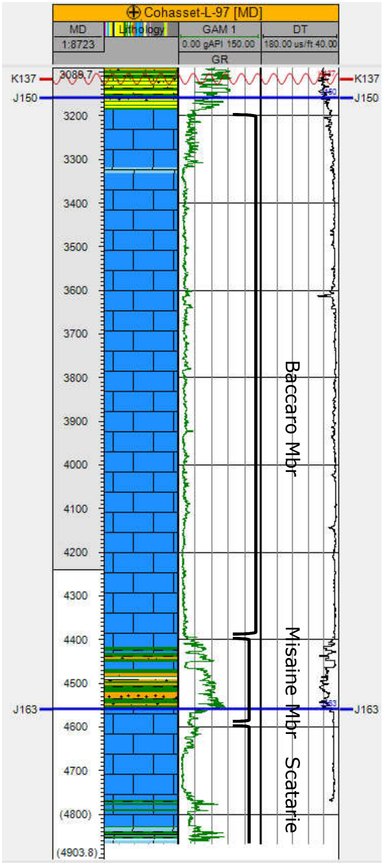


Figure 16: Mid to Late Jurassic succession in the Cohasset L-97 well. For this interval, the stratigraphic records show successively Scatarie, Misaine and Baccaro Mbrs.

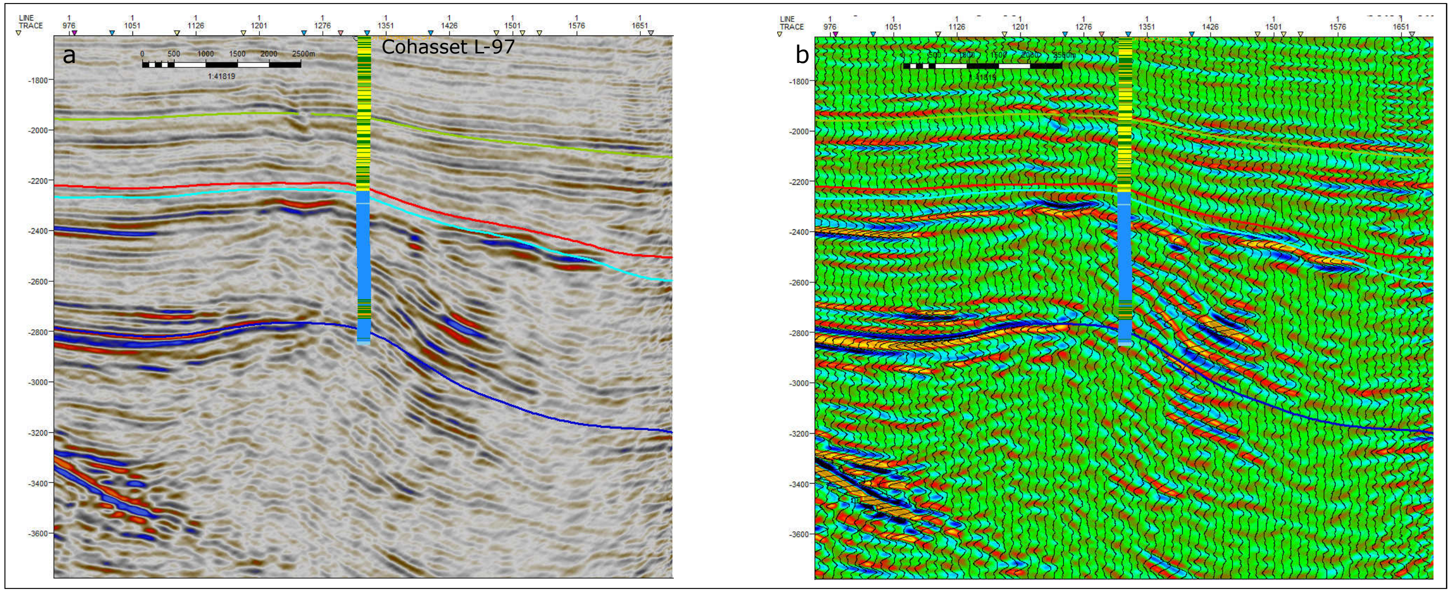


Figure 17: Seismic example of reefal buildup of the Abenaki formation, tie to Cohasset L-97 well. A: Standard seismic color scale; B: Seismic image in acoustic impedance with wiggles. Carbonate accumulation is about 1.6s twt thick.

MID TO LATE JURASSIC SEQUENCE (CALLOVIAN TO TITHONIAN) J163 – J150

The **Late Jurassic** period corresponds to the expansion of sedimentary environments that started to develop during the Early - Middle Jurassic. Carbonate environments evolve from unrimmed carbonate bank to rimmed reefal carbonate platforms (Figure 18). Correlation between wells shows rapid lateral changes in co-existing sedimentary environments from carbonate in Cohasset L-97 to fluvio-deltaic in Thebaud I-93 and Venture B-52. Carbonate production decreases rapidly and, by the beginning of the **Tithonian,** is almost absent except for sporadic pulses such as in Venture B-52 (Figures 19 and 20). From then, well records show prominent deltaic and prodeltaic successions in the Sable Sub-basin (Figure 19 and 20). During the **Kimmeridgian** and **Tithonian**, major environmental changes occur, coincident with the beginning of regional uplift and the opening of the North Atlantic (Wade and MacLean, 1990). Clastic inputs decrease drastically and sedimentation is dominated by shaly deposits (Figure 20) in contrast to the southern part of the margin which is dominated by the development of **Kimmeridgian – Tithonian** carbonate banks (OETR, 2011; South West Nova Scotia expansion, 2015). Remnants of carbonate are observed in the northwestern side of the study area, cut by river outlets (CNSOPB, 2012; PL. 6.3.5 and 6.3.6). The slope and rise of Sable Sub-basin is predominantly shaly excepted in early formed mini-basin on the backside of salt walls (PL. 6.3.5). The most notable event occurring in sable Sub-basin during this time frame is the formation of the Banquereau Synkinematic Wedge (BSW) which deeply restructured the northeastern part of the area (Deptuck et al., 2014; Chapter 2 PL. 2.1.19; PL. 6.3.7; Annex 2.4).

Sedimentary sequences between **Tithonian** and **Valanginian** are impacted by the near **base Cretaceous unconformity (K137)**, although in a less severe manner than in the southwest where the Tithonian source rock has been largely removed from the shelf of the Shelburne Sub-basin.

Identification

- Formation/Member equivalents: **Mic Mac** (continental clastics), **Abenaki Fm** Subdivided in **Misaine Mbr** (prodelta, open marine shale, deep water shale) and **Baccaro Mbr** (carbonate platform and reef margin), **Verrill Canyon Fm** (marine shale);
- Number of exploration wells that reached the mid to late Jurassic: 3 wells (. PL. 3.1.4 and 3.2.1; Appendixes 1.4.1, 1.4.10 and 1.4.11);
- Regional top sequence/seismic horizon: **J150 (Tithonian MFS)**;
- Chronostratigraphic cross-sections (PL 3.2.1 and 3.2.5);
- Lithostratigraphic cross-sections (PL 3.2.2and 3.2.5);
- Architectural cross-sections (PL. 6.1.1 to 6.1.3);
- Age: **Callovian – Tithonian.**

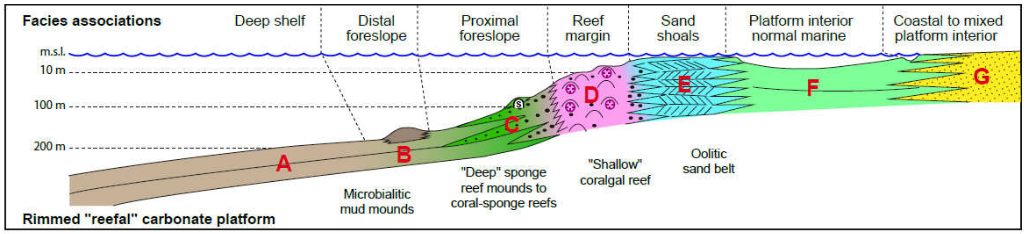


Figure 18: Typical depositional profiles for J150. identified from sedimentary facies. A: Laminated shales, siltstone to very fine sandstones, pelagic forams, radiolarian tests, ammonites; B: Same as A plus hexactinellids, hithistids, tubiphytes; C: "Deep" sponge reef mounds tocoral-sponge reefs; D: Shallow coralgal reef (chaetetids stromatoporids, crinoids, bivalves, scleractinian corals, milleporid corals, algae, gastropods, echinoids); E: Oolites, oncolites, skeletal grains; F: peloids, bivalves, gastropods, sandstones; G: Sandstones mixed with shells, corals debris and oolites.

J150 - J163 - Abenaki Fm/MicMac Fm/Verrill Canyon Fm

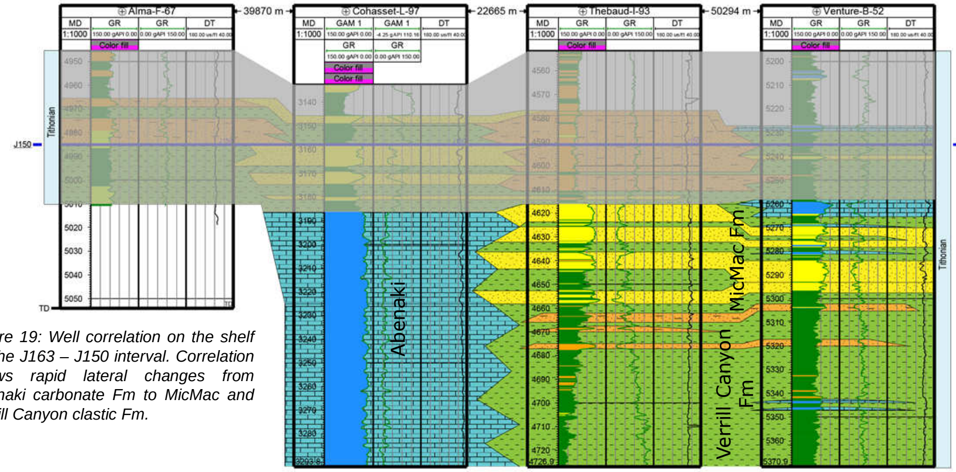


Figure 19: Well correlation on the shelf for the J163 – J150 interval. Correlation shows rapid lateral changes from Abenaki carbonate Fm to MicMac and Verrill Canyon clastic Fm.

J150

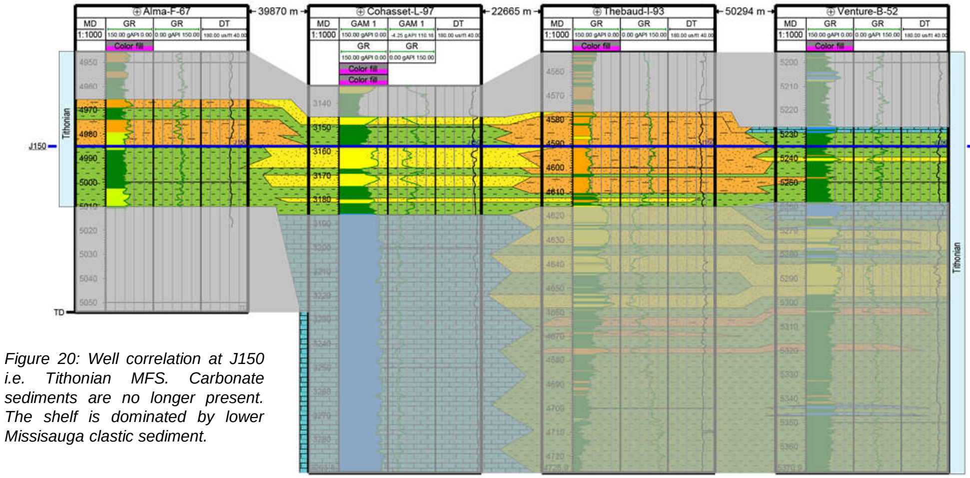
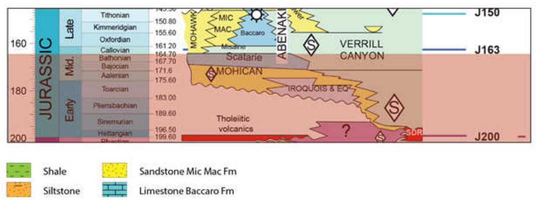
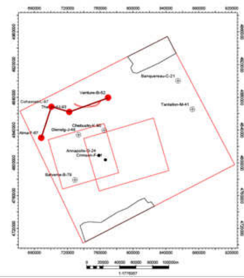


Figure 20: Well correlation at J150 i.e. Tithonian MFS. Carbonate sediments are no longer present. The shelf is dominated by lower Missisauga clastic sediment.





Description

Mic Mac Formation

The **Mic Mac Formation** is the lateral equivalent of the Mohawk Formation observed in the southern part of the Scotian Margin and corresponds to a mixed carbonate – clastic system (Figure 19, 20 and 22; PL 3.3.1, 3.3.2 and 6.3.5). The Mic Mac Fm is coeval to the Bacaro Member of the **Abenaki Fm** and spans the late-Middle to Late Jurassic. Its depositional environment is typically very shallow marine evolving quickly through time into outer neritic; these changes are controlled by the subsidence rate of the different parts of the Scotian Margin (Wade and MacLean, 1990). In Sable Sub-basin, the Formation is typically composed of sandstone and limestone topsets, sandstone to shale foresets and shale to sandstone bottomsets (Wade and MacLean, 1990). Significant lateral facies changes are observed, such as in Venture field area where shallow water sandstones quickly change to a predominance of shelfal shales interbedded with sandstones, siltstones and lilmestones (Figures 19 and 20). Distally, the Mic Mac facies grades into the **Verrill Canyon Formation** characterized by a fine grained basinal facies. The distinction between **Mic Mac** and **lower Missisauga Fms** is not evident as the contact is very often gradual (Figures 19 and 20). It is often considered that the transition between the two formations occurs during the Jurassic – Cretaceous transition (Wade and MacLean, 1990).

Verrill Canyon Formation

The **Verrill Canyon Formation** is a shale-dominated unit that formed from the **Jurassic to Early Cretaceous**. The Formation was deposited on the continental shelf, slope and rise and consists primarily of grey to brown calcareous shale with occasional thin beds of limestone, siltstone, and sandstone. **Verrill Canyon Formation** is the prodeltaic and deep water facies equivalent of the **Mohawk, Abenaki, Mic Mac, and Missisauga Formations**.

Abenaki Formation

The Abenaki Formation is a limestone-dominated unit corresponding to a prominent carbonate bank facies. The Formation extends across the Scotian Margin to Georges Bank (Figure 21). The Abenaki Formation forms an outer shelf carbonate bank complex and is subdivided into three members: The Scatarie Member, the Misaine Member and the Baccaro Member (Figure 14).

The **Misaine Member** is a dark grey calcareous shale-dominated unit with interbedded proximal sandstone deposited during the Callovian regional transgressive event. It is the only clastic-dominated unit of the Abenaki Fm (Kidson et al., 2005). It is a transgressive facies and overlies the Scatarie Mbr (Figure 16). The Misaine Member is observed in only a few wells in the area; mostly wells that have targeted the carbonate banks (PFA 2011). In Cohasset L-97 (Figure 16), the Misaine Mbr is 150 m thick, but thicknesses up to 250m have been described (PFA 2011).

The **Baccaro Member**, which developed from early Oxfordian to Tithonian times, is the thickest carbonate unit of the Abenaki Formation although relatively limited in areal extend (narrow structure of 15 – 20 km width). It is composed of numerous aggrading and prograding parasequences of oolitic limestone with minor shale and sand intervals.

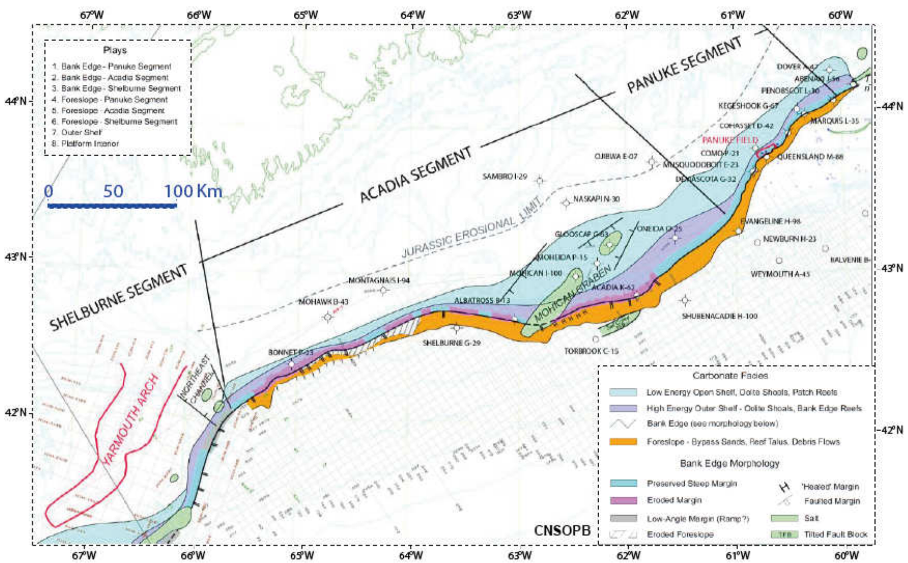
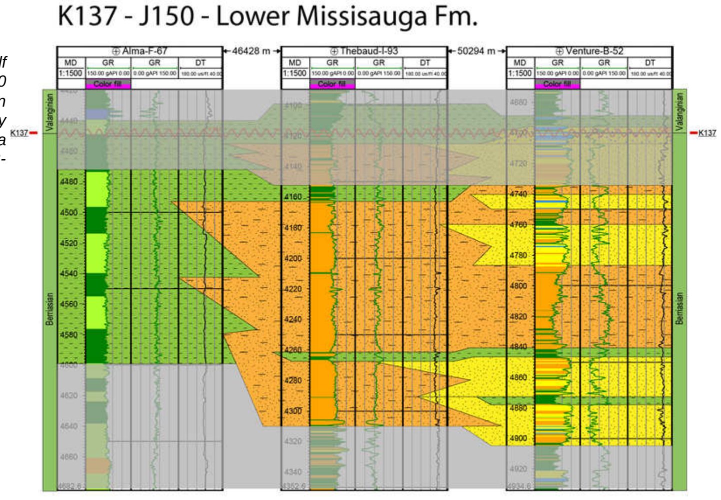
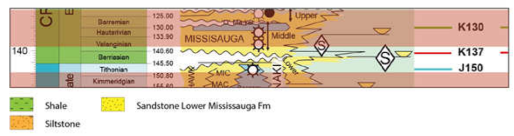
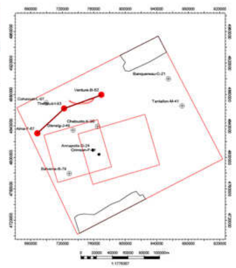


Figure 21: Abenaki Formation morphology, carbonate facies complex after A. Kidson et al., 2005.

Figure 22: Well correlation on the shelf focused on the Lower Missisauga Fm (J150 – K137 interval). The geological section shows thick clastic succession laterally shifting from a shale dominated area (Alma F-67) to sand dominated interval (Venture B-52).







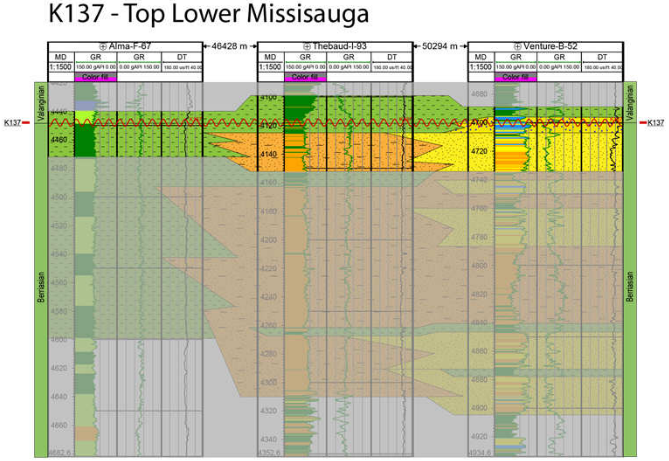
NEAR BASE CRETACEOUS UNCONFORMITY (TITHONIAN TO BERRIASIAN) J150 – K137

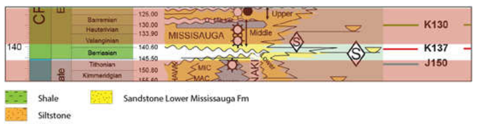
During the Late Jurassic, a second breakup episode occurred on the eastern Canadian margin related to the separation of Iberia and the Grand Banks. An uplift related to the opening developed beneath the Grand Banks and led to extensive erosion of Jurassic and older sediments. The resulting Avalon Unconformity is well recorded across the eastern Canadian margin (Jansa and Wade, 1975; MacLean et al., 1989; Wade and MacLean, 1990). The Avalon Uplift induced a massive erosion of upper Jurassic sequences resulting in a drastic reduction of space available to accommodate sedimentation. The impact of the Avalon Uplift decreases southward and therefore its impact is less severe in Sable Sub-basin where no clear angular unconformity is observed (PL. 4.3.2.7). This period coincides with a time of low sedimentation rates which is superimposed on the unconformity and is expressed as condensed sequences in the basinal part of the margin.

The Avalon Uplift was accompanied by magmatism and a thermal anomaly that lasted until Hauterivian – Barremian time (Bowman et al., 2012). Widespread volcanic activity has been evidenced from several wells and outcrops. Initially, it was proposed that the long-lived magma source would impact hydrocarbon maturation (Bowman et al., 2012). Nonetheless, recent work suggests that the anomalies observed in some Sable Sub-basin wells are more likely related to hydrothermal circulation along salt structures (Pe-Piper et al., 2015).

Identification

- Formation/Member equivalents: **Lower Missisauga** (continental clastics), **Verrill Canyon Fm**;
- Number of exploration wells that reached the late Jurassic: 4 wells (. PL. 3.1.4, 3.2.1 and 3.3.2; Appendixes 1.4.1, 1.4.8, 1.4.10 and 1.4.11);
- Regional top sequence/seismic horizon: **K137 (near base Cretaceous unconformity)**;
- Chronostratigraphic cross-sections (PL 3.2.1 and 3.2.5);
- Lithostratigraphic cross-sections (PL 3.2.2and 3.2.5);
- Architectural cross-sections (PL. 6.1.1 to 6.1.3);
- Age: **Tithonian – Berriasian.**





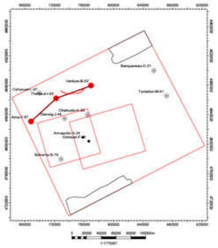
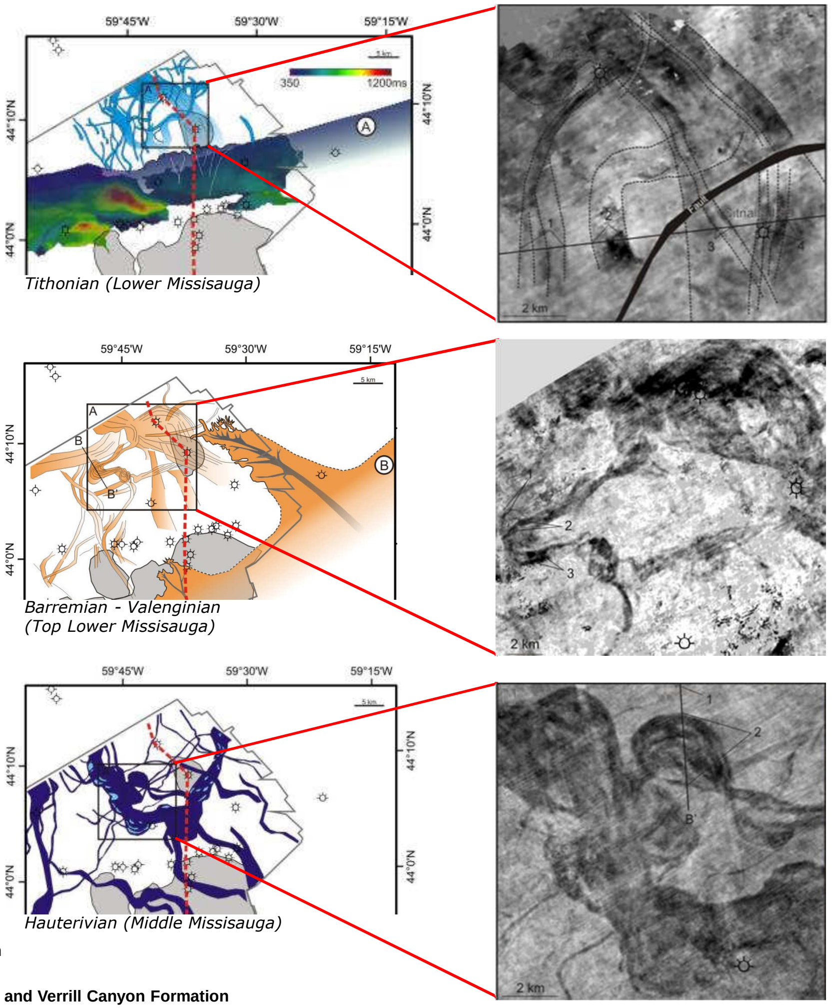


Figure 23: Well correlation on the shelf focused on the Near Base Cretaceous Unconformity (K 137) which tops the Lower Missisauga Fm. Sedimentary succession shows a uniform pattern for each well during the Lower Missisauga. The Lower Missisauga is topped by a shaly formation which marks the beginning of the Middle Missisauga.

Figure 24: Evidence and evolution of the Sable River system during the Middle Missisauga ***(from CNSOPB, 2012)****. This work shows evidence for an active and efficient transfer of sediment into deep-water. Remnants of Jurassic carbonate banks are eroded by the Sable River during the formation of the Lower Missisauga (Kimmeridgian – Tithonian). Note the well developed meandering river system during the Hauterivian – Barremian time (K130).*



EARLY CRETACEOUS SEQUENCE (BERRIASIAN - HAUTERIVIAN) K137-K130

The Early Cretaceous corresponds to a period of major change in river drainage area in response to the Avalon Uplift and subsequent regional unconformity, inducing an increase in sediment supply to Sable Sub-basin. The **Middle Missisauga Fm** is deposited during this time and is predominantly formed of thick sandstone deposited in a fluvio-deltaic environment (Figures 23 and 24). The Missisauga Fm is very important in regard to petroleum exploration, as it represents more than 75% of the gas discovery in the margin (CNSOPB, 2000).

The transition between the Lower to **Middle Missisauga** is not easy to pick and correlate across the margin, therefore, the **K137** marker is used as the top Lower Missisauga (Figure 23). This marker corresponds more or less to the time of transition between the two members of Missisauga Fm. The top of the Middle Missisauga is characterized by the presence of a thick transgressive oolitic limestone unit called the **"O" marker** and due to its preeminent response in seismic, this marker can be mapped almost regionally with a southward thinning trend toward La Have Platform (Wade and Maclean, 1990). Its presence in the wells used in the current study is less obvious as the unit is often eroded or absent because of the existence of fluvio – deltaic sandstones. This Early Cretaceous sequence ends with the **Hauterivian MFS (K130)** which tops the "O" Marker. No Roseway Formation is observed in the study area.

Identification

- Number of exploration wells reaching the Lower Cretaceous Fms: 9 wells (PL. 3.1.12, 3.2.1 to 3.2.5; Appendix 1.4.1, 1.4.2, 1.4.4 to 1.4.11);
- Formation/Members: Middle **Missisauga Mbr** and **Verrill Canyon** Formations;
- Regional top sequence seismic horizon: **Intra Hauterivian MFS (K130);**
- Chronostratigraphic cross-sections (PL 3.2.1, 3.2.3 and 3.2.5);
- Lithostratigraphic cross-sections (PL 3.2.2, 3.2.4 and 3.2.5);
- Architectural cross-sections (PL. 6.1.1 to 6.1.3);
- Age: **Valanginian – Hauterivian (K137-K130)**.

Description

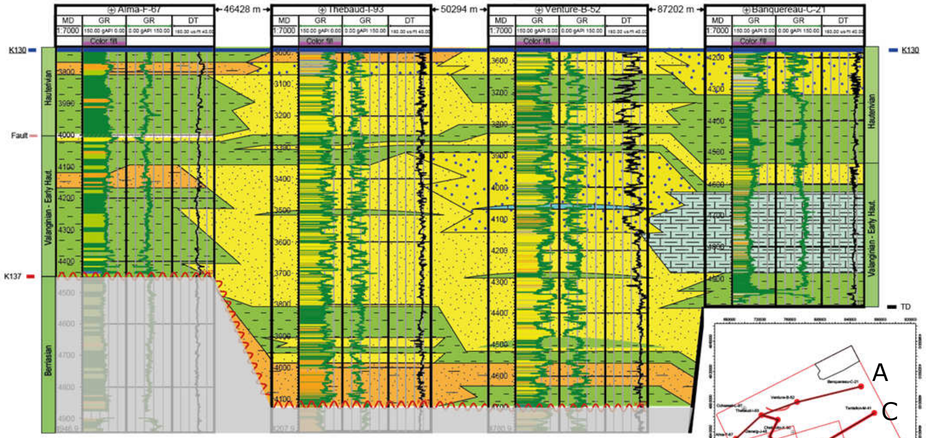
Missisauga and Verrill Canyon Formation

The sandstone-rich middle Missisauga Fm is particularly thick in Sable Sub-basin, with thicknesses over 2 km in average and exceeding 3 km in places. The Missisauga Fm is linked to the presence of a widespread deltaic system called the Sable Island Delta that lasts until the Cenomanian. The resulting sedimentary formation comprises fluvial, deltaic sands and derivative shelf sediments up to the shelf edge (Figure 17). This large deltaic system provided siliciclastic turbidites to the Sable Sub-basin. Basinward, canyons and valleys incise the slopes while basin floor fan systems develop on the rise (Deptuck et al., 2014). The basinal part of the Missisauga Fm corresponds to the Verrill Canyon Fm.

Well data show drastic changes in the sand – shale ratio from the shelf to the basin (Figure 25 to 27). All deep water exploration wells that have targeted Missisauga reservoirs have had little success in finding them (Kidson, 2007). The most successful well, Annapolis G-24, shows only 27 m of net pay out of 1620 m of Missisauga eq interval (Figures 26 and 27; PL. 3.3.3 to 3.3.5). Previous and current work show that sediment distribution is strongly controlled by salt tectonics (Deptuck, 2010; Deptuck and Kendell, 2012; Kendell et al., 2016; PL., 2.1.21.). Part of the evidence for this conclusion is the difficulty in identifying preserved canyons or long-lasting sediment conduits that connect the shelf to the slope. Work conducted on sediment delivery systems by CNSOPB in 2012 has shown existence of canyons crossing the shelf and connecting to river deltas (Figure 24), but understanding and identifying sediment pathways downslope remains challenging. Nonetheless, integration of results from seismic interpretation, seismic characterization, stratigraphy and seismic stratigraphy coupled with stratigraphic modelling suggests the presence of a large sandstone reservoir on the slope and rise of the basin (Chapter 6). One of the main conclusions drawn from this work is that to understand reservoir distribution, one must first understand the timing of salt deformation and its impact on the sediment delivery system.

K130 - K137 - Middle Mississauga Fm. Shelf section

A



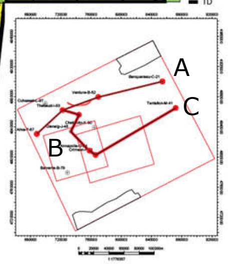


Figure 25: Well correlation on the shelf for the K137 – K130 interval. As for the previous sections, correlation shows rapid lateral changes. The axial part of the area (Thebaud I-93 and Venture B-52) appears to be very sandy compared to Alma F-67 and Banquereau C-21. The Thebaud and Venture wells seem to be within or close to the main axis of sediment input.

K130 - K137 - Middle Mississauga Fm. Dip section

C

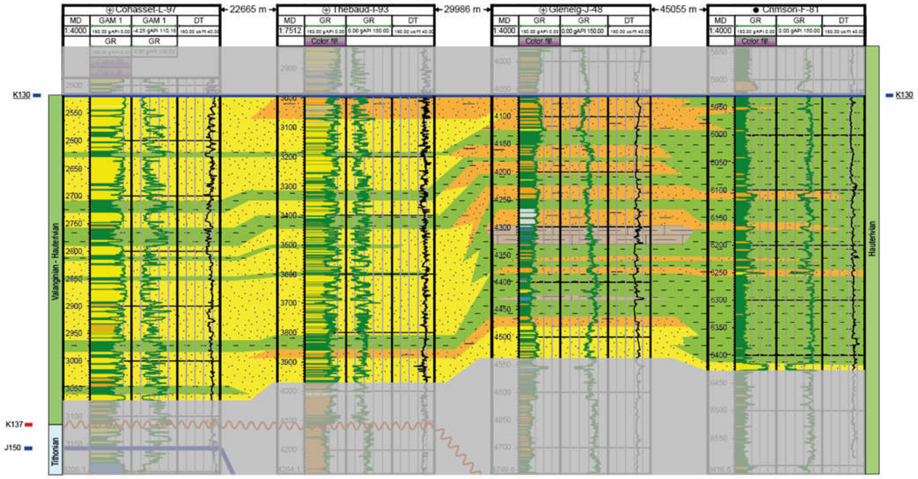


Figure 27: Well correlation on a dip section for the K137 – K130 interval. This section shows the rapid disappearance of sand from the shelf to deep-water and highlights the problem of sand distribution on the slopes.

K130 - K137 - Middle Mississauga Fm. Slope section

B

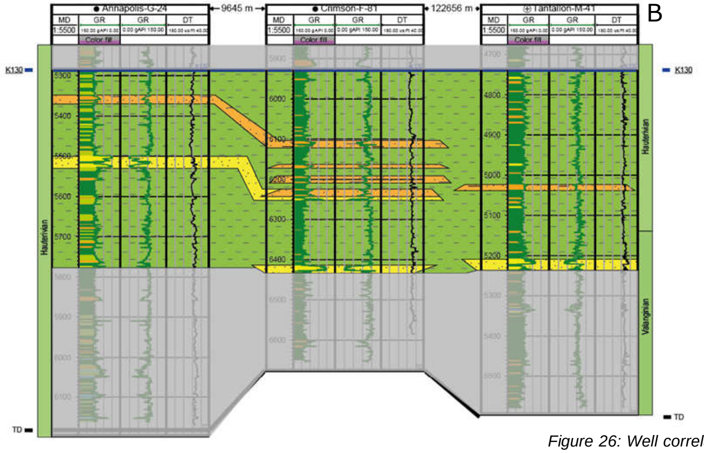
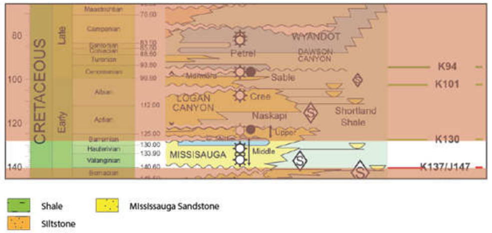


Figure 26: Well correlation on the slope for the K137 – K130 interval. This section is parallel to the section on the shelf (Figure 25). In contrast to what is observed on the shelf, these wells show very few sand rich layers. Additionally, it is hardly possible to correlate between the wells. Although Crimson and Annapolis are nearby (~10 km) on each side of a mini-basin, they have a different sedimentary record which highlights the role of salt tectonics in sediment distribution.



K130

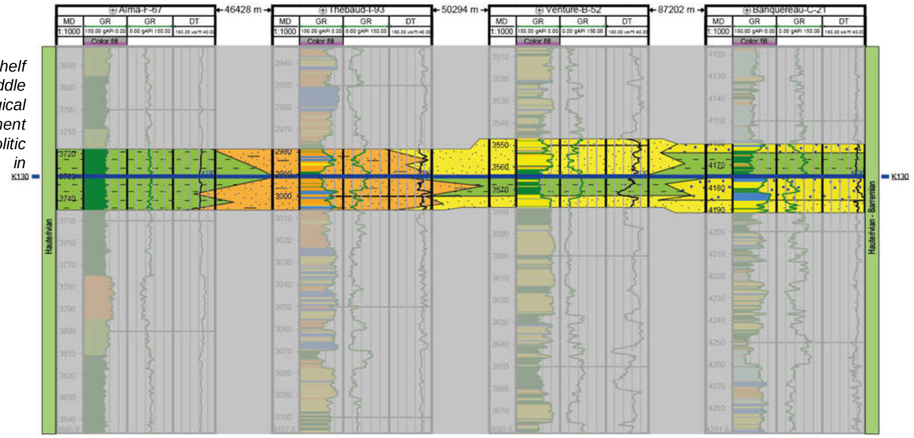
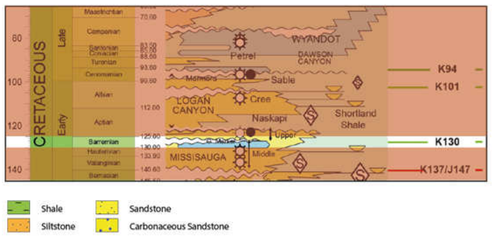
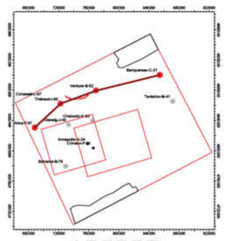


Figure 28: Well correlation on the shelf focused on the termination of the Middle Missisauga Fm (K 130). The geological section shows a significant lateral sediment variability with the appearance of oolitic carbonate sediments and an increase in shaliness toward K130.





THE BARREMIAN – CENOMANIAN SEQUENCE K130-K94

The **Barremian – Cenomanian** time interval encompasses the **Upper Missisauga and Logan Canyon Formations** (Figure 2). It correspond to a period of drastic changes in sedimentary succession related to the reconfiguration of deep watersheds combined with environmental changes. During the **Barremian – Albian** transition, an abrupt shift of the St. Lawrence proto-river to the Bay of Fundy (Strathdee, 2012; Tsikouras et al., 2012) caused a reduction in sediment input, which is expressed in the sedimentary record by a low sedimentation rate and the formation of a thick shale interval on the shelf, the **Naskapi Fm** (Wade and MacLean, 1990).

After the deposition of the “O” Marker and the Hauterivian MFS, the sedimentation returns to a predominantly fluvio – deltaic margin. Around **125 Ma**, the **Aptian – Barremian** transition is marked by an erosional surface which corresponds to the shift of the ancestral St. Lawrence River to the Bay of Fundy (Strathdee, 2012; Tsikouras et al., 2012) and marks the end of the Missisauga Fm. The sedimentation is then replaced by a prodeltaic shaly succession with average thickness of about 200m in the wells (Figures 29 and 30). By the **mid to late Aptian,** the sandstone succession returns and marks the end of the **Naskapi Fm** at around 112 Ma. Clastic input increases again through the **late Aptian to mid Albian** and feeds the basin with clastic turbidites. Return of a sustained sediment supply coincides with the return of the ancestral St. Lawrence River to near its former location. The sand content remains much less than during the Missisauga as observed in wells, and it is particularly obvious for deep water wells (Figure 30).

By the **late Albian**, a major erosional event called the **Late Albian Unconformity (K101)** is observed. This unconformity has a variable impact on sedimentation across the Sub-basin. Downslope, the erosional effect is masked by the active salt-tectonic deformation on which the unconformity event is superimposed. The **K101 unconformity** marks the transition between the **Cree Mbr** and **Marmora Mbr** of the **Logan Canyon Fm.**

During the K101 – K94 interval, sediments accumulated mostly at the shelf edge and slope mini-basins. Toward the end of the Albian up to the Cenomanian, the shaliness of the formation increases significantly (Figures 29 and 30.). At the end of the Cenomanian, another major unconformity occurs but has a lesser impact on sedimentation than the late Albian unconformity. The unconformity is called the **Cenomanian – Turonian unconformity (K94)** and tops the Logan Canyon Fm.

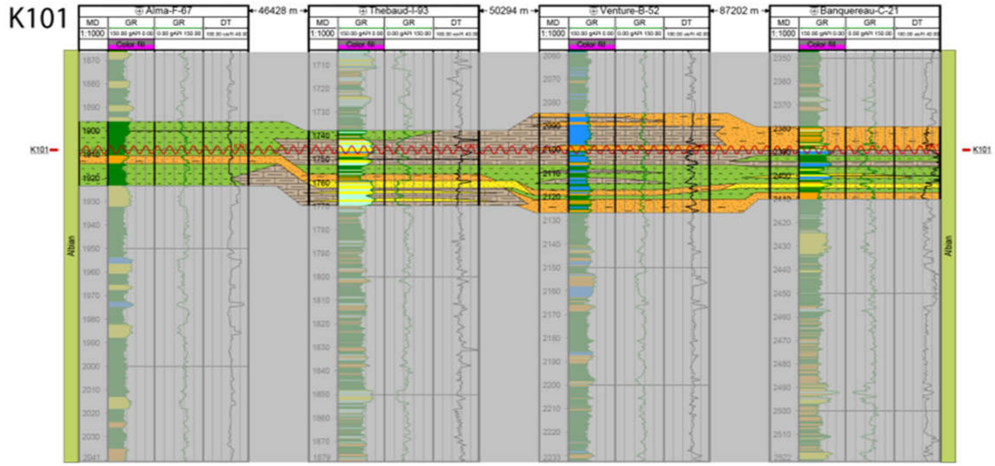


Figure 29: Well correlation on the shelf around the Late Albian Unconformity marker (K 101). The section shows a more shaly succession interbedded with thin sandstone and siltstone layer. The incursion of mudstone and marlstone is to be noted.

Identication

- Number of exploration wells reaching the Barremian – Cenomanian Sequence: 9 wells (PL. 3.1.12, 3.2.1 to 3.2.5; Appendixes 1.4.1, 1.4.2, 1.4.4 to 1.4.11);
- Formations: **Upper Missisauga Mbr**; **Logan Canyon Fm**; **Naskapi Mbr; Cree Mbr; Marmora Mbr; Shortland Shale Fm**;
- Regional top sequence: Aptian – Barremian Unconformity; Intra Aptian MFS; Albian – Aptian boundary MFS; Mid Albian Unconformity; Late Albian Unconformity (**K101**); Turonian – Cenomanian Unconformity (**K94**);
- Chronostratigraphic cross-sections (PL 3.2.1, 3.2.3 and 3.2.5);
- Lithostratigraphic cross-sections (PL 3.2.2, 3.2.4 and 3.2.5);
- Architectural cross-sections (PL. 6.1.1 to 6.1.3);
- Age: **Barremian – Cenomanian.**

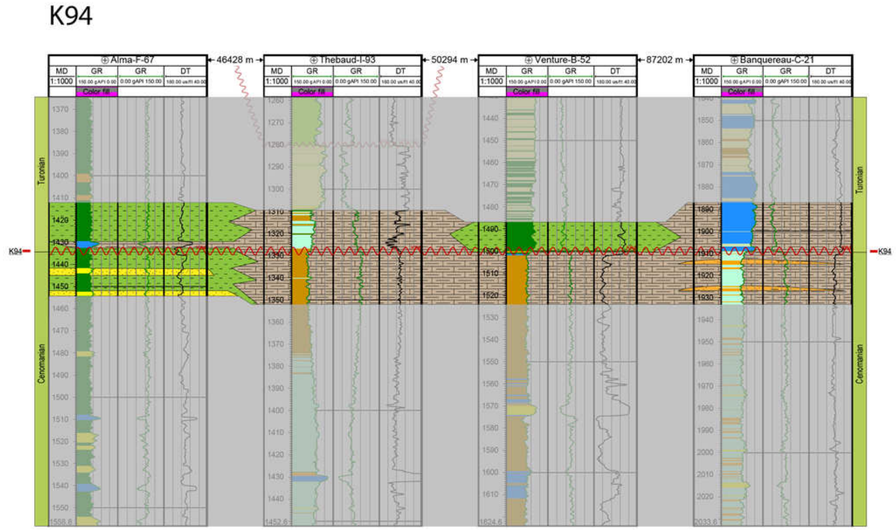
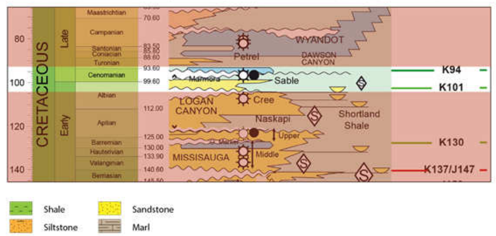
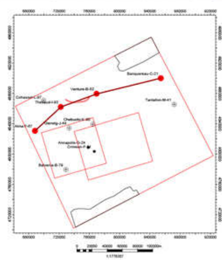


Figure 30: Well correlation on the shelf around the Cenomanian Unconformity marker (K 94). The section shows the predominance of marlstone and chalk marking the transition to the Petrel Mbr of the Dawson Fm.





Description

Upper Missisauga

The Upper Missisauga Mbr does not show marked differences from its two lower members except that it shows the transition to a tidal to marginal marine dominated environment of the Naskapi Mbr.

Logan Canyon Fm

Logan Canyon Fm spans the Aptian – Cenomanian interval. The formation has an upward fining trend similar to the Missisauga Fm. It has been subdivided into four members: Naskapi, Sable Shale, Cree and Marmora Mbrs. The **Naskapi** and **Sable Shale Mbrs** are shale dominated, whereas the **Cree** and **Marmora Mbrs** correspond to shallow marine sandstones representing alternatively transgressive and regressive facies (MacLean and Wade, 1993). The formation is generally interpreted to have been deposited in an estuarine and shallow marine clastic shelf environment during a long term transgression that extended from Aptian to Cenomanian, culminating during the Late Cretaceous. The end of the Logan Canyon Fm shows the appearance and regular increase of carbonate rich facies characterised by mudstone and chalk (Figure 30). The Logan Canyon eq. Fm grades distally to the **Shortland Shale**, a slope and deep water shale facies.

Cree Member

Cree Member is late Aptian – late Albian, predominantly sandy and consists of interbedded sandstones and shales with minor siltstones. The Cree Mbr corresponds to most of the middle Logan Canyon deposit in Sable Sub-basin.

Naskapi Member

Naskapi Member was deposited during the shift of the St. Lawrence proto-river to the Bay of Fundy. The member is characterized by a thick, dark brown to black shaly unit separating the top Upper Missisauga from the Cree Mbr.

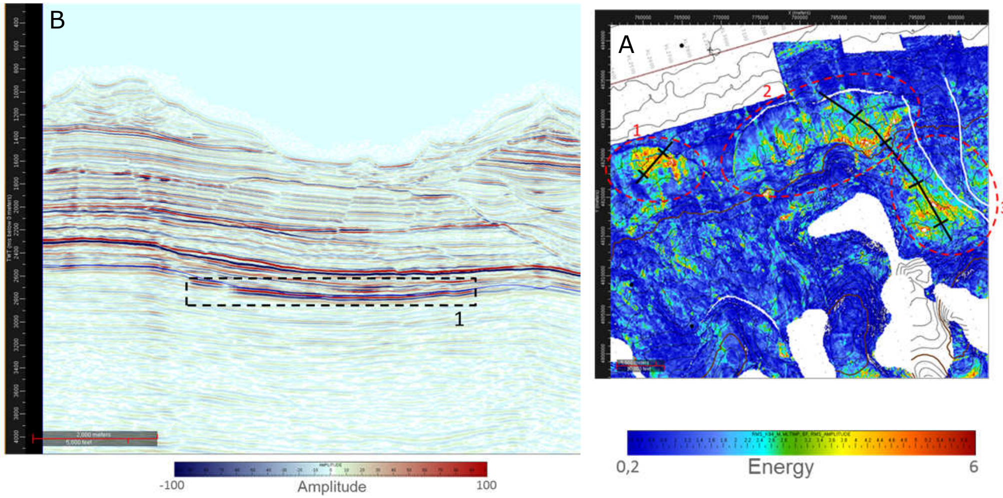


Figure 31: (a) RMS map calculated at K 94 on Marathon seismic (Figure from Chapter 5 PL. 5.9). Anomalies are bounded by listric faults; B: Section 1 showing the seismic amplitude anomaly associated with a turbidite deposit just off of the prograding wedge.

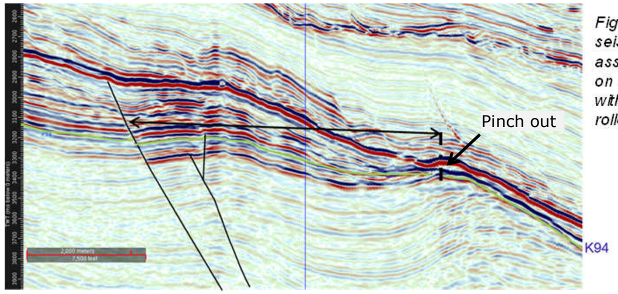


Figure 32: Section 2 showing the seismic amplitude anomaly associated with a turbidite deposit on the top of a rollover structure, with the pinch against the top of the rollover.

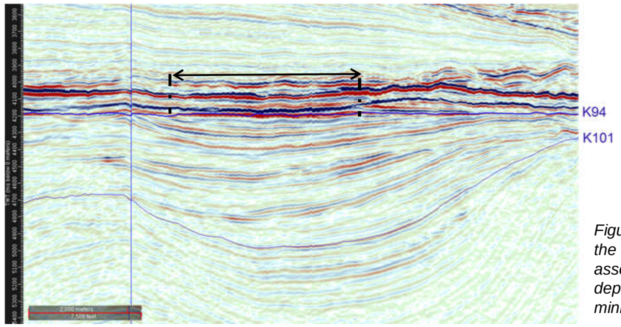


Figure 33: Section 3 showing the seismic amplitude anomaly associated with a turbidite deposit within the axial part of a mini basin.

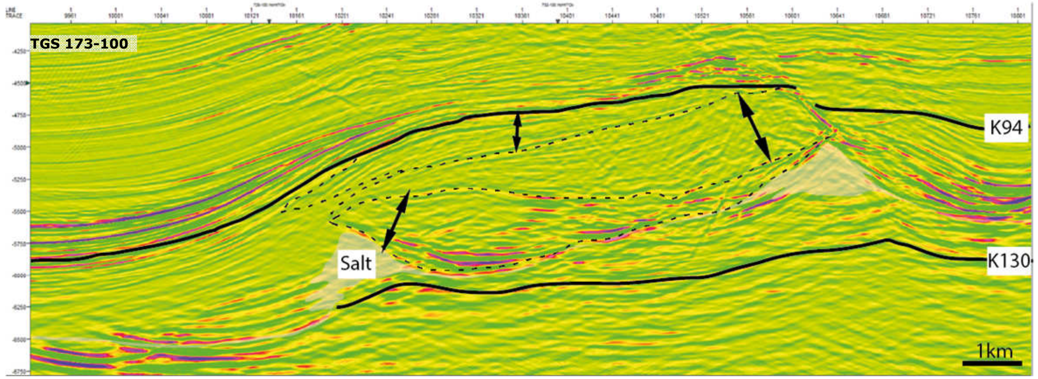


Figure 34: Seismic section illustrating salt movement and depocenter shift during the Missisauga and Logan Canyon intervals. Here the section shows an inverted mini basin. The interval clearly shows the lateral shift of depocenter illustrated by lateral variation of thickness. It is to be noted that the K101 is missing from this section, due either to a non deposition or intense erosion, in both cases related to salt tectonics.

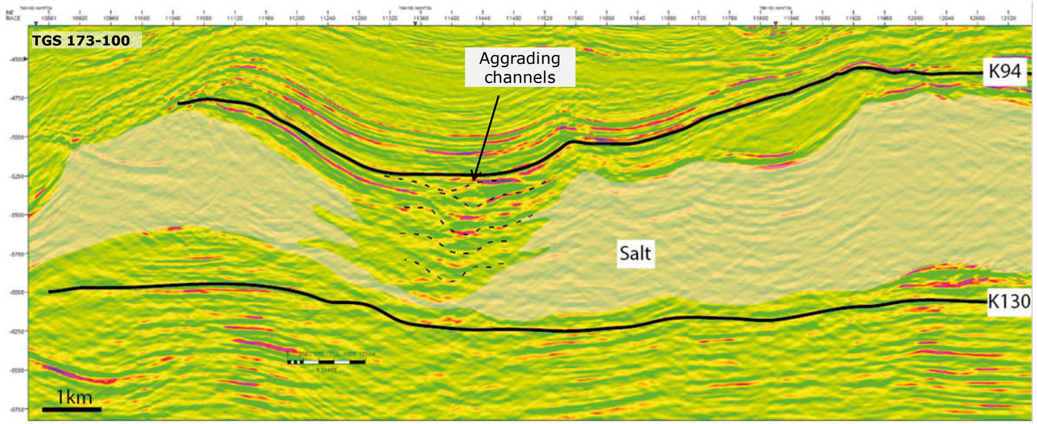
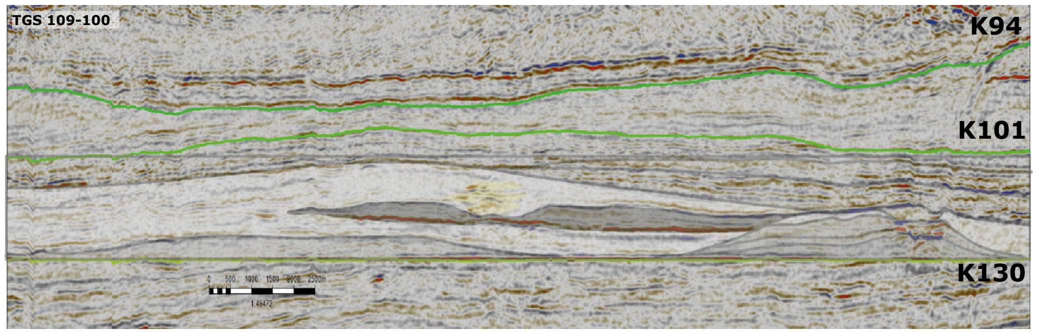


Figure 35: Seismic section showing evidence for sediment conduits to deep-water. Here is illustrated the presence of aggrading channels within a small mini basin on top of the salt canopy. It is to be noted that here again the K101 is absent.

Figure 36: Example of well developed turbidite lobes for the Missisauga and Logan period in the very distal part of the study area. Turbidite lobes are particularly well developed for the K130 – K101 interval.



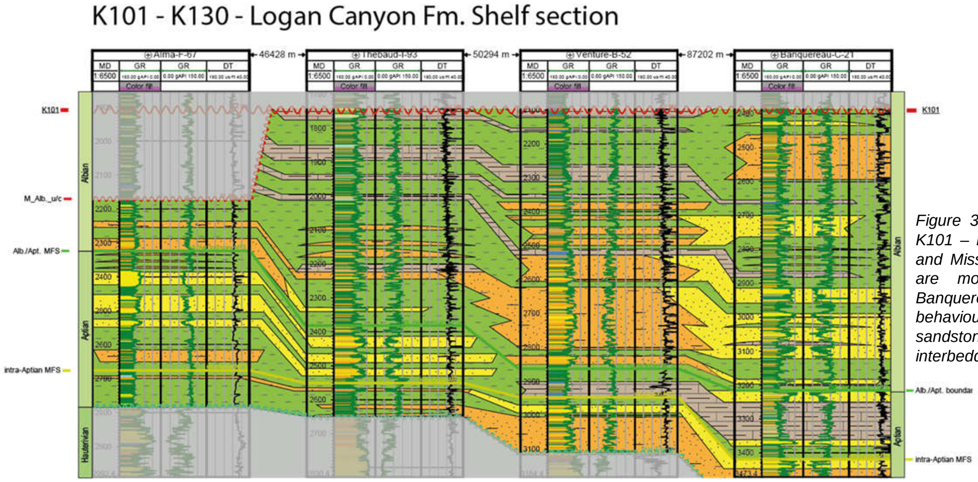
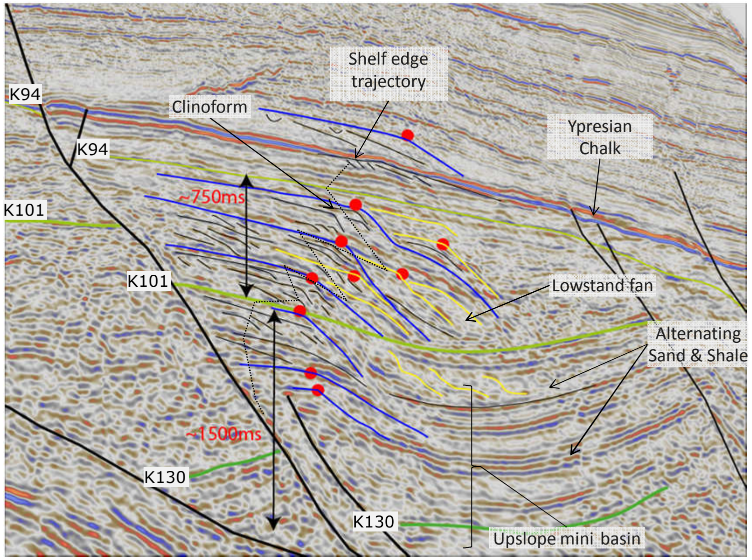
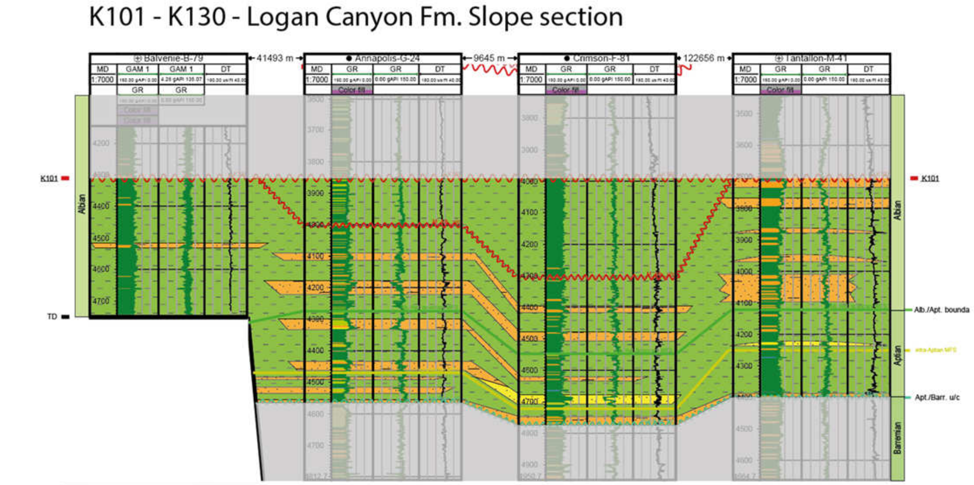
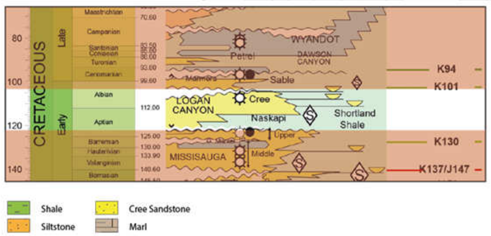


Figure 37: Well correlation on the shelf for the K101 – K130 interval. In contrast to the MicMac and Missisauga intervals, here sandstone layers are more represented in Alma F67 and Banquereau C21, suggesting a change in river behaviour and sediment input. Moreover, sandstone layers are less massive and interbedded with thick layers of shale.

Figure 39: (a) RMS map calculated at K94 on Marathon seismic showing 3 energy anomaly zones - (b) Seismic section on Marathon going through zone 1.







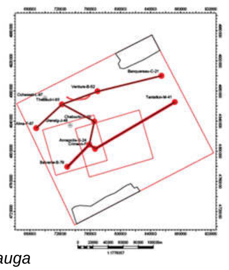


Figure 38: Wells correlation on a the slope for the K101 – K130 interval. As for the Missisauga interval, the wells are characterized by a largely shale dominated interval. The better correlation of siltstone layers between Annapolis G24 and Crimson F81 is to be noted.

CENOMANIAN TO EOCENE SEQUENCE K94-T50

Identication

- Number of exploration wells reaching the Late Cretaceous to Eocene Sequence: 4 wells (PL. 3.1.12, 3.2.1 to 3.2.5; Appendixes 1.4.2, 1.4.3, 1.4.6 and 1.4.8);
- Formations: **Dawson Canyon Fm; Petrel Mbr; Wyandot Fm;, Ypresian Chalk**;
- Age: Dawson Canyon (**Turonian to Campanian**), Wyandot (**Santonian-Maastrichtian**), Ypresian Chalk (**Base Eocene**);
- Regional top sequence: **Ypresian Unconformity (T50);**
- Chronostratigraphic cross-sections (PL 3.2.1, 3.2.3 and 3.2.5);
- Lithostratigraphic cross-sections (PL 3.2.2, 3.2.4 and 3.2.5);
- Architectural cross-sections (PL. 6.1.1 to 6.1.3).

Description

Dawson Canyon Formation and Petrel Mbr

Dawson Canyon Fm consists of thick marine shales interbedded with chalk and limestone layers near the early Turonian. The Formation is characterized by a series of limestone beds which correspond to the **Petrel Mbr** of the **Dawson Canyon Fm**. The Formation is found all across the Scotian Shelf, but the sequence of deposition appears to be diachronous (OETR, 2011). The Formation spans the Cenomanian to Santonian period. The **Petrel Mbr** is of Turonian age; its separation from the **Wyandot Fm** can be difficult as the Wyandot appears to be continuous with the **Petrel Mbr** in the eastern part of the margin. The **Wyandot Fm** is a distinctive unit on the margin composed predominantly of chalk, marls and chalky mudstones. On the shelf of the study area, the **Wyandot Fm** can be a reservoir as observed in Eagle D-21 well, for which the associated structure contains an estimated 1.3 Tcf (Smith et al., 2016).

Ypresian Chalk Formation

The Ypresian Chalk is an Early Eocene age formation. It is a widespread unit composed of chalk and corresponds to a regional transgressive episode.

Ypresian Unconformity (T50) and Montagnais Impact

The Ypresian Unconformity is a regional regressive event occurring at or near the base of the Ypresian Chalk (Weston et al., 2012) leading to massive erosion on the shelf and slope of the Scotian Basin (Wade and MacLean, 1990). The Montagnais marine bolide impact is coincident or close in timing to the Ypresian Unconformity (Deptuck and Campbell, 2012; Weston et al., 2012). The meteor impact led to a widespread margin collapse associated with intense erosion that drastically increased the impact of the Ypresian Unconformity on pre-existing sedimentary successions.

LATE EOCENE TO PRESENT SEQUENCES

Banquereau Fm

Sedimentary successions above the top Ypresian correspond to the Banquereau Formation. The sequence corresponds to a Tertiary succession of downlapping or prograding sequences. In more detail, the Banquereau Formation represents Plio-Quaternary progradational wedges consisting of over 1500m of glaciomarine and marine sediment. The Formation is thinner on the shelf and tends to be thicker towards the outer shelf and slope.

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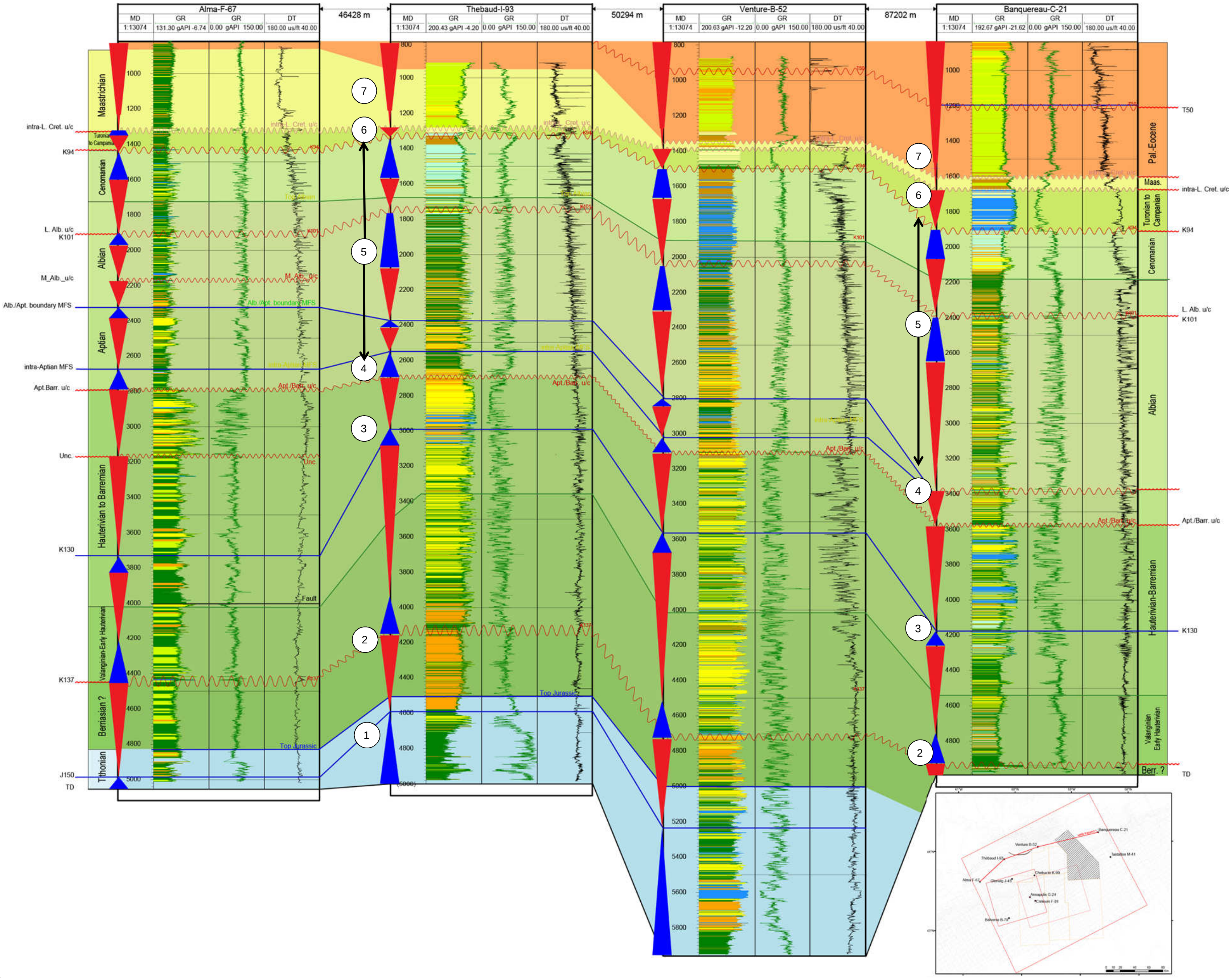
CHAPTER 3.2

STRATIGRAPHY
GEOLOGICAL CROSS SECTIONS



Hettangian-Valanginian Sequences (Sequences 1 and 2)

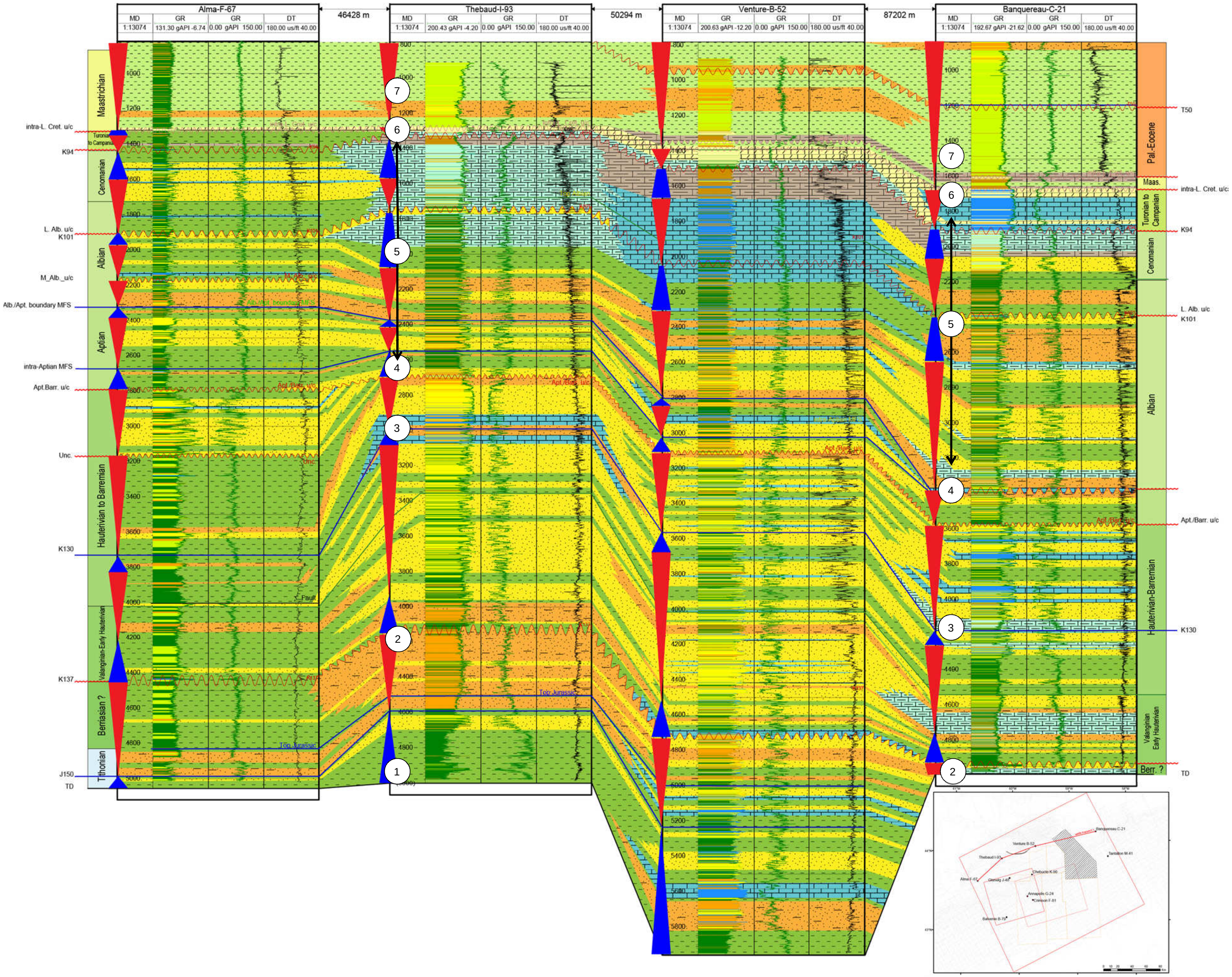
The oldest sediments within the wells are Tithonian to Kimmeridgian in age (Venture B-52) and correspond to the Lower Missisauga and termination of the Abenaki Fm. This period is marked by the predominance of clastic sediment over carbonate sediment. The top of the Late Jurassic deposits is eroded by the Berriasian-Valanginian Unconformity (BCU), recognized biostratigraphically across the margin.

Valanginian-Aptian Sequence (Sequence 3 to 5)

The BCU (K137) marks a shift in sedimentary environment with a major increase in sand content within the wells, which corresponds to the start of the Middle and Upper Missisauga successions. At this time the Sable River delta system was well developed and deposited a minimum of over 2000m of sediment within a 12 My window.

As seen in PL 3.1.10, the Sable River delta was a well developed meandering system and as a consequence rapid and significant lateral variation of facies is observed. Overall, thick sandstone accumulations are observed from Thebaud to Banquereau, but Alma remained more shaly until the upper Hauterivian. Sediment signature suggests that Thebaud and Venture are more axial to the sediment delivery system.

Deformation related to salt tectonics as well as successive erosive events had a significant impact on sediment preservation. For instance sediment preservation during the Missisauga was more important near Alma and decreased toward Banquereau. During the Aptian/Hauterivian Interval, sediment preservation was more important in Alma and Banquereau, highlighting a higher impact of the Aptian – Hauterivian Unconformity in Thebaud and Venture area.



Aptian-Cenomanian Sequence (Sequence 5)

Sequence 5 coincides with the deposition of the Logan Canyon Fm. The sedimentary environment changed to a more tide dominated environment with deposits evolving laterally from shoreface to estuarine or river mouth environment. The amount of shale ~~has~~ drastically increased compared to the Missisauga Fm, particularly toward the late Albian which sees an increase in mudstone and chalky sediments. In the Naskapi Mbr (Aptian), accumulation of sediment remained high, particularly during the Albian – Cenomanian. Overall in the wells, the Logan Canyon Fm recorded over 1500 m of sediment.

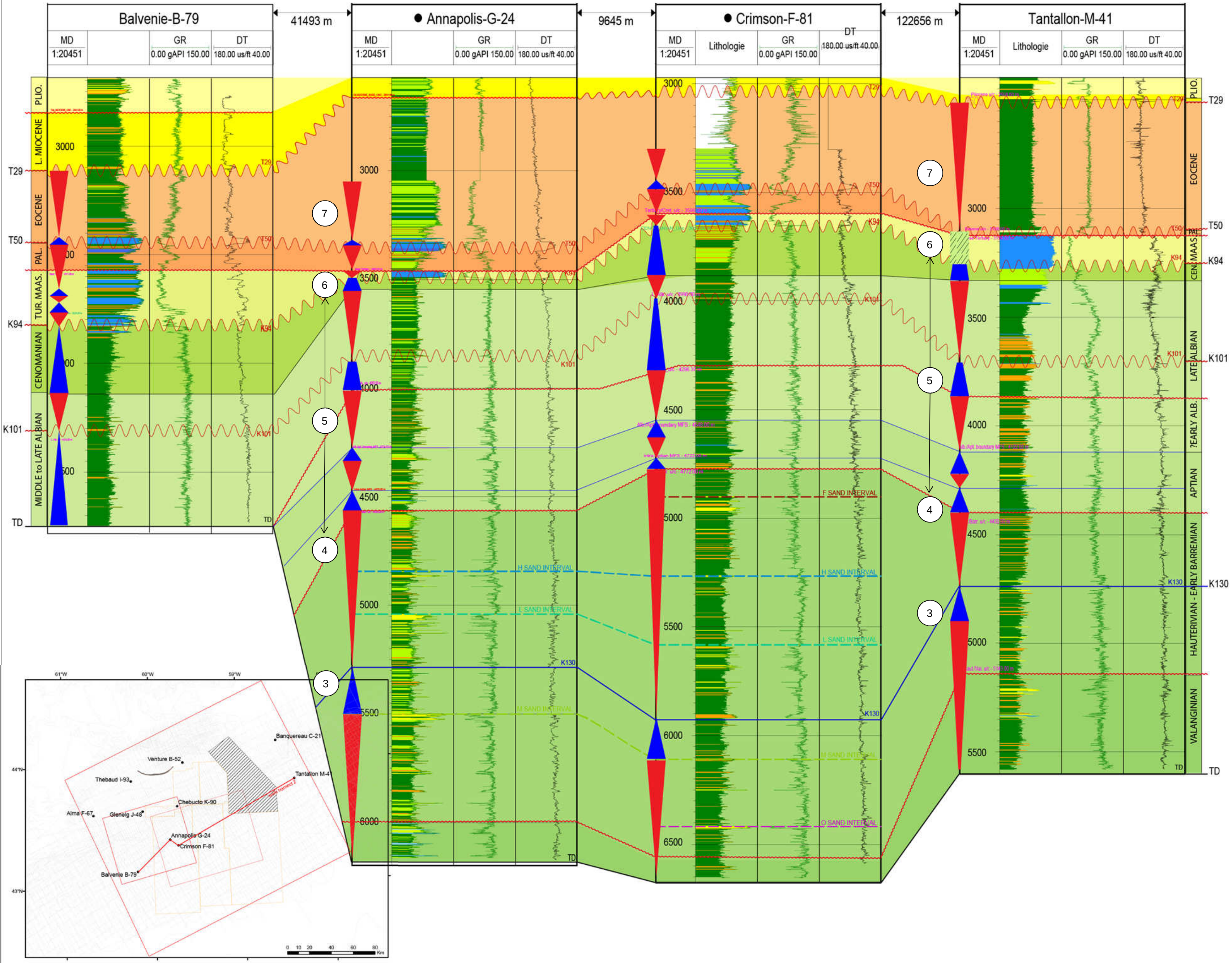
Sediment preservation is opposite to the Missisauga interval, with more preservation toward Banquereau and less toward Alma. Well correlations show a significant impact of the K101 with about 200 m of sediment missing in Alma compared to Banquereau. The Cenomanian Unconformity (K94) is recognized across the margin.

Turonian-Campanian Sequence (Sequence 6)

The Turonian-Campanian sequence is characterized by a marked reduction in siliciclastic influx and concomitant chalk sedimentation under deep, open-marine conditions. Pelagic carbonate sedimentation begins during the Turonian and extends across the margin during the Santonian. The upper part of the chalk formation is eroded by the intra Late Cretaceous unconformity.

Campanian-Ypresian Sequence (Sequence 7)

For two of the wells, sediment recovery stopped at the transition of between the Maastrichtian and Paleocene. Laterally the thickness of the Maastrichtian drastically decreased due to the impact of the base Tertiary unconformity. During the Tertiary, the former Sable River started to migrate northward toward what is now the St. Lawrence estuary. The shift is well illustrated by the impact of the Ypresian Unconformity which increases toward Banquereau.

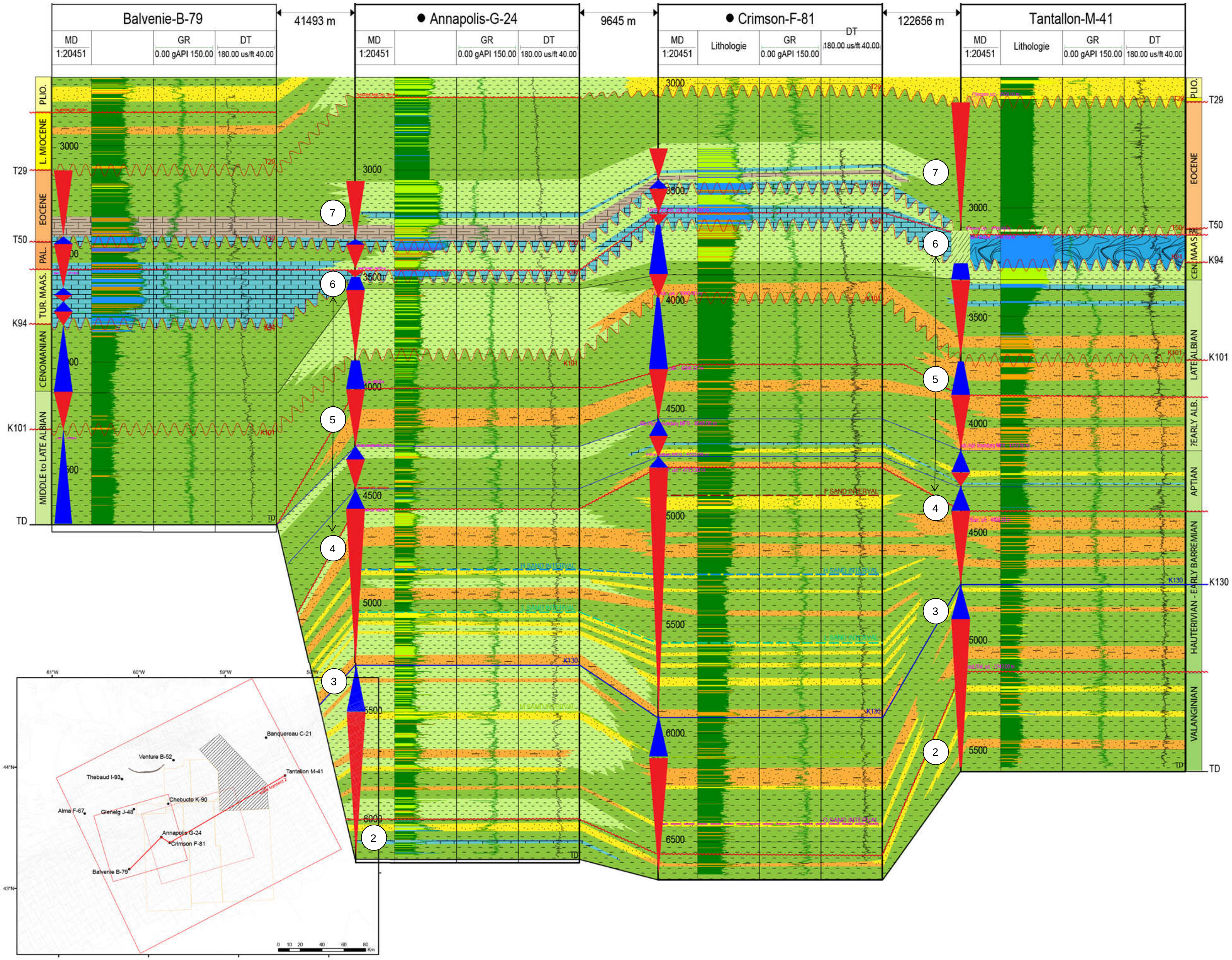


Valanginian-Aptian Sequence (Sequence 3 to 5)

In this transect the first sediments within the wells are Valanginian in age and correspond to the Middle and Upper Missisauga equivalent, i.e. the Verrill Canyon Fm. As for the shelf, this period is marked by the predominance of clastic sediment. Nonetheless the interval is shalier than on the shelf, with only a few thin layers of sandstone turdibites (the maximum thickness reaches 20m in Annapolis). Most of the sandy successions are observed within the Valanginian – Barremian interval. It's to be noted that gas is observed every time reservoirs are penetrated.

Sediment accumulation is quite thick for this 15 My window, with 1000 to 2000 m of preserved sediment recorded in the wells. Sediment accumulation/preservation is higher in Annapolis and Crimson wells, which are located downslope of the main clastic output.

Here more than on the shelf, deformation related to salt tectonics had a significant impact on sediment preservation and most importantly, on sediment distribution. Rapid lateral variation of thickness between Crimson and Annapolis, which are only 10 km apart but on different structures, highlights the impact of salt movement and related mini-basin migration.



Aptian-Cenomanian Sequence (Sequence 5)

Sequence 5 coincides with the deposition of the Logan Canyon Fm equivalent, i.e. the Shortland Shale Fm. The sedimentary environment remained the same as during the Missisauga, i.e. deep water. The amount of shale drastically increased compared to the Missisauga Fm, which echoes the sedimentary changes observed on the shelf at the same time.

Sediment accumulation remained high with about 800 to 1000 m of Shortland shale, compared to the 1500 m of Logan Canyon Fm deposited on the shelf. The overall sediment preservation is homogeneous, but in detail there is a lot of lateral variability in sediment thickness related to the successive erosion occurring at that time, particularly the K101.

The Late Albian saw an increase in shale and the appearance of mudstone and chalky sediments toward the Albian – Cenomanian transition. The Cenomanian Unconformity (K94) is also recognized here across the slopes of the margin.

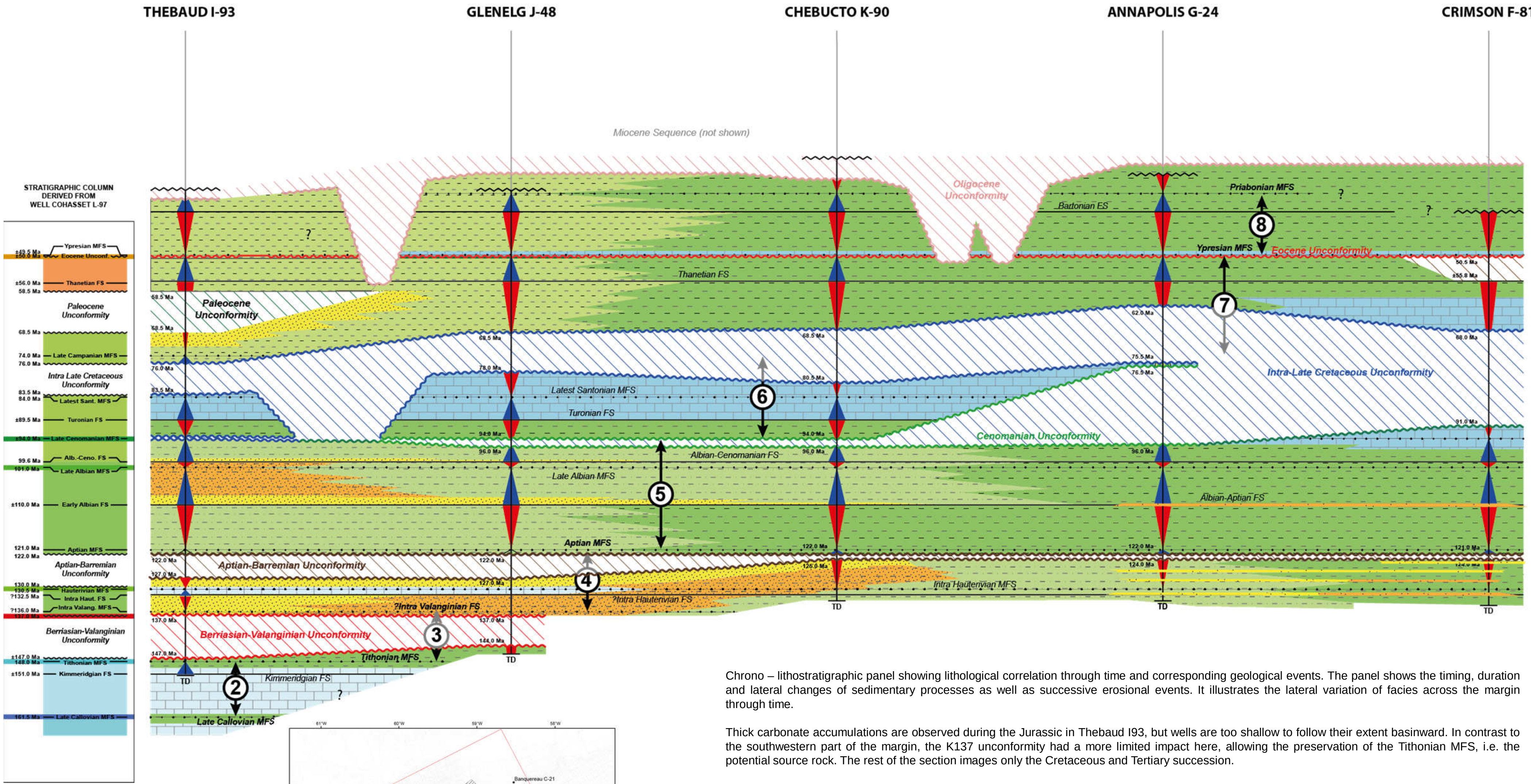
Turonian-Maastrichtian Sequence (Sequence 6)

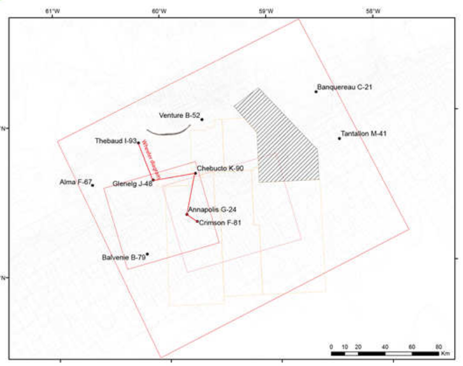
The Turonian-Campanian sequence is characterized by a well developed chalk unit. Pelagic carbonate sedimentation began during the Turonian and extended across the margin during the Santonian. The upper part of the chalk formation is eroded by the intra Late Cretaceous unconformity.

Maastrichtian-Ypresian Sequence (Sequence 7)

Paleocene sediments were strongly affected by the Ypresian Unconformity (T50). Laterally the thickness of the Maastrichtian decreased drastically due to the impact of the base Tertiary unconformity. In contrast to the shelf, Eocene sediments are better preserved in the area. During the Tertiary, the former Sable River started to migrate northward toward what is now the St. Lawrence estuary. Sands returned during the Pliocene

 GEOLOGICAL CROSS SECTIONS – SLOPE TRANSECT





Chrono – lithostratigraphic panel showing lithological correlation through time and corresponding geological events. The panel shows the timing, duration and lateral changes of sedimentary processes as well as successive erosional events. It illustrates the lateral variation of facies across the margin through time.

Thick carbonate accumulations are observed during the Jurassic in Thebaud I93, but wells are too shallow to follow their extent basinward. In contrast to the southwestern part of the margin, the K137 unconformity had a more limited impact here, allowing the preservation of the Tithonian MFS, i.e. the potential source rock. The rest of the section images only the Cretaceous and Tertiary succession.

The influx of clastic sediment was significant during the middle Missisauga (Valanginian – Barremian), but sand content quickly decreased towards the basin. Although the shelf was only a few kilometers away at the time of the deposition, and considering the good connection between the shelf and the slope, the transition between Chebucto and Annapolis is quite abrupt. It is perhaps surprising not to observe more sandstones in Annapolis and Chebucto wells. This raises the question about whether the sand is stored on the shelf or has bypassed the well locations. One of the obvious possibilities is that deep water wells have been mislocated and therefore are not representative of the sedimentary record on the slopes. Another possibility is that there may be a trapping system upslope between Chebucto and Annapolis created in response to active salt tectonic deformation occurring at that time. Structure maps and seismic attribute displays suggest that Annapolis was not located in the optimum sand fairway (see Chapter 6)
Well correlations indicate that the upper Cretaceous is not well preserved on a large portion of the central slopes, mostly due to the intra late Cretaceous erosional events. The K101 unconformity has less impact than the K94.