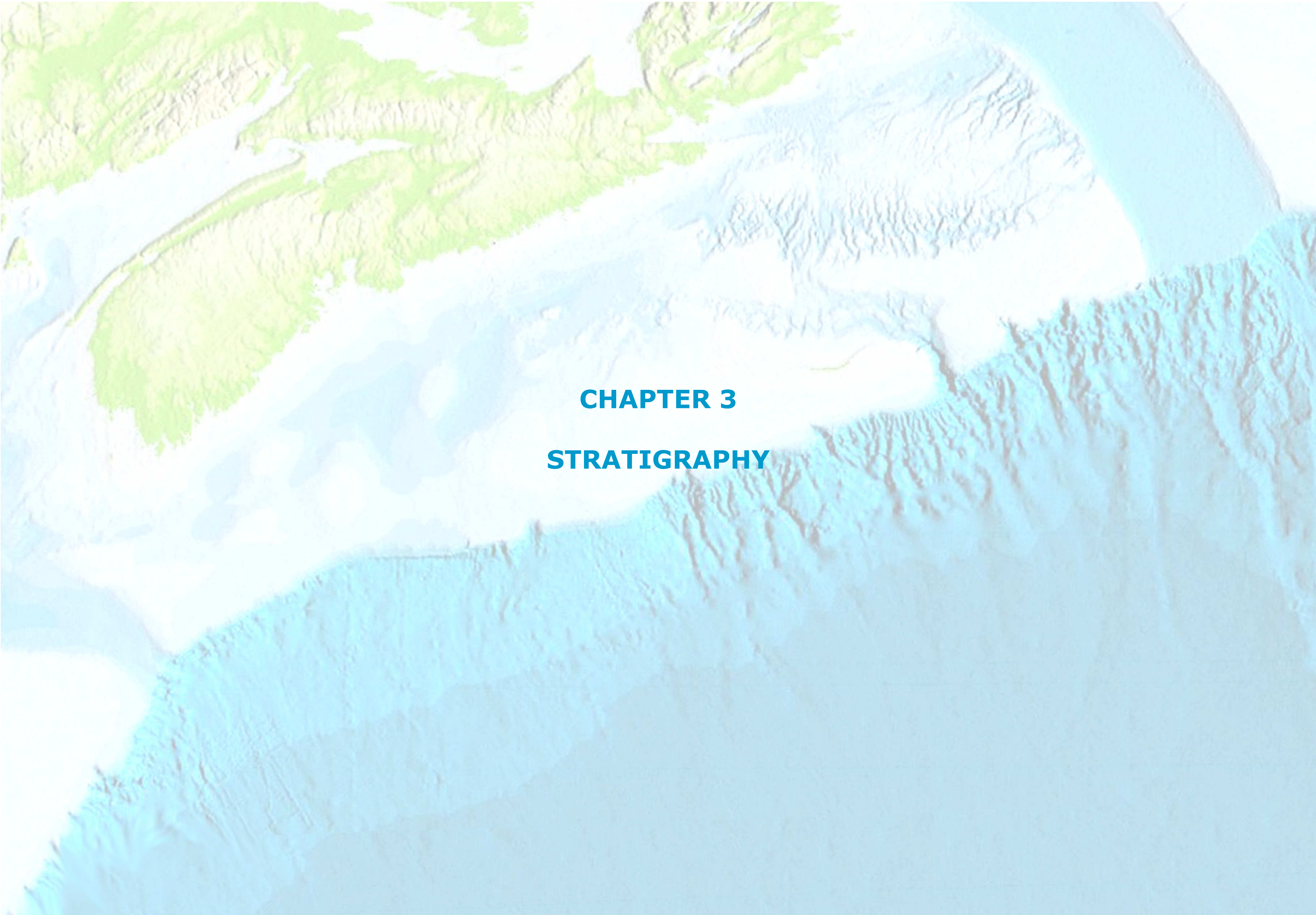


CHAPTER 3

STRATIGRAPHY

INTRODUCTION

Objectives

The objective of Chapter 3 is to extend the Mesozoic-Cenozoic stratigraphic framework of the South Scotian margin to Georges Bank Basin in order to better understand the Shelburne sub basin Petroleum system.

The study results are follows:

- A lithostratigraphic overview of the Shelburne sub basin based on facies and lithological interpretation, for 8 relevant stratigraphic surfaces delimited by 9 key seismic horizons
- A second order sequence stratigraphic breakdown for each well studied illustrating the major stratigraphic sequences (Plates 3.3.1 and 3.3.2; Enclosures 3.3 and 3.4)
- A stratigraphic and lithostratigraphic chart for the Shelburne Basin (PL 3.2.12 and Enclosures 3.7 and 3.8) adapted from the updated Scotian Margin stratigraphic chart presented in Figure 3
- A chronostratigraphic and lithostratigraphic interpretation of 2 key seismic transects

Well database and methodology

The well database consists of a selection of 3 key wells (Table 1 present study) distributed over Georges Bank and the southwestern Scotian shelf (Figure 1). These 3 wells are used as a basis for defining the lithostratigraphy and sequence stratigraphy of the Shelburne sub basin.

The geological composite well logs are presented in Enclosures 3.3 to 3.4. They display (1) a suite of logs (GR, NPHI curve, RHOB); (2) a lithological column; (3) biostratigraphic surfaces; (4) formation tops; (5) sequence stratigraphy breakdown and (6) depositional environments.

- *Wells Lithology and Petrophysics*

Lithological interpretation was performed on the 3 key wells and are shown in their respective composite log. For each well, lithologies are obtained from final well reports, excepted for Mohawk for which an electrofacies analysis was also performed. Such information includes qualitative log interpretations, mud reports, geological mud logs, existing composite well logs, and master logs.

Petrophysical analysis was run on Mohawk B93 only. 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*

New quantitative biostratigraphic analysis of the 3 key wells and Moheida P15 were carried out to support the sequence stratigraphy and seismic correlations across Shelburne sub basin.

Biostratigraphic interpretation for each well provides the timeframe and stratigraphic age references (datum) to construct the sequence stratigraphic breakdown as well as defining depositional environments.

- *Sequence stratigraphic breakdown and depositional environment in wells*

Sequence stratigraphic breakdown is performed on the 3 key wells based on biostratigraphic and lithological information. For each well, formation tops are identified from biostratigraphic dating. Between the main stratigraphic surfaces, depositional environments are obtained through combination of lithologies, log responses and biofacies. Resulting vertical stacking of depositional environments are interpreted in terms of balance between Accommodation and Sedimentation (A/S ratio). The A/S ratio controls and reflects the stratigraphic architecture and spatial distribution of sediments through time. Increasing A/S implies landward movement of the shoreline (retrogradation); decreasing A/S implies seaward shift of the shoreline (progradation). The surface separation between retrogradation and progradation is called Maximum Flooding Surface (MFS). The surface separation between progradation and retrogradation is called Flooding Surface (FS).

Up to 5 second order stratigraphic sequences, with average duration of 3-15 Ma, are defined from Middle Jurassic to late Oligocene.

Obtained 2nd order sequences are propagated at the Shelburne sub basin scale through seismic mapping and wells correlation.

- *Wells correlation*

In order to provide a broad picture of the Shelburne petroleum system, 2 wells from the 2011 PFA were added to the correlation. These wells are used to constrain the stratigraphic and lithostratigraphic correlations across the margin.

Content

Chapter 3 includes the following:

- A Lithologic and stratigraphic overview of Shelburne sub basin supported by an updated stratigraphic Chart of the Scotian Margin (Figures 3 and 7). This overview sets up the stratigraphic framework that will be used in the current PFA.
- A summary of the Biostratigraphy that calibrates formation tops and their integration into the stratigraphic chart (Table 2 to 5; Plates 3.1.1 and 3.1.2)
- 2 well correlation panels that illustrate the vertical and lateral variation of sedimentary facies and depositional environment through time (Figure 15; PL 3.3.1 and 3.3.2)
- 2 Chronostratigraphic and lithostratigraphic sections in time that shows the impact of geological events on sequences thickness and spatial distribution of depositional sequences (Plates 3.2.12, 3.3.1 and 3.3.2)
- 2 key seismic transects interpreted in term of Seismic Stratigraphy (Plates 3.4.1 to 3.4.3) showing the 2D geometry of the full sedimentary system and successive depositional sequences in response to geological events.

WELL	Geographic Coordinates		Company	TD (MD)	WD (M)	Formation at TD	Target	Year	Oil Shows	Comments	Study
	Latitude	Longitude									
Mohawk B93	42° 42' 10.716" N	64° 43' 53.04" W	Shell	2126	117	Basement	Anticlinal structure	1972	No show	Dry well	Present Study
Bonnet P23	45° 15' 04.79" N	54° 23' 16.85" W	Petro-Canada	4336	133.5	Iroquois	Mohican and Mohawk Fms	1984	No Show	Dry Well	
Cost G2	40° 50' 11.41" N	67° 30' 29.784" W	Consortium	6642	83	Iroquois	Lower Jurassic	1977	N/A	Stratigraphic well	
Glooscap C63	43° 12' 9.83" N	62° 09' 56.75" W	Husky Bow Valley et al	4542	99	Argo Salt		1984	Gas Show Top Cree	Dry well	PFA 2011 Updated 2015
Moheida P-15	43° 04' 56.32" N	62° 16' 44.33" W	Petro-Canada	4298	29.9	Eurydice		1977		Dry well	

Table 1: Selected wells for the stratigraphic framework study : 3 key wells (Mohawk B93, Bonnet P23, Cost G2) and 2 additional wells from the 2011 PFA study

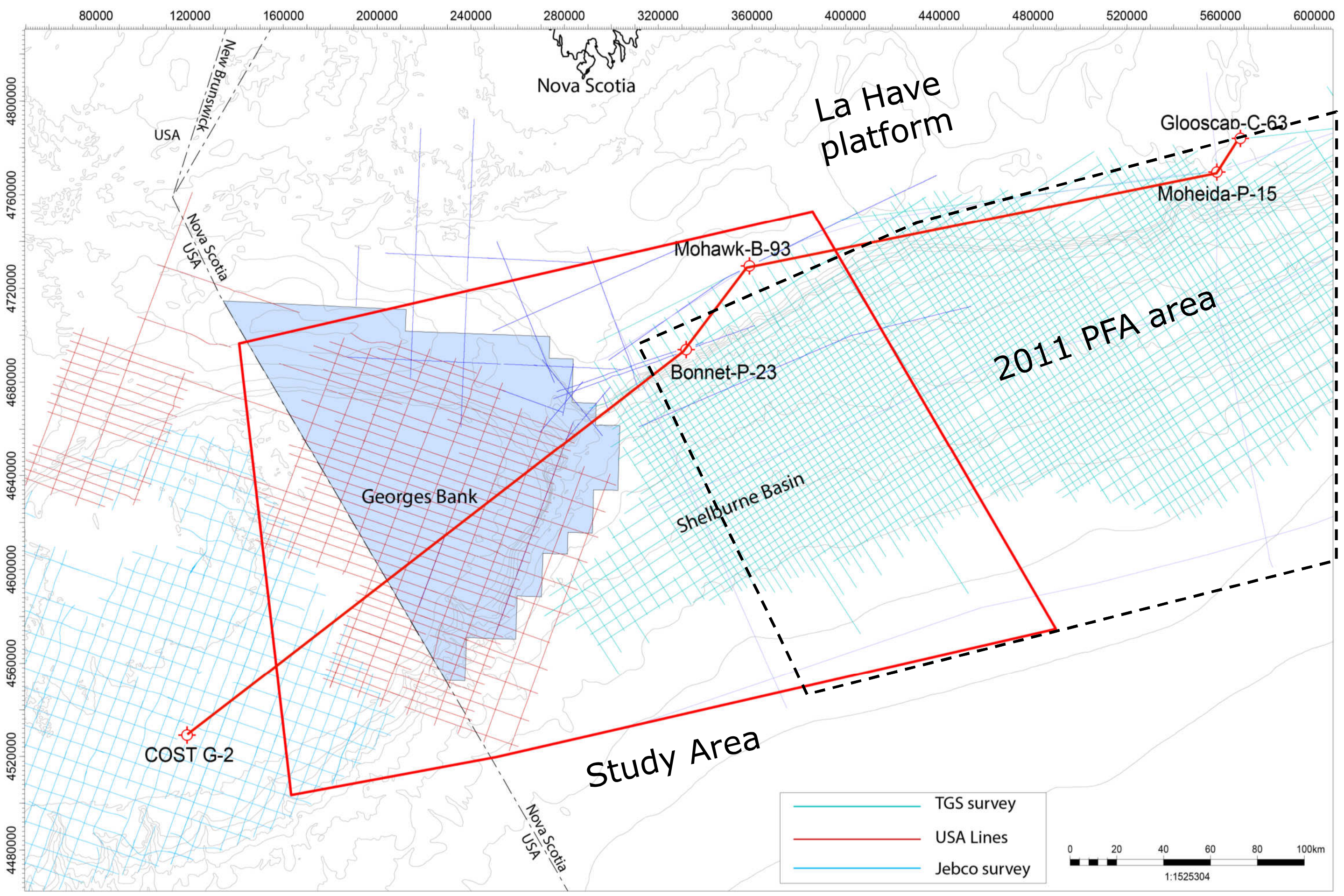


*Figure 1: Wells and correlation transect location across the **Shelburne subbasin***

CHAPTER 3.1

BIOSTRATIGRAPHY

This chapter summarizes the results of new biostratigraphic studies of 2 wells from the southern Scotian Margin (Moheida P-15 and Mohawk B-93), plus COST G-2 (a stratigraphic test section) from the Georges Bank Basin. This updates a biostratigraphic study of the Moheida P-15 well included within the 2011 PFA with new analyses. The current biostratigraphy study was designed to calibrate the seismic mapping of the Shelburne Basin on the South Scotian Margin. The results from the new wells have been correlated to, and form an extension of, the study published previously from the Scotian Margin (A Revised Biostratigraphic and Well-log Sequence Stratigraphic Framework for the Scotian Margin, offshore eastern Canada; Weston *et al*., 2012)*. The interpretations have been correlated with two main wells from the 2011 PFA; Bonnet P-23 and Glooscap C-63. For well locations, see Figure 1, Stratigraphy – Introduction.

Numerical ages reference Gradstein *et al.* (2005) to be compatible with the 2011 PFA study. The new samples analysed biostratigraphically and the disciplines of the biostratigraphic data reviewed are outlined in Table 2 and a fuller summary of all results of the study is included in Annexe 1. Summary charts showing the stratigraphic breakdowns of the 3 new wells are provided in Annexe 1 as Enclosures 3.1.1, 3.1.4 and 3.1.8, while the stratigraphies are summarized in Table 3. Range charts showing the biostratigraphic data derived from new analyses are included in Annexe 1 as Enclosures 3.1.2 – 3.1.3 (Moheida P15) and 3.1.5 – 3.1.7 (Mohawk B-93). A report detailing the biostratigraphic results from the core samples analysed from COST G-2 is also included in Annexe 1.

The biostratigraphic data interpreted from the 3 new wells comprise pre-existing data of various vintages, supplemented by targeted new analyses in Moheida P-15 and COST G-2 and a more extensive analysis programme in Mohawk B-93 (see Table 2). Data comprised:
• internal GSCA data and reports, mainly consisting of 'top' occurrences of palynological and micropalaeontological species (all three wells);
• industrial reports on Moheida P-15 and Mohawk B-93 that sometimes include data in the form of range charts (e.g. Moheida P-15 palynology);
• various published biostratigraphic and geological studies of the COST G-2 well from the 1980's and early 1990's;
• new quantitative analyses undertaken for this project (see Table 2).

Within the Scotian Margin PFA (2011), 8 major surfaces were recognised biostratigraphically that could be tied seismically (Weston *et al*., 2012). The seismic horizons and the biostratigraphically recognised surfaces that are closely associated with them are (from top to bottom):
• T29 (Intra-Oligocene Unconformity)
• T50 (Ypresian Unconformity)
• K94 (Turonian/Cenomanian Unconformity)
• K101 (Late Albian Unconformity)
• K130 (Intra-Hauterivian MFS)
• K137 (Near Base Cretaceous Unconformity)
• J150 (Tithonian MFS)
• J163 (close to Base Callovian MFS)

Within this study, only sediments of Turonian and older age were analysed/reviewed in the new wells. Table 4 shows the depths of the major Cretaceous-Jurassic surfaces, where recognised, within each of the well sections, plus other regional biostratigraphically distinct surfaces from the 2011 PFA and a later extension of the PFA into the Laurentian Basin to the northeast. These surfaces are highlighted on the Stratigraphic Summary Logs for each of the wells (see Enclosures 3.1.1, 3.1.4 and 3.1.8 in Annexe 1).

Key results of the study of **Moheida P-15** are:
• Better stratigraphic resolution of the Early Cretaceous to Middle Jurassic section;
• The positions of major well-log sequence stratigraphic surfaces were generally confirmed, but some surfaces were found to have been previously picked either too low (i.e. Intra-Hauterivian MFS; K130) or too high (i.e . Top Callovian MFS);
• Positions for a Middle Albian Unconformity and the Base Callovian MFS were interpreted;
• Samples from the top of the Iroquois Formation (Core 3) were proven to be marine and no older than Middle Jurassic (Late Bajocian);
• The surfaces recognized showed excellent seismic correlation to the biostratigraphically-constrained seismic surfaces in Glooscap C-63.

Key results of the study of **Mohawk B-93** are:
• Accurate stratigraphic subdivision of the 'mid' Cretaceous to Jurassic section (see Table 3);
• Major truncation of the Cretaceous section beneath the Late Albian Unconformity (K101);
• Stratigraphic subdivision of the Early Cretaceous carbonates of the Roseway Formation, including tentative recognition of the Intra-Hauterivian MFS (K130);
• Recognition of a major stratigraphic break across the Near Base Cretaceous Unconformity (K137), where sediments of Early Valanginian to 'mid' Tithonian age are absent (including the major Tithonian MFS, J150);
• Recognition of a highly condensed interval of greenish, more argillaceous sediments between 1926m and 1932m that appears to represent both the Top Callovian MFS and the Base Callovian MFS (close to J163);
• Recognition at 2058m of the Bathonian MFS, a surface defined in the Laurentian Basin study and correlated to the Bathonian/Bajocian MFS tentatively identified in Cohasset L-97 from the 2011 PFA;
• The base of the section overlying basement in this well is Late Bathonian;
• The surfaces recognized fitted well against the seismically predicted picks derived from correlation to Bonnet P-23.

*Weston *et al.* 2012. A revised biostratigraphic and well-log sequence stratigraphic framework for the Scotian Margin, offshore eastern Canada. *Can J. Earth Sci.*, vol. 49, p. 1417-1462 + supplementary data.

Well Name	Samples Analysed			Biostratigraphic Data Reviewed	Interval
Scotian Shelf	**Micropalaeo**	**Nannopalaeo**	**Palynology**		
Bonnet P-23 (PFA 2011)	(66)	(66)	(66)	M, P	530-3945m
Glooscap C-63 (PFA 2011)	(138)	(138)	(146)	P	520-4520m
Moheida P-15	**0**	**25**	**5 (core 3)**	M, P	**1572-4298m**
Mohawk B-93	**58**	**59**	**59**	M, N, P	**975-2109m**
Georges Bank					
COST G-2	**6 TS (cores 2-6)**	**5 (cores 2-4)**	**24 (cores 1-9)**	M, N, P	**646-21,285ft**
Corsair Canyon 975-1	**0**	**0**	**1 (core 1)**	P	**11,143-14,155ft**

M = micropalaeontology
N = Nannofossils
P = Palynology
(66) Analyses for 2011 PFA

Table 2: *Table showing number of new samples analysed in the present study and disciplines of the biostratigraphic data reviewed for each of the wells. Numbers in parentheses represent samples analysed for the original 2011 PFA*

Moheida P-15	
Depth (m)	**Age**
1572-1645	Middle to Early Cenomanian
1645-2382	Albian to Aptian undifferentiated
2382-2629	Hauterivian to Valanginian
2629-3389	Tithonian to ?Oxfordian
3389-3642	Callovian to Late Bathonian
3642-3749	Middle Jurassic, no older than Late Bajocian
3749-4298	Indeterminate, Jurassic to ?Late Triassic

Mohawk B-93	
Depth (m)	**Age**
975-1040	Middle to Early Turonian
1040-1158	Cenomanian
1158-1324	Late Albian
1324-1340	Early Aptian
1340-1402	Barremian
1402-1573	Hauterivian
1573-1635	Valanginian
1635-1872	Early Tithonian to Kimmeridgian
1872-1908	Kimmeridgian to Callovian
1908-1944.5	Callovian
1944.5-2109	Late Bathonian

COST G-2	
Depth (m)	**Age**
646-677	Turonian
677-710	Cenomanian
710-1194.5	Albian or Aptian/Barremian
1194.5-1678	Hauterivian to ?Valanginian
1678-1814	Berriasian to Tithonian
1942-3109	Kimmeridgian to ?Oxfordian
3109-3350	Early Oxfordian to Callovian
3350-3444	Callovian
3444-3601	Callovian to Late Bathonian
3601-3614	Bathonian
3614-4034	Bathonian to Bajocian
4034-4442	Bajocian to Middle Aalenian
4442-5707	?No older than Toarcian
5707-6264	Indeterminate, ?Jurassic
6264-6488	Middle to Early Jurassic, ?Hettangian
6488-6648	Indeterminate

Corsair Canyon 975-1	
Depth (m)	**Age**
4311-4314	'Mid' Cretaceous to Jurassic, no older than Toarcian

Unconformity surfaces

Table 3: Summaries of the stratigraphic breakdowns of the 4 wells with new data in this study

Event Depth (m)	Bonnet P-23	Glooscap C-63	Moheida P-15	Mohawk B-93	COST G-2
Turonian/Cenomanian Unc. (K94)	Truncated beneath Eocene Unc.	1322	NR	?1040	?677
Late Albian Unc. (K101)	Truncated beneath Eocene Unc.	1712	2047	1324	NR
Albian/Aptian boundary MFS	NR	2098	NR	Truncated beneath L. Alb. Unc.	NR
Intra-Aptian MFS	NR	2192	2348	1336	NR
Aptian/Barremian Unc.	NR	2240	2382	1340	NR
Intra-Hauterivian MFS (K130)	?1903	2403	2437.5	?1404	?1267
Near Base Cretaceous Unc. (K137)	2065	2561	2629	1635	?1678
Tithonian MFS (J150)	Truncated beneath Unc.	2587	2688	Truncated beneath Unc.	1784
Base Tithonian MFS	NR	2805	?2852	1666.5	NR
Top Callovian MFS	3491	?3334	?3437	1926	?3104
Base Callovian MFS (J163)	?3712	?3538	?3584	1932	NR
Bathonian MFS (J166)	NR	NR	NR	2058	?3602
Top Basement	NP	NP	NP	2112	NP

NR = Not Recognised
NP = Not Penetrated

Table 4: Surfaces recognised in the 5 wells shown in Figure 1 from the South Scotian Margin and Georges Bank. Seismic horizon numbers are given in parentheses for relevant surfaces and key seismic surfaces are highlighted blue.

Published biostratigraphic data from the **COST G-2** well showed significant disagreements between the various disciplines and authors. In the Cretaceous section of this well, this has lead to the relatively broad stratigraphic breakdown provided within Table 3 and the recognition of relatively few Cretaceous well-log sequence stratigraphic surfaces (Table 4). Below 8750ft (2670m), there were 9 cores taken from the COST G-2 well, which are stored at the Delaware Geological Survey, USA. New sampling of all the cores, targeting optimal lithofacies for biostratigraphic recovery, was therefore undertaken as a part of this study. The published Late to Middle Jurassic ages of samples from cores 1-4 were less contentious, but samples from cores 5-9 had been variably dated as Middle to Early Jurassic or Triassic. The results of these new analyses are discussed in a report included within Annexe 1; they imply that the lower part of the COST G-2 well comprises a thick sequence of Jurassic dolomitic/evaporitic sediments overlying the salt penetrated at the base of the section.

The biostratigraphic data reviewed and the new samples analysed from the COST G-2 well enabled recognition of:
- a section ranging in age from Turonian to Middle/Early Jurassic (?Hettangian);
- unlike in some published biostratigraphic reports, no biostratigraphic evidence was recovered to suggest the presence of Triassic palynomorphs within cores 5-9 of the COST G-2 well section;
- 6 potential biostratigraphically constrained surfaces were defined, 4 of which represent key seismic surfaces for correlation to the Scotian Margin;
- Sediments from core 1 (2670-2673m) are Late Jurassic;
- Sediments from cores 2-5 (3350-4444m) are Middle Jurassic;
- Sediments from core 6 (5701-5712m) are Middle to Early Jurassic, no older than late Early Jurassic (Toarcian);
- Sediments from cores 7 and 8 (6260-6488m) are Middle to Early Jurassic and possibly Hettangian;
- Deposition was in a shallow marine setting down to at least core 6 (5712m); a coastal depositional setting is envisaged for cores 7 and 8 (6260-6488m);
- Possible unconformity surfaces within the Middle to Early Jurassic are suggested by changes in palynofloral preservation and composition between cored intervals (see Figure 2). The unconformities are suggested to be at around 4150m and 6095m, based on wireline log criteria.

While sampling the COST G-2 cores in the Delaware Geological Survey, a single composite sample from core 1 (14143-14155ft; 4311-4314m) in the **Corsair Canyon 975-1** well from the Georges Bank Basin to the northwest of the COST G-2 well was also collected. This core lies beneath halite beds in an interval that had previously been dated as Late Triassic. This salt appeared on seismic data to lie within much younger strata than the salt penetrated at the base of the COST G-2 well. Although palynological recovery was poor from this single core sample, marker taxa recorded indicate an age no older than late Early Jurassic (Toarcian) , while the overall assemblage is similar to those derived from core 6 in the COST G-2 well. This implies that this higher salt in the Corsair Canyon 975-1 well is probably Middle to late Early Jurassic in age and correlative to a part of the section characterized by dolomitic/anhydritic sediments in COST G-2. Details of this analysis are provided within the report on the COST G-2 core samples included within Annexe 1.

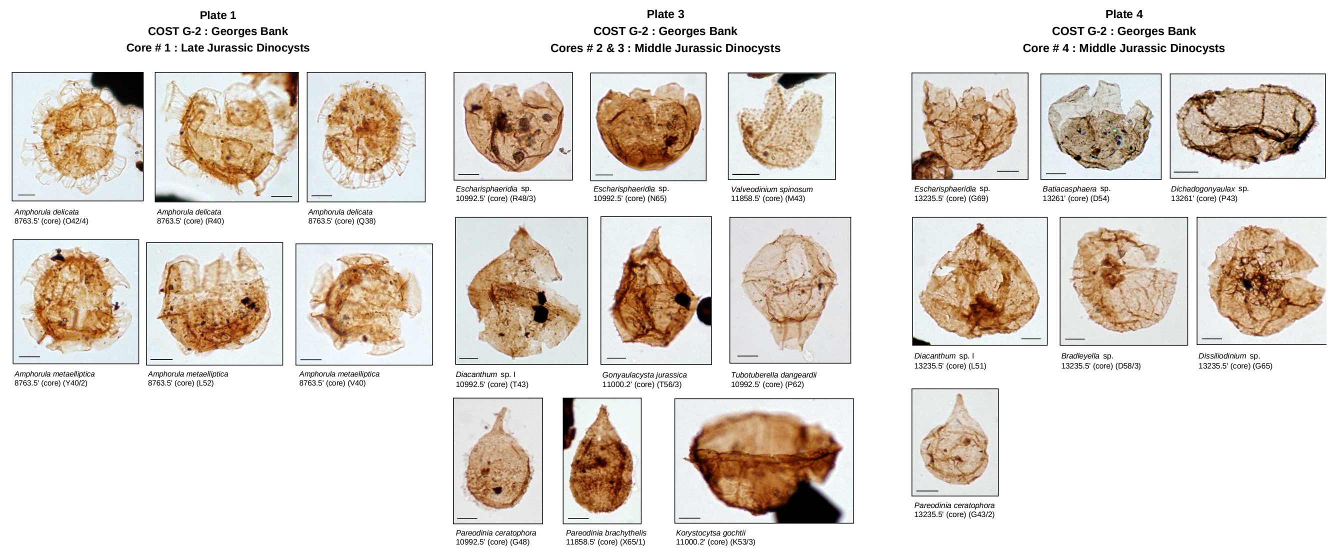
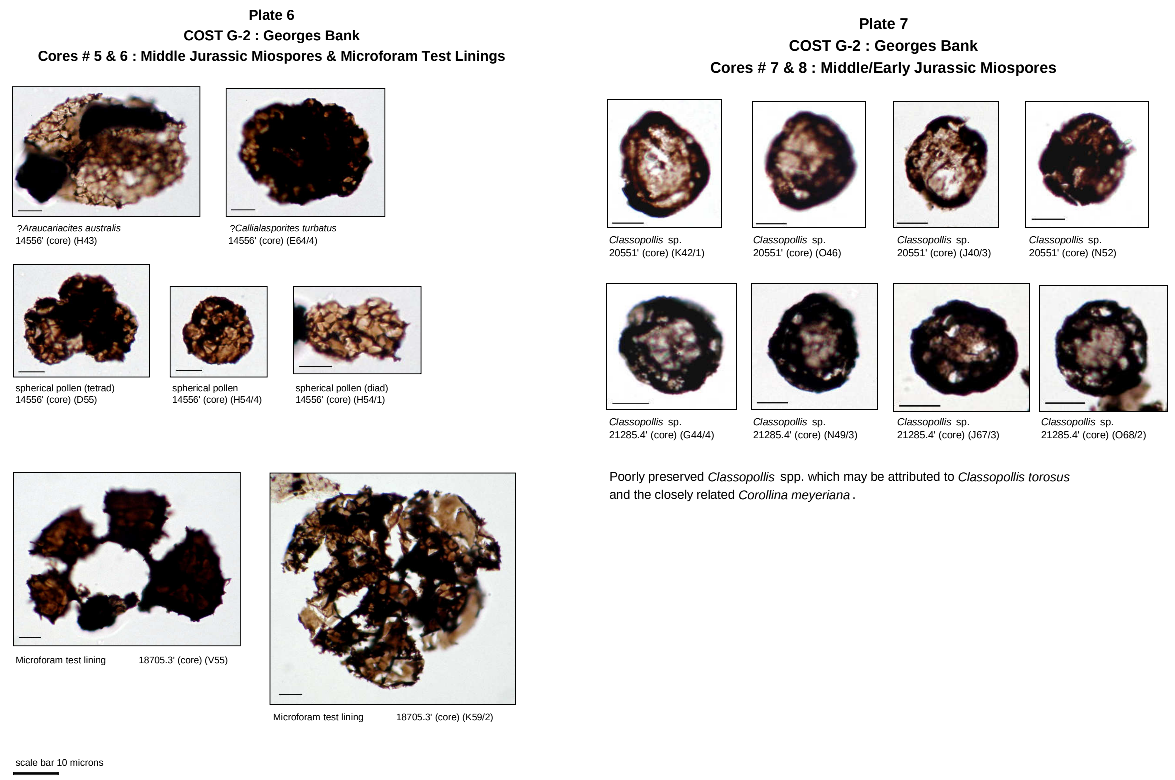
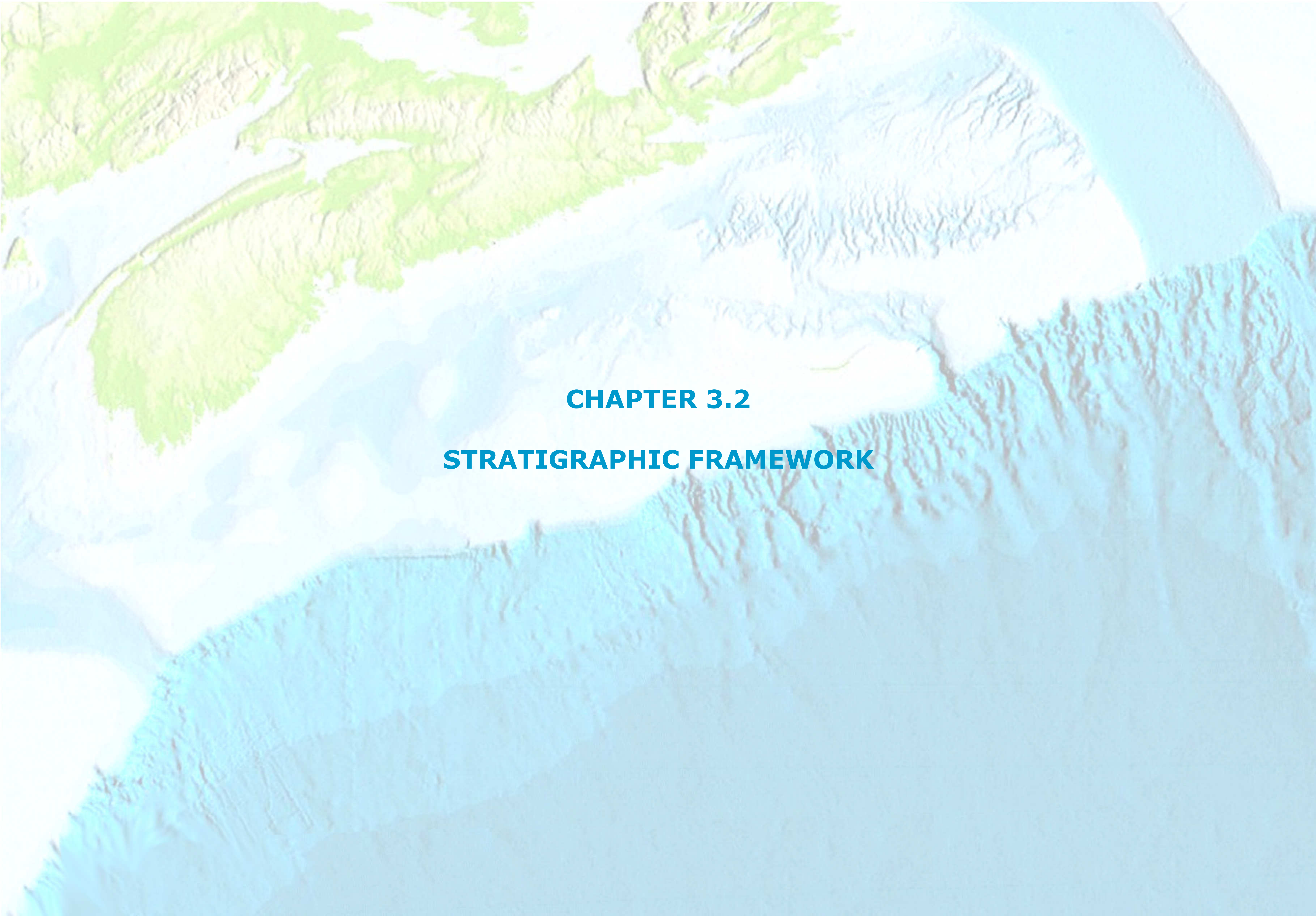


Figure 2: Significant change in palynofloral preservation and composition between cores 4 and 5 suggests the presence of a significant intra-Middle Jurassic stratigraphic break within the COST G-2 section (possibly c.4150m at the top of the evaporitic section). Further change in palynofloral composition between cores 6 and 7 suggests the position of another significant intra-Jurassic stratigraphic break (possibly c.6095m).





CHAPTER 3.2

STRATIGRAPHIC FRAMEWORK

Regional Geology and Stratigraphic framework overview

The Shelburne subbasin is an offshore basin bordered by La Have Platform and Georges Bank subbasin (Figure 1). It is a subdivision of the southwestern part of the Scotian margin which is a classic passive volcanic margin. Its history spans the last 250 million years with continuous sedimentation from the initial opening of the Atlantic Ocean to recent post-glacial history. The Shelburne subbasin covers an area of a little bit less than 100,000 km^2 and contain up to 15 kilometers of sediments in places. The subbasin is fed clastic sediment by a large drainage system located on the northeastern flank of the Appalachian Orogeny extending from Massachusetts to New Brunswick. The exact size of the drainage system and organisation of related tributaries are not known, nonetheless shelf and deep water sedimentary records show that it provided a continuous supply of sediments that accumulated in a number of complex, interconnected subbasins. Early synrift, fluvial-deltaic-lacustrine carbonate margin and deep water depositional systems are all represented in the stratigraphic succession (Figures 3 and 4).

PRE-RIFT

The southwestern Scotian Basin developed after the break-up of Pangea when North America rifted and separated from the African continent (see Plates in Chapter 2). It consists of a series of alternating horst and Graben, or platforms and depocentres. From the southwest to the northeast they are named Yarmouth Arch, Georges Bank subbasin, Shelburne Subbasin, Mohawk Ridge, Mohican subbasin, and LaHave Platform (Plate 1.1).

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 asserted a strong control on sediment distribution in the region for more than 250 million years.

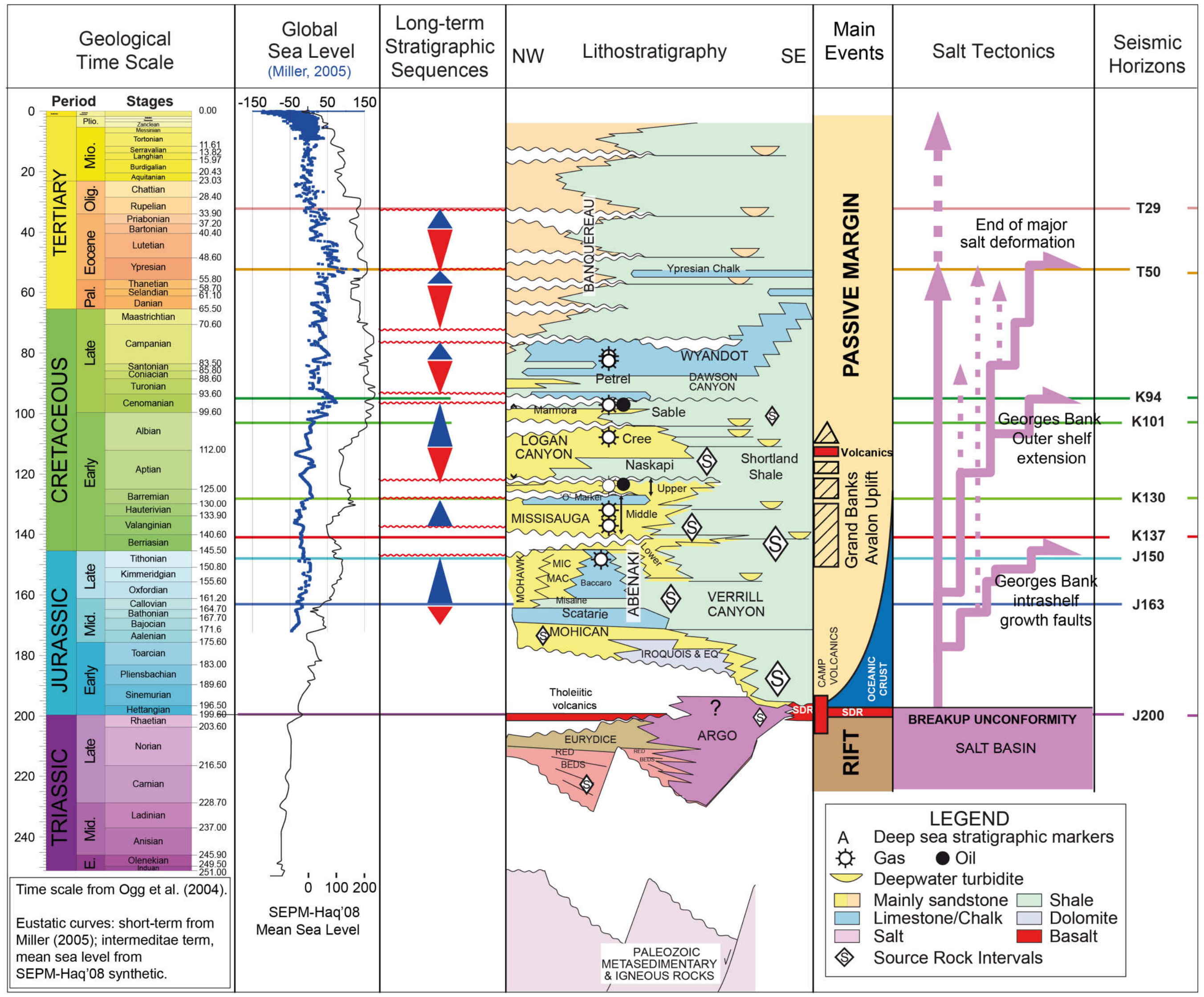
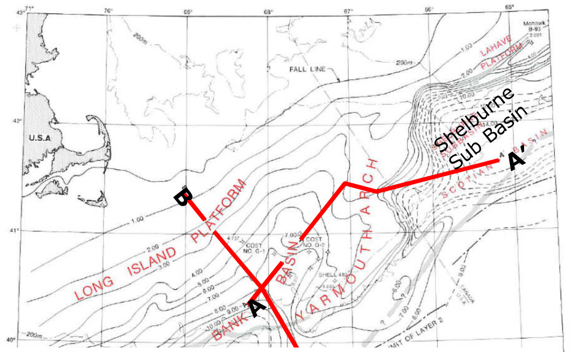
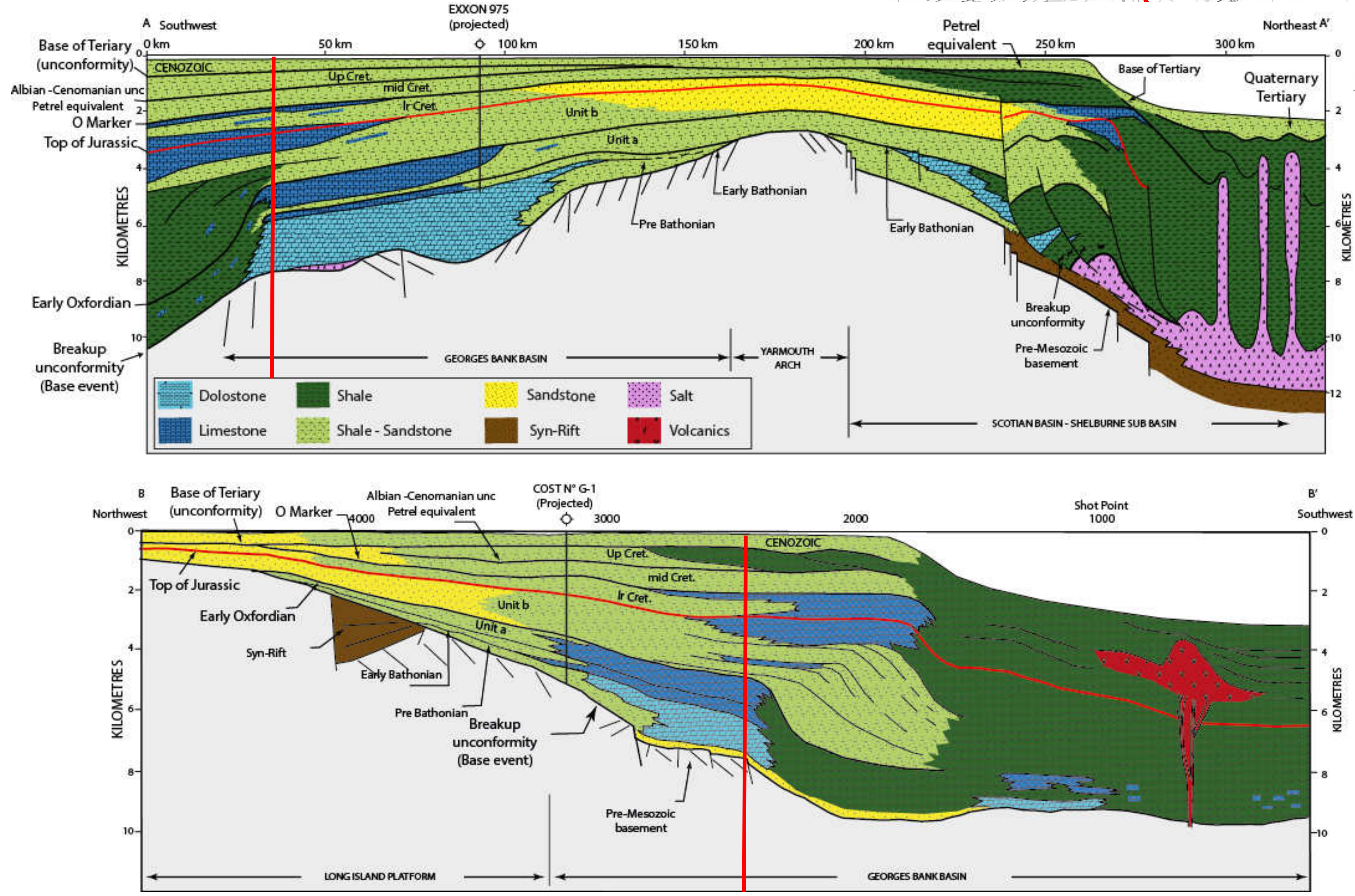


Figure 3: Updated Stratigraphic chart for southwestern Scotian Basin, Offshore Nova Scotia (Updated from 2011 and 2014 PFA project)

Figure 4: Geological cross-section showing stratigraphic relationship. A: A-A' Cross-section from Georges Bank Basin to the Scotian Basin.; B: Cross-section B-B' on Georges Bank Basin. (Modified from Wade and MacLean, 1990)





SYN-RIFT

Red beds and evaporites were the dominant deposits during the late pre-rift phase (Wade and MacLean, 1990) (Figure 3A and B).

Rifting began in the middle-early Late Triassic Period, about 250 – 225 million years ago (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. At 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; Figures 3, 4 and 5). 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 two kilometers thick in the central parts of the rift system (Argo Formation; Figures 4 and 5).

An late Triassic phase of siliciclastic deposition is observed along Georges Bank and Mohican Graben. This eastward-directed pulse of red bed sediments conformably overlies and deforms the Argo salt (Pl. 2.10 & 2.9). Grabens formed during the rifting acted as loci for clastic deposition for newly established fluvial drainage systems (Figure 4).

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 (BU), 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 BU, the heavily faulted, complex terrane of grabens and basement highs along the Scotian margin underwent a significant degree on peneplanation.

EARLY POST-RIFT

Marine transgression occurring after the Break up unconformity (**J200 maker**), led to the development of a shallow and restricted sea within which thin sequences of carbonate and clastic sediments accumulated. By late Early Jurassic, tidally influenced dolomites and clastics formed in localized areas under slightly restricted marine conditions (**Iroquois Formation**). In the mean time a thick succession of coarse grained clastic sediments and shales from fluvial sources is deposited on the margins (**Mohican Formation**). Clastic sediments were provided by adjacent terranes and started to infill the grabens. Basement highs were buried by the early Middle Jurassic (Wade and MacLean, 1990) (Figures 4 and 5). The deep water part of the basin was infilled with marine mud that blanketed newly formed oceanic crust.

The combination of sea-floor spreading, basin subsidence and global sea level rise caused the Atlantic Ocean to become broader and deeper (~1000 m) by the Middle Jurassic. Prominent carbonate banks developed on Georges Bank and La Have platform (Figures 4 and 5) and persisted until late Jurassic – early Cretaceous. 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, 4 and 5) which can be subdivided into 3 members:

- **Scatarie Member** correspond to 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** resulted from the continuing margin subsidence coupled with global sea level rise. During this time interval, the carbonates and clastic sediments on the shelf were blanketed by transgressive marine shales.
- **Baccaro Member** formed during the late-Middle to late Jurassic. The succession corresponds to carbonate reef, bank and platform environments formed along the basin hinge line on LaHave Platform and Georges Bank subbasin.

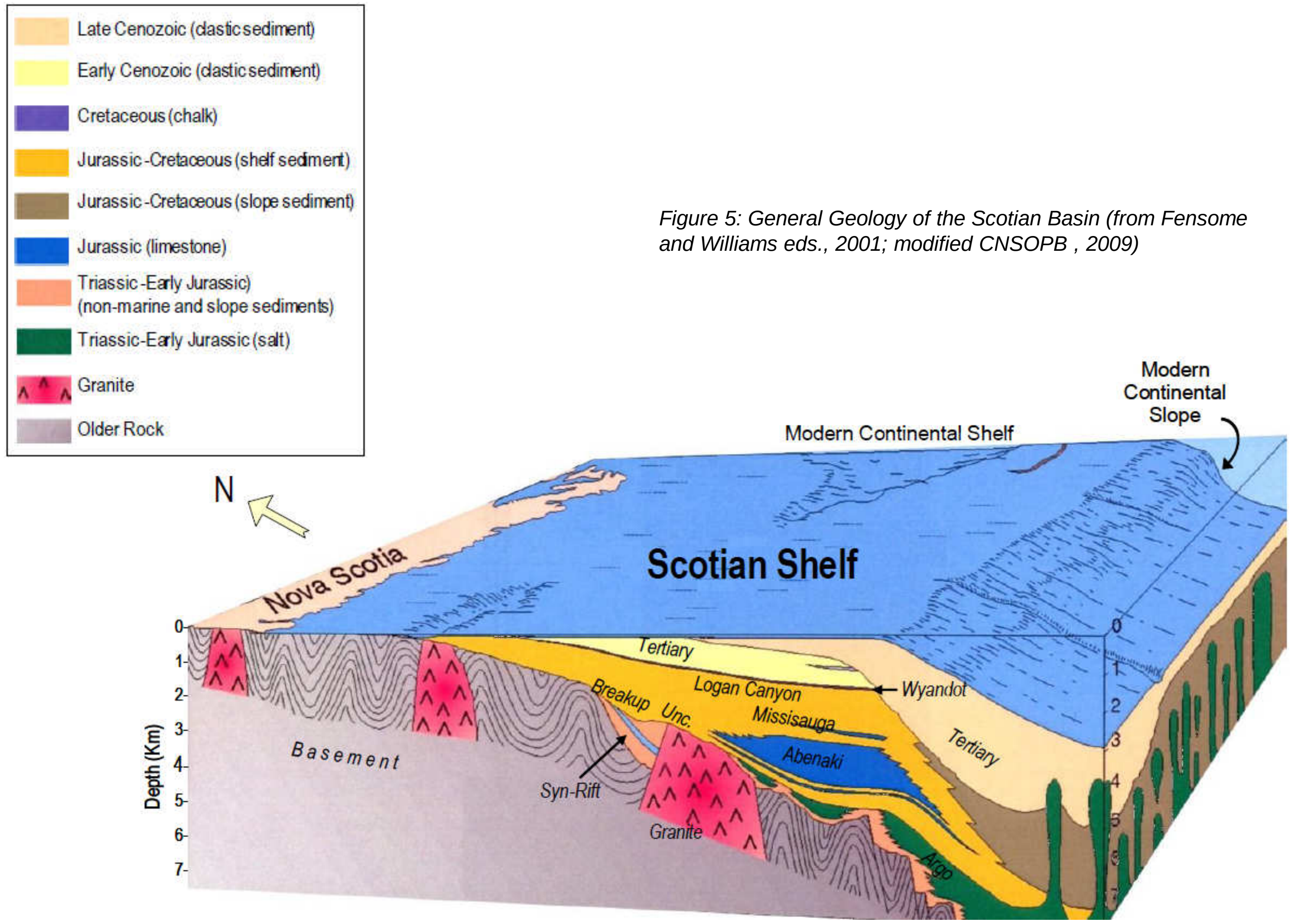


Figure 5: General Geology of the Scotian Basin (from Fensome and Williams eds., 2001; modified CNSOPB , 2009)

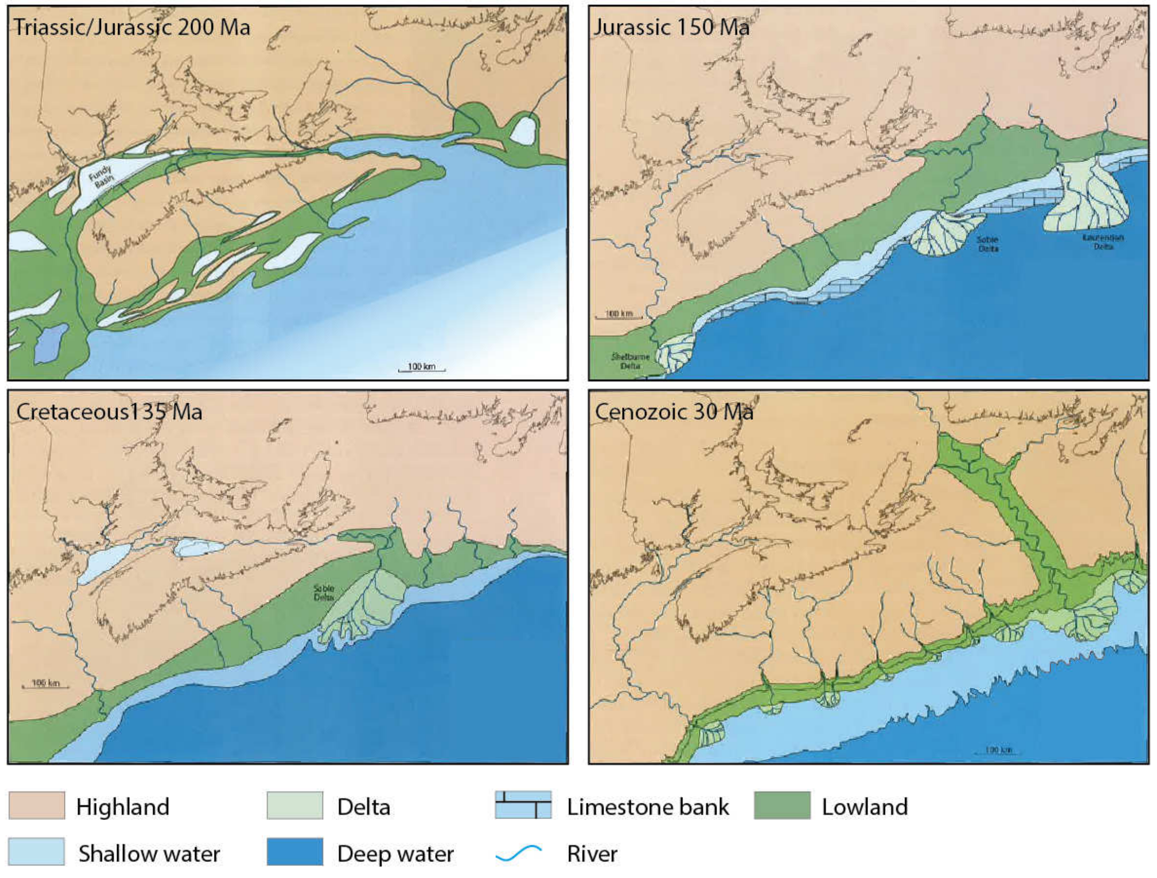


Figure 6: Regional Paleogeography of the Maritime for the last 200 million years (adapted from Fensome and Williams eds., 2001)

LATE POST RIFT

The **Late Jurassic (Oxfordian – Tithonian)** sees the establishment of large clastic sedimentary system, for instance the Sable Delta complex in the Huron and Laurentian Sub-basins, and slightly later in the Sable Sub-basin, as well as the Shelburne Delta In the southwest at the vicinity of the U.S.-Canada border (Figure 6). These sediments were primarily sourced from the adjacent Silurian to Permian sediments that covered the entire Atlantic Provinces region and parts of New England (Pe-Piper & Piper, 2004; Pe-Piper & MacKay, 2006). This first phase of delta progradation correspond to the **Mic-Mac Formation and equivalent** (Figure 3**).** 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** (Figure 3). During the **Middle Jurassic and Cretaceous** the sediments load on the shelf edge and slopes accentuate the subsidence and also mobilized the salt creating a complex slope morphology (e.g. Kidston et al., 2002; Shimeld, 2004) analogous to other basins with mobile salt substrates (e.g. Gulf of Mexico). Shelf and slope deformation are associated with the development of seaward-dipping growth faults (see Chapter 7-2). This time interval also coincide with the beginning of a regional uplift related to one or more significant thermal anomalies (Bowman et al., 2012; Pe-Piper et al., 2015). This uplift phase ***induces*** an increase of sediment supply leading to the development of significant deltas along the coast. Around the late Hauterivian – late Cenomanian time, the uplift induce a rerouting of the Laurentian channel to the South through the Bay of Fundy which lead to a massive input of sediment into the Shelburne Basin (Li et al., 2012; Stradhee, 2012; Figures 13 and 17). The overall Increases of sediment load during the Late Jurassic and early Cretaceous accentuated salt mobility leading to the formation of diapirs, pillows, canopies and related salt features. During periods of low sea level, extant rivers incised exposed outer shelf sediments and formed shelf-edge delta complexes (Cummings & Arnott, 2005; 2006). Such deltas supplied turbidity currents and mass transport deposits to the slope generating potential reservoirs in canyons and intra-slope and salt mini basins (Pl. 5.3.1.4 to 5.3.1.6).

In the **early Cretaceous** the ancestral St. Lawrence River was well established, and so was the unnamed river feeding the Shelburne Delta (Figure 6). Increases of clastic sediment supply into the Scotian Basin overwhelmed and buried the carbonate reefs and banks from Georges Bank to the Banquereau Platform. A series of thick sand-rich deltaic strand plain, carbonate shoals and shallow marine shelf successions dominated the sedimentation throughout the Early Cretaceous (**Missisauga Formation and equivalent**; Figures 3 and 5). The Sable Delta prograded rapidly southwest into the Laurentian, Huron and Sable Sub-basins and over the Banquereau Platform, while in the Shelburne Sub-basin the Shelburne Delta continued into Barremian time (Figure 6). Along the La Have Platform, small local rivers draining from southwest Nova Scotia mainland provided modest amounts of sands and shales to this region (Figure 6). In the **late Early Cretaceous** a major marine transgression called the **Aptian MFS** was followed by a drastic decreases of deltaic sedimentation replaced by thick marine shales corresponding to the **Naskapi Member of the Logan Canyon Formation** (Figure 3 and 5). Transgressive shales were periodically interrupted by influx of coarse clastic sediment in the **Albian-Cenomanian** (**Cree and Marmora Members of the Logan Canyon Formation**; Wade and MacLean, 1990; Figures 5 and 6). The sand was deposited along a broad costal plain and shallow shelf. During the **Turonian- Santonian** sediment supply decreased from the lower relief hinterland and the sand was replaced by deeper water marine shales and some limestones corresponding to the **Dawson Canyon Formation** (Figure 3.). The **Late Cretaceous** was characterized by a significant relative sea level rise related to basin subsidence. During this period, the Scotian Basin recorded marine marls and chalks of the **Wyandot Formation** (Figure 3 and 5).

These strata are overlaid by **Tertiary** marine mudstones and sandstones corresponding to the **Banquereau Formation** (Figure 3 and 5). Several major unconformities related to relative sea level falls occurred throughout the **Tertiary**,. Shelf and slope sediments were reworked during lowstand periods and transported into deep water slopes and abyssal plain (Figures 5 and 6). During the **Quaternary** several hundred meters of glacio-marine sediments were deposited across the Scotian Basin.

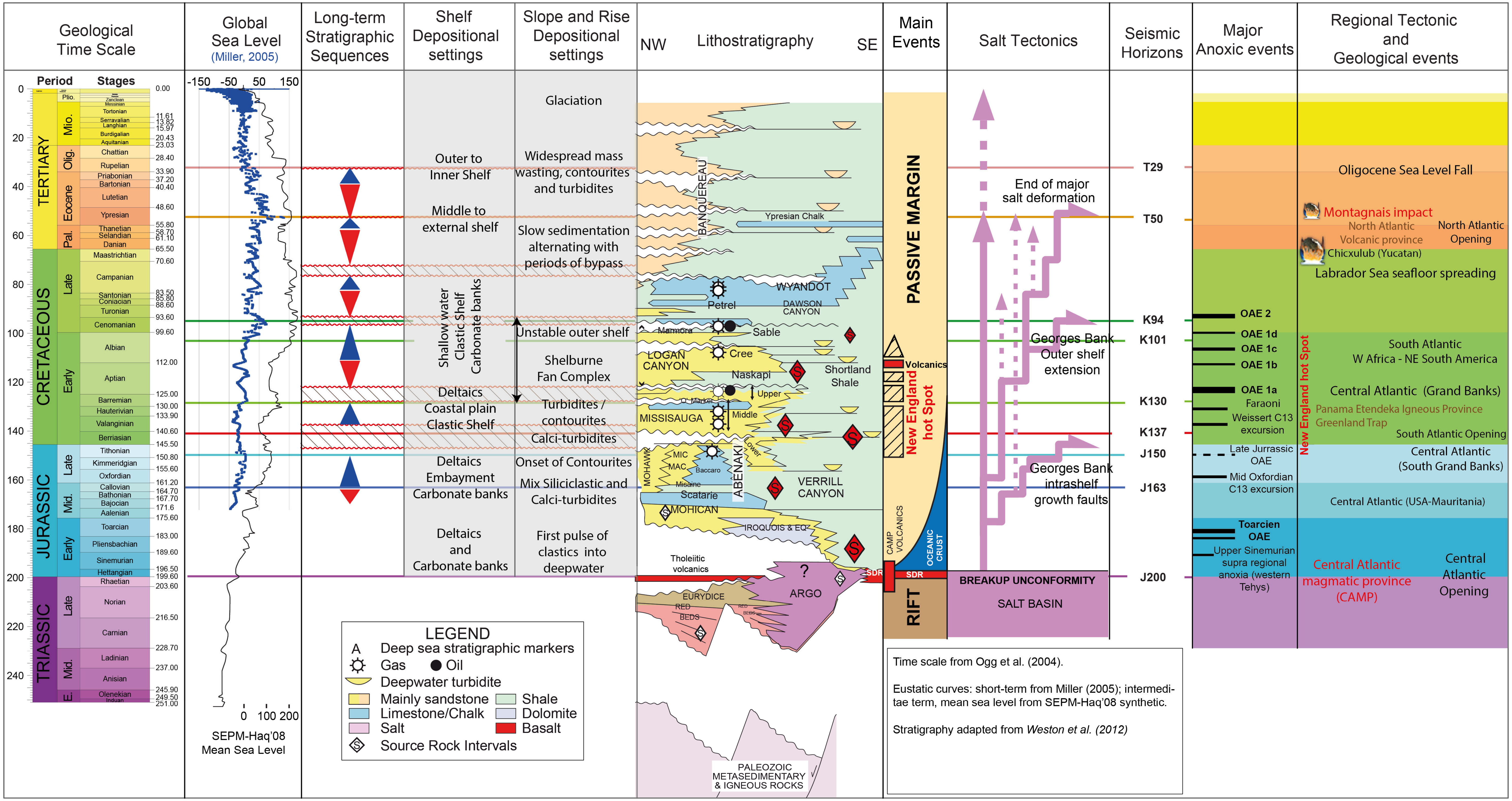
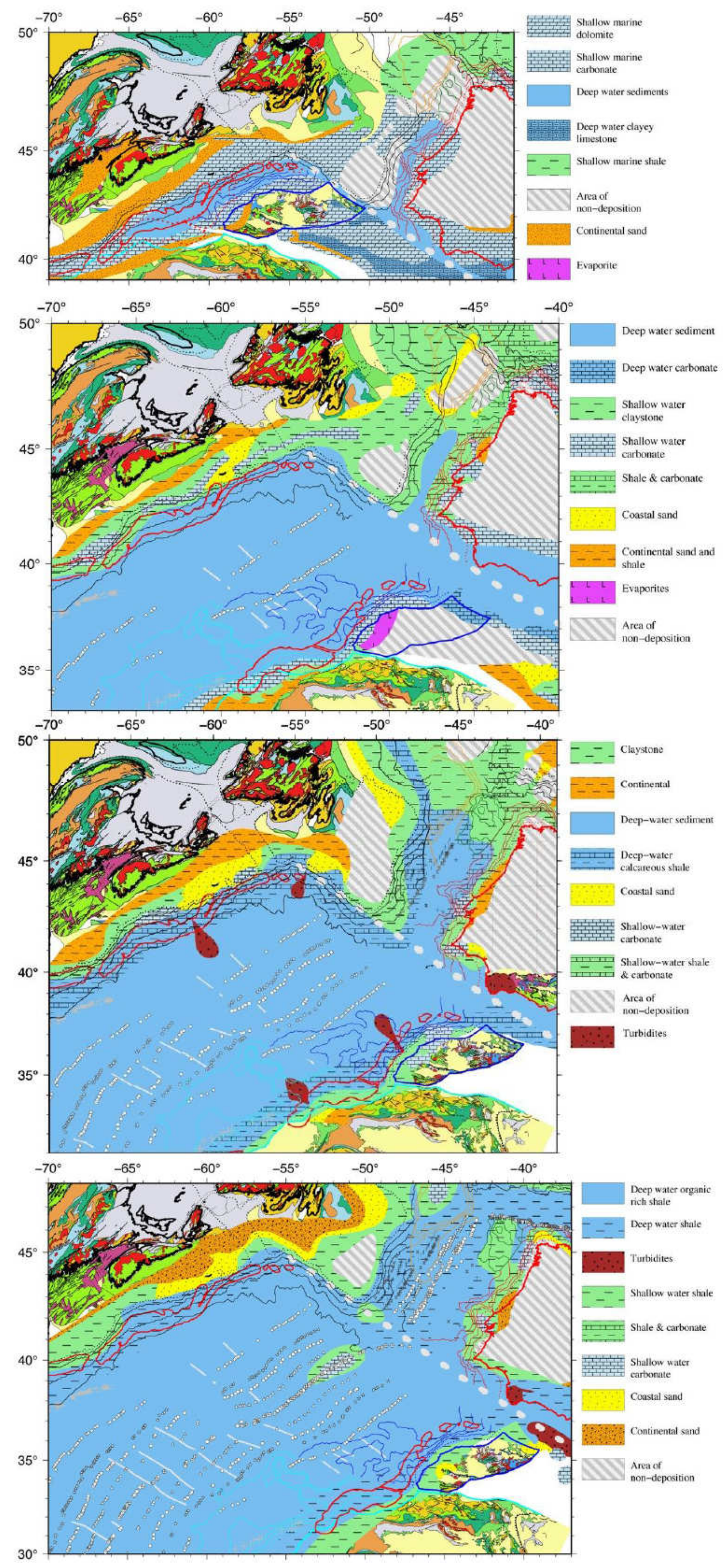


Figure 7: Detailed Stratigraphic Chart incorporating all sedimentary and geological events as well as major anoxic events. (Modified and updated from PFA 2011 and PFA 2014).



Early Jurassic (Sinemurian - Toarcian)

Late Jurassic (Oxfordian - Tithonian)

Early Cretaceous (Berriasian - Barremian)

Middle Cretaceous (Aptian - Albian)

Figure 8: Paleogeography of Eastern Canadian Margin from Early Jurassic to Middle Cretaceous (Sibuet et al., 2012)

Generalized stratigraphy of the Scotian Basin

The Scotian Basin contains Mesozoic-Cenozoic sedimentary rocks up to 15 km thick in places that were deposited during the rifting of Pangea and the opening of the North Atlantic (Figure 8). The earliest basin infill occurred during the Triassic rifting, and consists of red continental clastic sediments and evaporites (**Euridice and Argo Formation**; Figure 9). During the **Early Jurassic** rift basins were gradually infilled by clastic and carbonate sediments (Figure 7). Fully marine conditions developed by **Mid Jurassic**, leading to a set of alluvial plains, deltaic and carbonate environments. Consecutive to the **Avalon uplift** in the North and **New England hot spot** uplift in the South, the **Early Cretaceous** was dominated by deltaic progradation and shelf clastic deposits. **Late Cretaceous/ Early Tertiary sedimentary** deposits were dominated by transgressive shale, sporadic influx of deltaic sands, limestone, and chalk sequences. 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.

Stratigraphic Marker	Stratigraphic surface	Stage	Equivalent Formation	Cost G2	Bonnet P23	Mohawk B93	Moheida P15	Glooscap C63
T29	Unconformity	Rupelian	Banquereau		1672 m			
T50	Unconformity	Ypresian	Dawson Canyon Petrel Wyandot Ypresian chalk		1762.5 m	612 m		523 m
K/T unc.	Unconformity	Maastrichtian/ Campanian						543 m
K94	Unconformity	Cenomanian		677 m		1040 m		1322 m
K101	Unconformity	Albian	Logan Canyon Shortland Shale Naskapi Roseway		1822 m	1324 m	2047 m	1712 m
Mid Alb unc	Unconformity	Albian						1795 m
Alb/Apt mfs	MFS	Albian/Aptian						2098 m
Intra Aptian mfs	MFS	Aptian				1336 m	2348 m	2192 m
Apt/Barr unc	Unconformity	Aptian/ Barremian				1340 m	2382 m	2240 m
K130	MFS	Hauterivian	Roseway Missisauga	1267 m	1903 m	1404 m	2469 m	2403 m
K137	Unconformity	Valanginian		1678 m	2065 m	1635 m	2629 m	2561 m
J150	MFS	Tithonian	Abenaki Verrill Canyon Mohawk Mohican Iroquois	1784 m			2688 m	2587 m
Base Tith mfs	MFS				2178 m	1665.5 m	2852 m	
Kimm fs	FS	Kimmeridgian			2245 m			
J163	MFS	Callovian		3104 m	3491 m	1926 m	3440 m	3298 m
Base Call. mfs	MFS				3712 m	1932 m	3589 m	3538 m
J200	Unconformity	Hettangian/ Rahetian		6640 m			4043 m	4045 m
Basement	Unconformity	Paleozoic				2112 m		

Table 5: Well markers and biostratigraphic surfaces

BASEMENT AND PRESERVED CARBONIFEROUS - EARLY TRIASSIC DEPOSITS

The basement is composed of granite complex and metamorphic rocks (gneiss and schist). Seismic data allowed the recognition of tilted blocks and associated infilled troughs with Early Triassic salt and undefined sedimentary deposits. Onshore, these sediments outcrop on the western rim of the Scotian shield mainly along the Bay of Fundy. Eastward from Halifax, the geological map indicates limited outcrops of Carboniferous age. In the current PFA, Mohawk B-93 is the only well that reached a granitic basement on the Mohawk ridge (Figure 10). Cutting data shows an Orthoclase Granitic basement topped by middle Jurassic fluvial sandstone.

TRIASSIC

Formations: Eurydice and Argo Salt Equivalent (Figure 9)

Glooscap C-63 and Moheida P-15 are the only wells that recorded pre break-up sedimentation i.e. Eurydice and Argo Fms. Cost-G2 well on Georges Bank subbasin just scratched the top of the salt formation (PL. 3.3.1 and 3.3.2 ; Enclosure 3.5 and 3.6; Table 1 and 2).

Eurydice Formation corresponds to the oldest synrift sequence linked to the Atlantic opening. The formation corresponds to thick series of Late Triassic red sandstones, siltstones and shales. The Euridice Formation is a wide spread sedimentary successions across the margin encountered from Georges Bank up to the Grand Banks. The thickest known area so far is In Orpheus and Naskapi Grabens where seismic data indicate a total thickness over 3 000 m (Wade and MacLean; 1990). In the Moheida P15 well the Eurydice Fm shows a thick clastic section (Figures 1 Pl.3 and 7 Pl. 3.2.3) composed of sands and shales locally contemporaneous of the Argo Salt Fm (Figure 9 Pl).

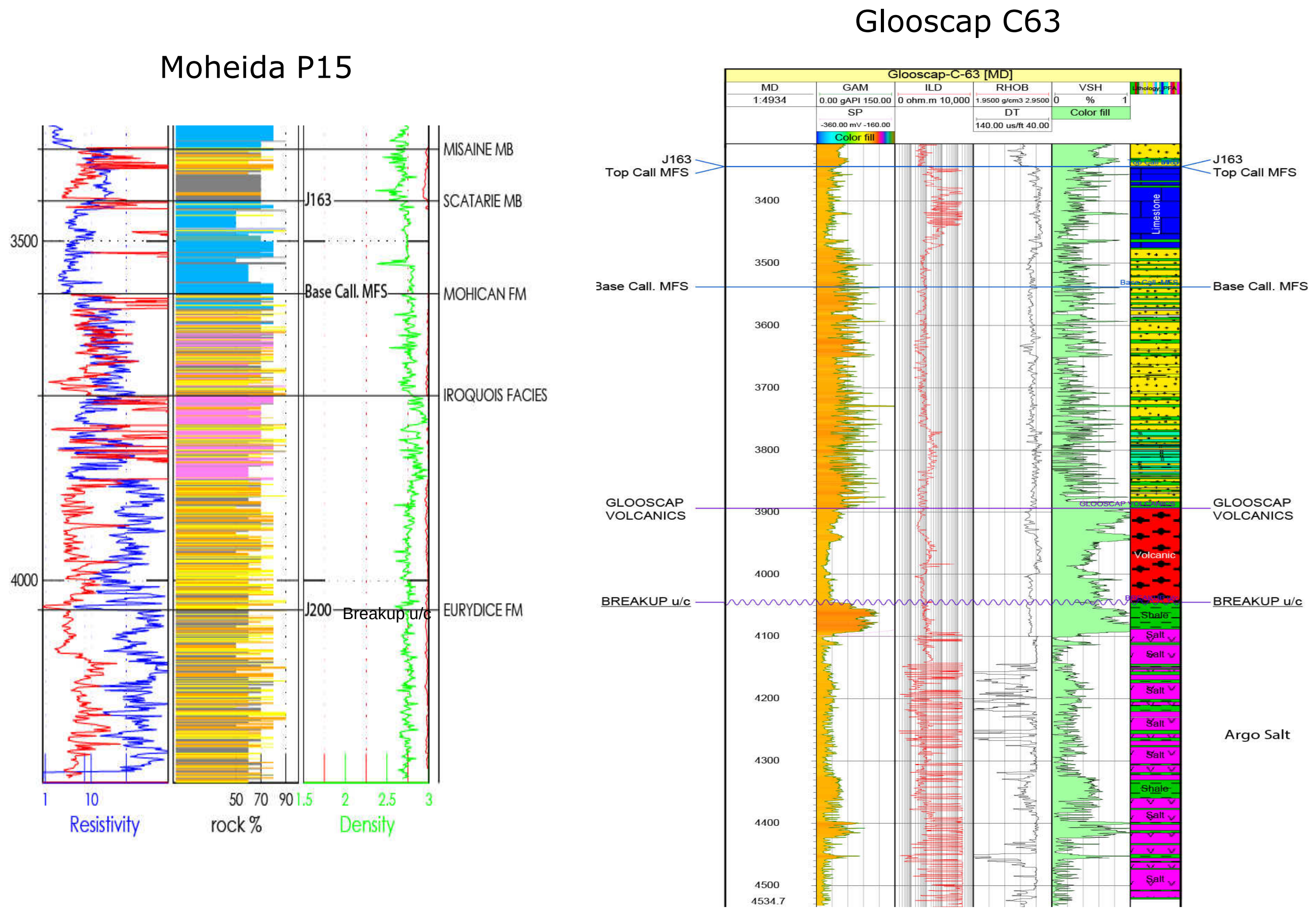


Figure 9: Late Triassic to mid Jurrassic litholog interpretation. A: Moheida P15 (after Fensome, modified); B: Glooscap C63

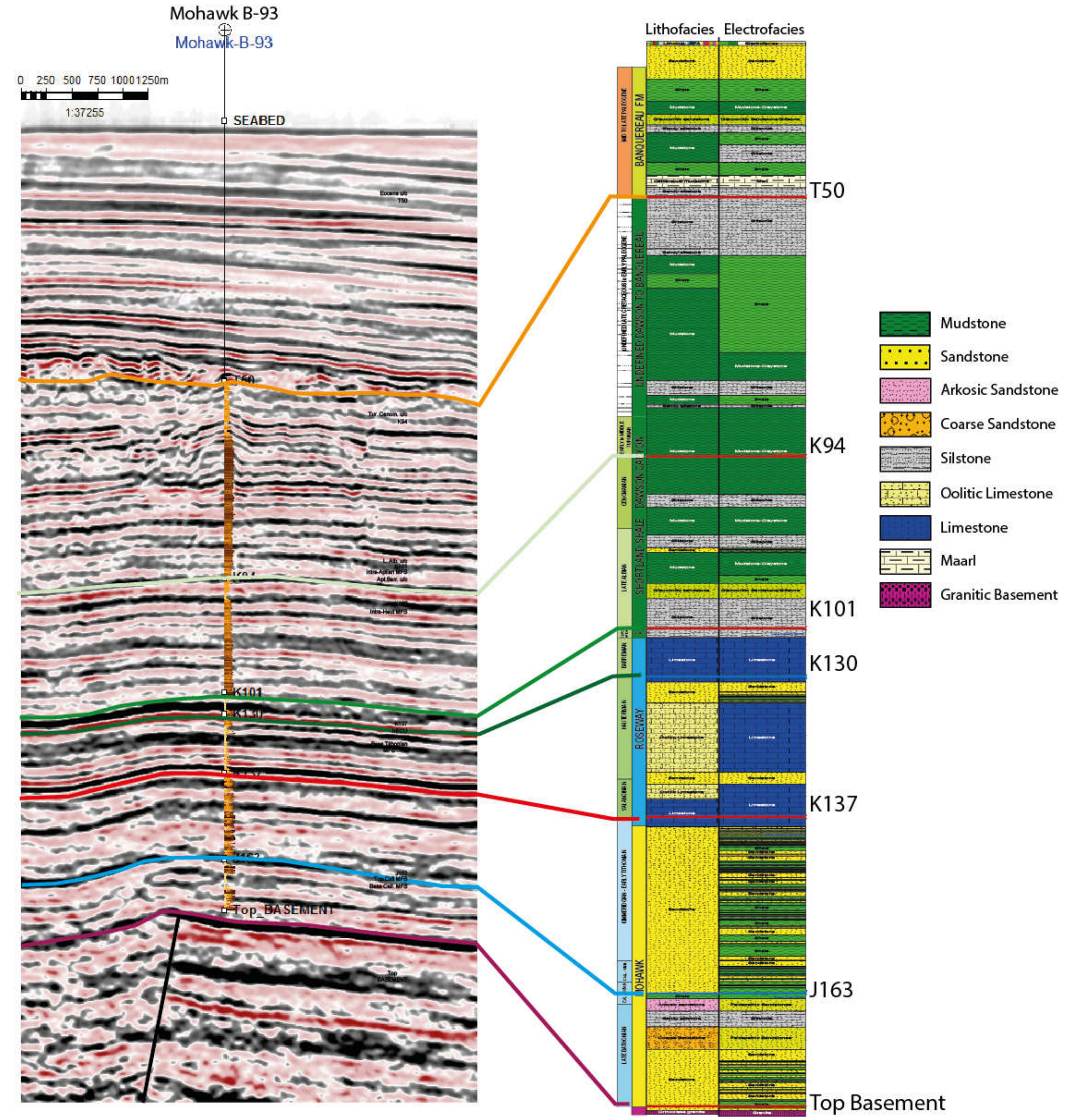


Figure 10: Location of Mohawk B93 on a basement high (nearshore from Bonnet). The Jurassic (predominantly clastic) is characterized by non marine to deltaic sandstone. The Cretaceous composes most of the recorded succession and shows a thick Oolitic interval between K137 and K130. Due to its location, Mohawk B93 shows a better preserved Cretaceous sedimentary record than Bonnet P23. The depositional environment is characteristic of very shallow to shallow water environment until the Turonian – Cenomanian (K94) unconformity.

The **Argo Formation** is coeval or overlies the Eurydice Formation. The Argo Formation consists of massive beds of pale orange salt interbedded with thin red shales units. The distribution of salt along the Scotian margin coincides with major basement trends and suggests that the basins morphology are shaped by inherited structural networks and continental – oceanic crust boundary (Figure 11)

Total salt thickness at prior to break-up is estimated to be 2000 m at least (Wade and MacLean, 1990). During the rifting in Georges Bank, and shortly after the rifting for most of the margin, the salt flowed extensively due to subsequent sediment loads and possible periods of reactivation of rift related faults. Salt pillows, diapirs and canopies are common along the margin from Georges Bank up to western Grand Banks.

BREAKUP UNCONFORMITY- J200

J200 Breakup Unconformity is dated at early Jurassic (200 Ma) and separates the synrift and post rift sequences (PL 3.4.1 to 3-4.3 and 5.2.18). The unconformity corresponds to the opening of the North Atlantic Ocean and is traced from the Shelburne subbasin up to the Laurentian subbasin. Seismically the unconformity is characterized by a strong regionally mappable reflection. The Mohican Formation completes the rift infilling and overlaps basement highs.

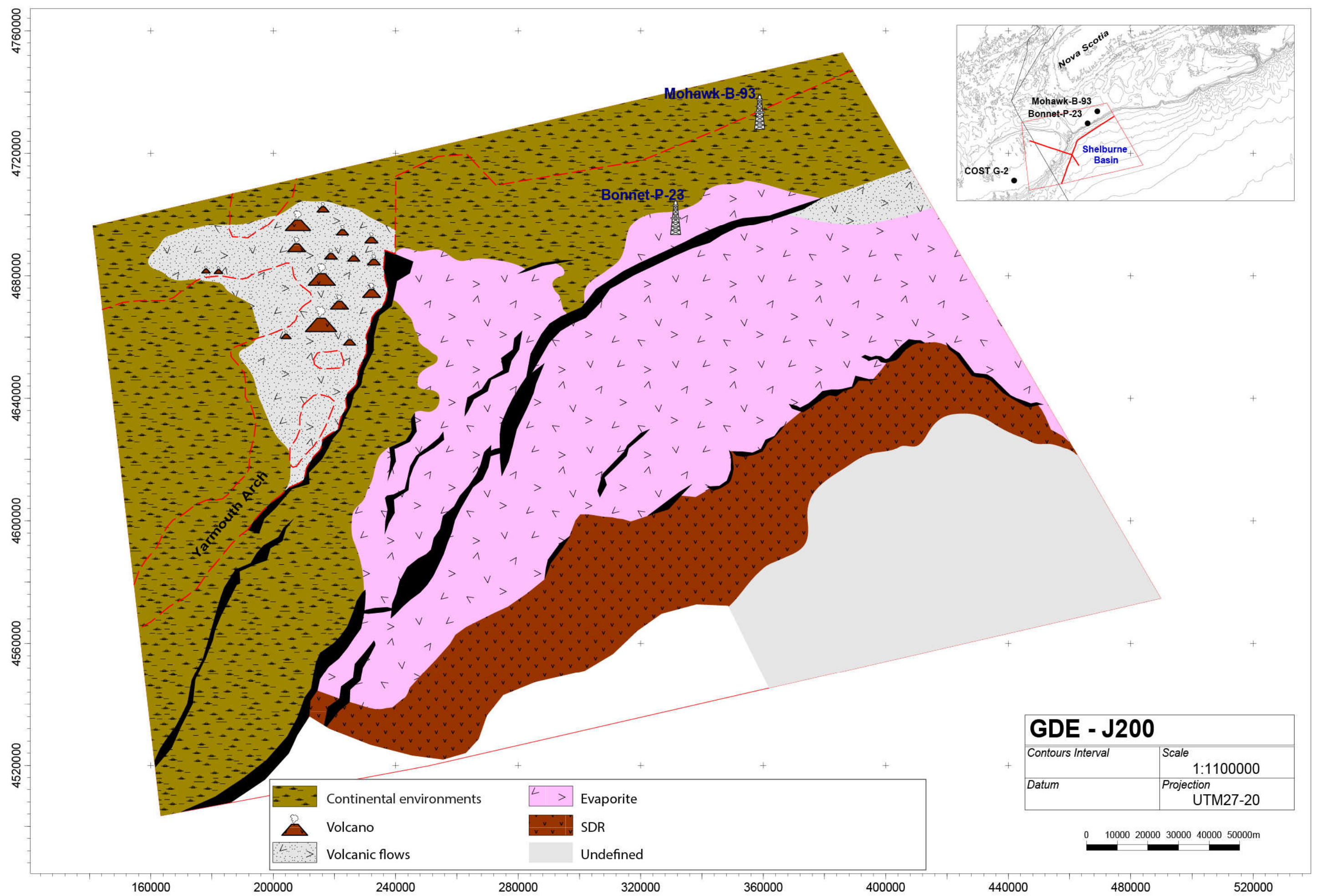
EARLY TO MIDDLE JURASSIC - J200–J163

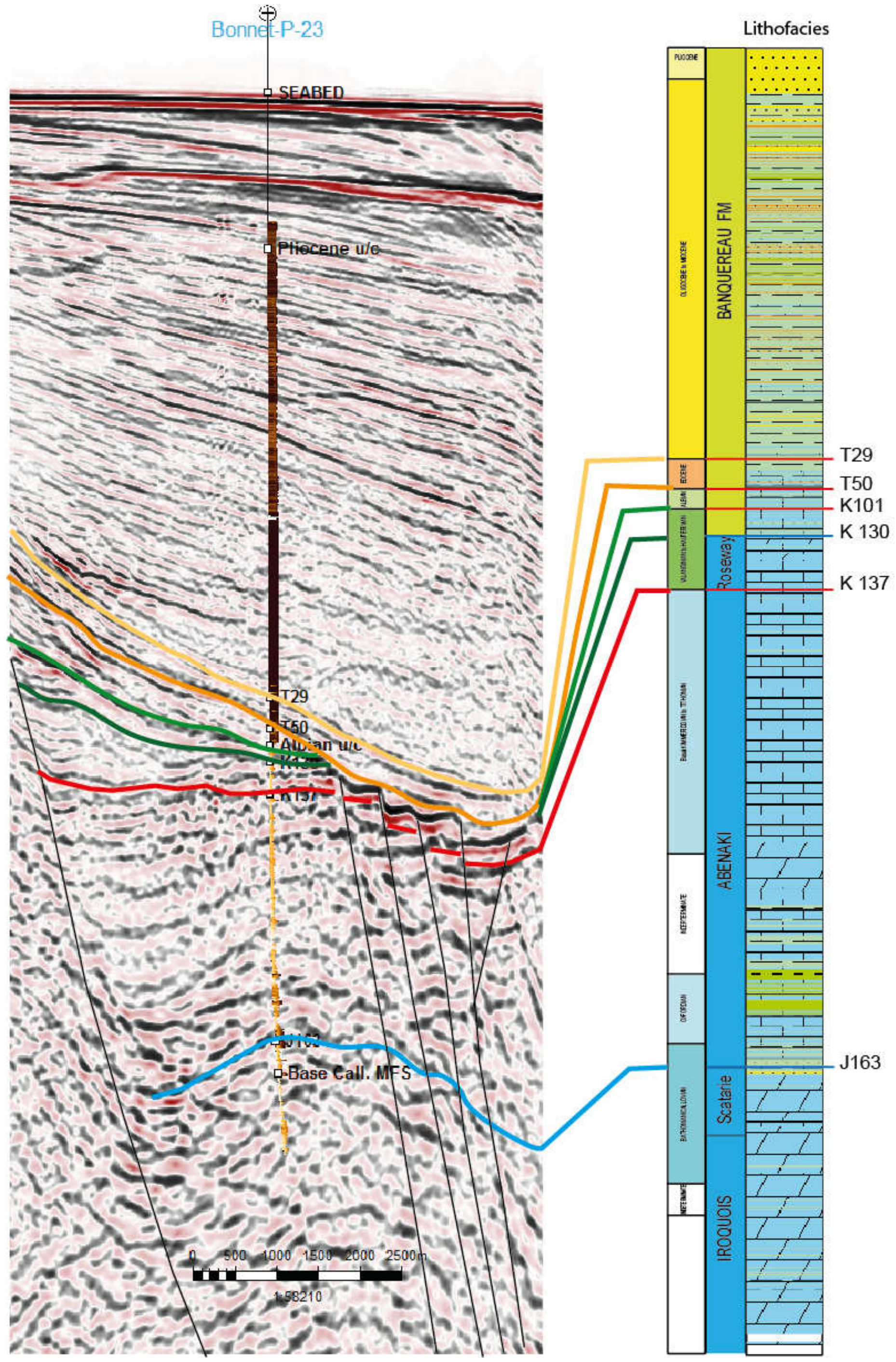
The early to middle Jurassic stage corresponds to the development of large river systems and their thick delta, deltaic environment along the shore, large carbonate rims and platforms on the shelf (Figures 6, 12 and 14; PL 3.4.1 to 3.4.3 and 5.2.14 to 5.2.16). Around the Mohican ridge, a wide delta developed at a river mouth complex system (Figures 6, 10 and 14). Southwest of the deltaic area a carbonate platform extends to the so the south of the margin occasionally cut by sets of deltaic complexes. The Shelburne subbasin records the first pulses of clastic and carbonate sediments forming the first turbidite deposits (Figures 7 and 14; PL. 3.4.1 to 3.4.3). In the mean time Georges Bank area is characterized by thick carbonate succession corresponding to Iroquois and Scatarie Fms. Clastic inputs in Georges Bank starts significantly during the Callovian after J163.

Identification

- Formations/Members equivalent: **Iroquois** (carbonate platform), **Mohican** (clastic sands)
- Number of exploration wells that reached the Early to Middle Jurassic: Iroquois Fm is recorded in Cost G2, Bonnet P23, Moheida P15 and Glooscap C63; Mohican equivalent is observed only Mohawk B93, Moheida P15 and Glooscap C63 (PL. 3.3.1, 3.3.2; Enclosure 3.3 to 3.8)
- Regional top sequence/seismic horizon: **J163 (Top Scatarie; Callovian MFS)**
- Lithostratigraphic cross-sections (Plate 3.3.1 and 3.3.2)
- Architectural cross-sections (PL. 3.4.1to 3.4.3)
- Age: **Hettangian – Callovian**

Figure 11: Gross depositional environment map at J200 (Hettangian). J200 period is the transition from rifting to drifting. J200 is characterized by the co-existence of Volcanics on Yarmouth Arch, thick salt in the basin and SDR outside the basin.





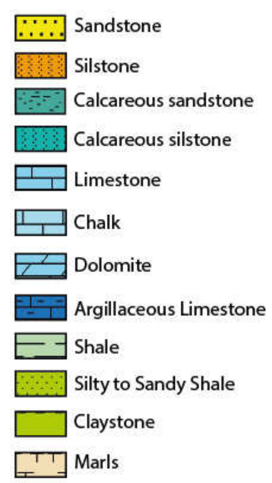


Figure 12: Location of Bonnet P23. Bonnet is located near the shelf edge. The Jurassic (predominantly carbonate) composes most of the recorded succession whereas the Cretaceous (predominantly clastic) is not well preserved. The low sediment preservation at that location is related to stacked unconformities, but particularly the impact of the Ypresian unconformity (T50) which also coincides with the Montagnais impact. Until the NBCU (K137), the sediment corresponds to a shallow water environment with alternating prodeltaic and lagoonal environments. During the upper Jurassic the environment appear quite stable. After K101 a major change in environment appear with a well marked deepening trend after K94.

Description

Along Shelburne subbasin, the early to middle Jurassic Formations overlie the breakup unconformity separating post rift sediments from the Argo salt and Euridice Fms (Figure 9 and 11; PL 3.4.1 to 3.4.3, 5.2.16 and 5.2.18). Iroquois and Mohican Formations cover the timespan between the Hettangian and Bajocian (Figure 7). Iroquois Fm is a transgressive formation which consists primarily of dolomite deposited under slightly restricted marine conditions (Figure 12, 13 and 14; Enclosure 3.2 and 3.3). The dolomite is observed until the Toarcian except in Bonnet P23 where it extends until the Bathonian (Figure 12). The Iroquois Formation is coeval with the lower part of the Mohican Formation due to coexisting carbonate rims and deltaic formations (Figure 10). Mohican sandstones and shales form a very thick early to middle Jurassic clastic sequence in the Scotian Basin (Figure 15; PL 3.3.1 and 3.3.2; PL 3.4.1 to 3.4.3). The formation is widespread on the Scotian Shelf and tends to decrease toward Georges Bank basin where carbonate formations tend to be particularly thick, with thickness over 3000 m (Figure 15).

Mohican Formation is topped by Scatarie and lower Mohawk equivalent Formations (Figure 10 and 12), covering the Bajocian – Callovian interval. Proximal facies are predominantly shallow water limestones and oolitic limestones interrupted by thin prodeltaic shale on Georges Bank. On Mohawk ridge, proximal facies are predominantly fluvio-tidal sandstones. Basin slopes show evidence for carbonate breccia accumulation across Shelburne Basin and toe of slope carbonate fan (Figure 14). Offshore sedimentation is predominantly a mix of calci-turbidite and clastic turbidites until the Callovian.

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 time. Sedimentary records in wells show prominent deltaic and prodeltaic successions on Georges Bank and Mohawk ridge. Carbonate production decreases during the Callovian and is restricted to the outer shelf in the area under clastic influence, such as in the southwest of Mohawk ridge where carbonate growth restarts quickly during the Callovian until the Cretaceous (Figures 10 and 12). Georges Bank shows a slightly different sedimentary record, with a drastic increases in clastic input from mid Callovian up to the Kimmeridgian (Figure 15; PL 3.3.1 to 3.4.3). During the Kimmeridgian and Tithonian major environment changes occur coincident with the beginning of regional uplift and the opening of the North Atlantic (Figure 7). Clastic inputs decrease drastically and sedimentation is dominated by shaly deposits associated to the development of Kimmeridgian – Tithonian carbonate banks across the margin (Figures 10, 14 and 15; PL 3.3.1 and 3.3.2). The slope and rise record well developed mixed clastic-carbonate turbidite systems. Turbidite systems are predominantly clastic during the Callovian – Kimmeridgian period. During the mid Kimmeridgian and Tithonian interval the slopes record mostly toe of slope carbonate fans. The basin is predominantly shaly.

Sedimentary sequences between Tithonian and Valanginian are absent from the southwestern part of the Scotian Margin and partly on Georges Bank due to the impact of the near base Cretaceous unconformity (K137). As a consequence, the Tithonian source rock is absent from the shelf and upper slope on the Scotian shelf, but preserved on Georges Bank as well as in Shelburne subbasin.

Identification

- Formations/Members equivalent: **Mohawk** (continental clastics), **Misaine** (prodelta, open marine shale, deep water shale), **Abenaki** (carbonate platform and reef margin)
- Number of exploration wells that reached the mid to late Jurassic : 5 wells (PL 3.3.1 and 3.3.2; Enclosure 3.3 and 3.4)
- Regional top sequence/seismic horizon: **J150 (Tithonian MFS)**; **K137 (near base Cretaceous unconformity)**
- Lithostratigraphic cross-sections (PL 3.2.12, 3.3.1 and 3.3.2; Enclosure xx to xx)
- Architectural cross-sections (PL. 3.4.1 to 3.4.2; Enclosure 3.9 and 3.10)
- Age: **Callovian – Tithonian**

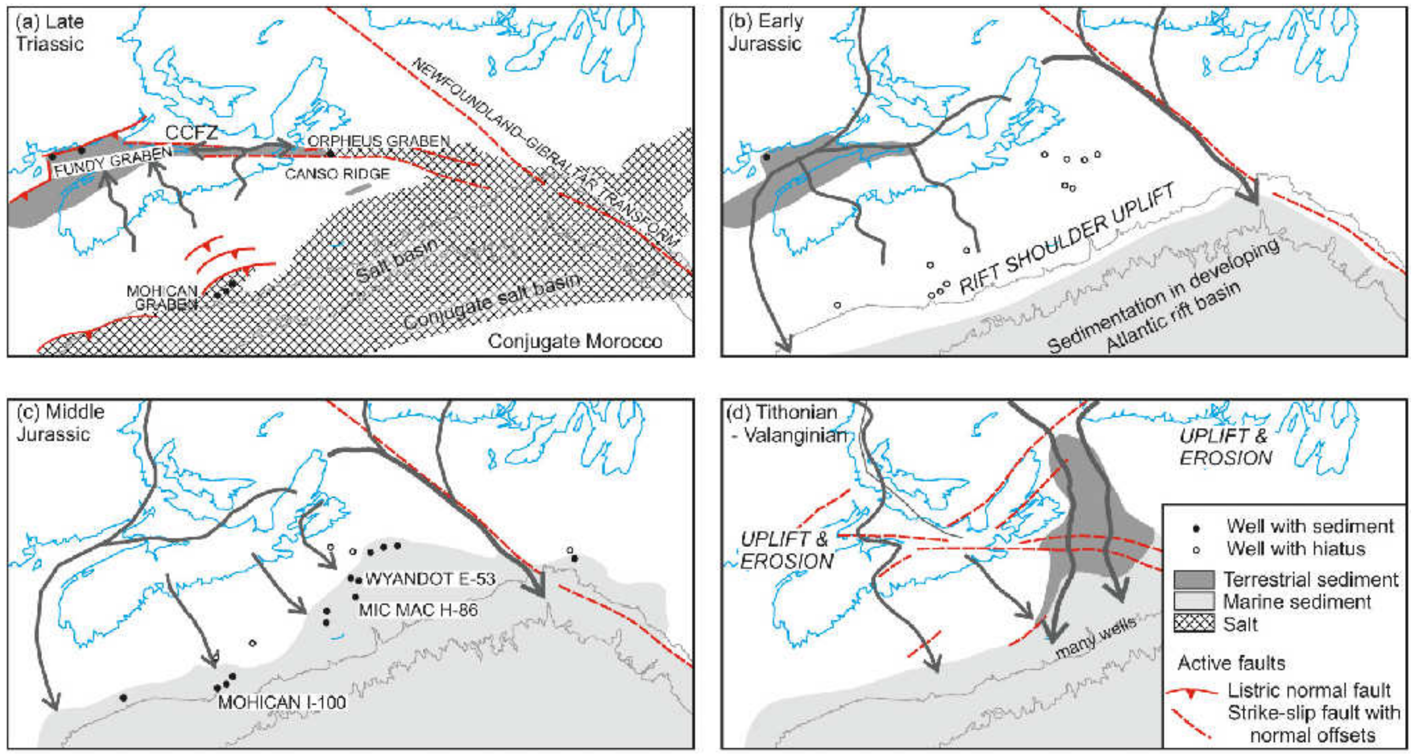


Figure 13: Map showing the structural and geomorphic evolution of the Scotian Basin and its hinterland from late Triassic to early Cretaceous: (a) late Triassic; (b) early Jurassic; (c) middle Jurassic; (d) Tithonian–Valanginian. (From Li et al., 2012).

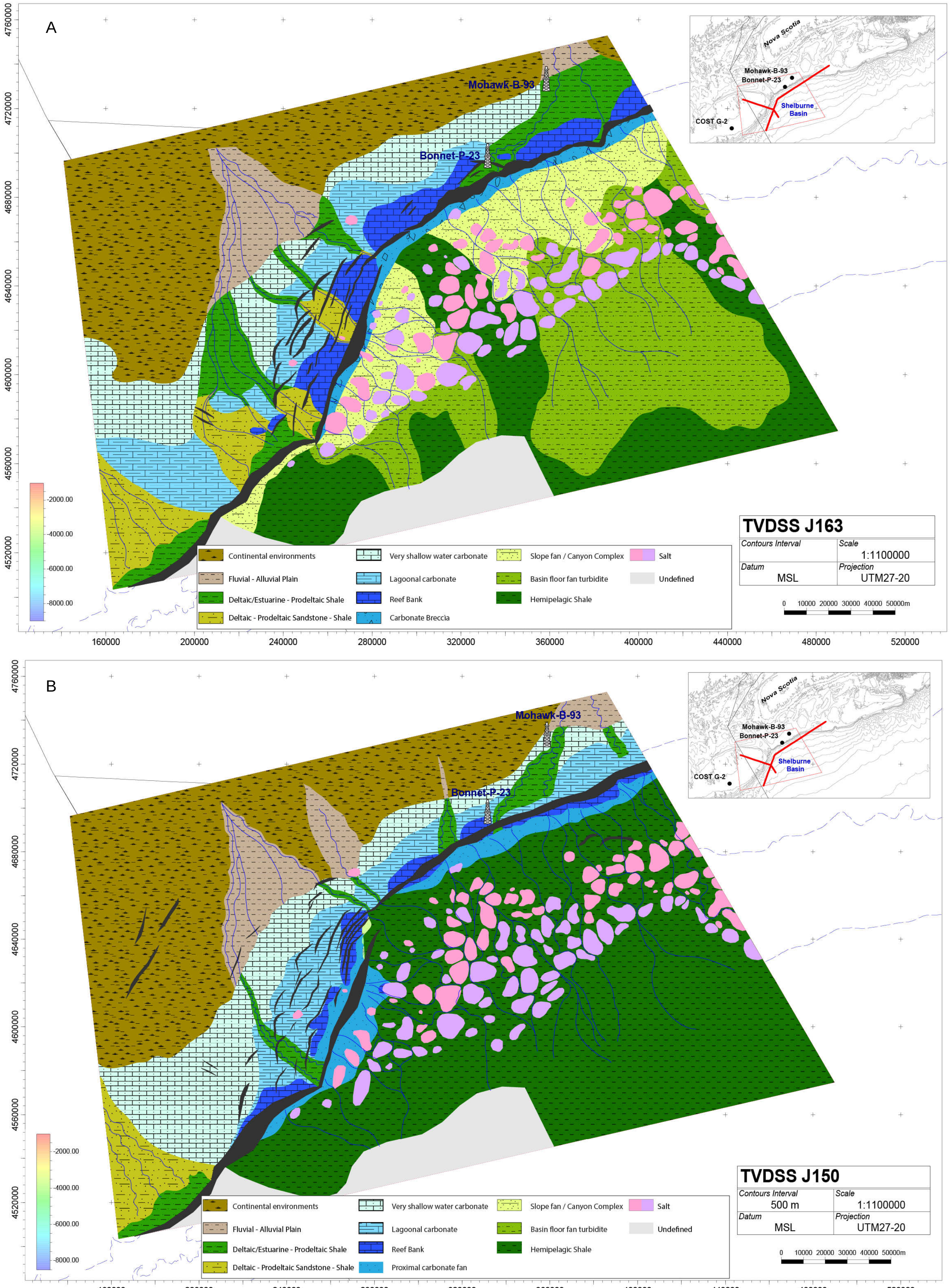


*Figure 14: A) GDE map at the Callovian MFS; **B**) GDE map at the Tithonian MFS. The J163 – J150 interval corresponds to the Mohawk/Mic Mac and Abenaki formations. During this time frame, carbonate banks developed but are stressed by an increase of clastic influx particularly on Georges Bank area.*

Description

Mohawk Formation

Mohawk Formation is the lateral equivalent of the Mic Mac Formation. It correspond to a thick clastic fluvio-marine deltaic prograding system developed over Georges Bank and Mohawk ridge (Figure 10). Mohawk Fm overlays the Scatarie member and the Mohican Fm. Mohawk Fm and its lateral equivalents (Misaine and Abenaki Fms) span the late-Middle and Late Jurassic. Mohawk Fm thickness ranges from few hundred meters to over 1500 m on Georges Bank and consists of interbedded sandstones siltstones and shales (Figures 10 and 15). Between Mohawk ridge and Georges Bank basin, Mohawk Fm facies consist of shale with thin to thick interbedded sandstones. Distally, the clastic facies grade into fine grained basinal facies, the **Verrill Canyon or equivalent Formation**.

Verrill Canyon Formation

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

Abenaki Formation

Abenaki Formation is a limestone dominated unit corresponding to a prominent carbonate bank facies (Figure 16). The formation extends across the Scotian Margin up to Georges Bank. The Abenaki Formation forms an outer shelf carbonate bank complex (Figures 15 and 16) and is subdivided into three Members : The Scatarie Member, the Misaine Member and the Baccaro Member.

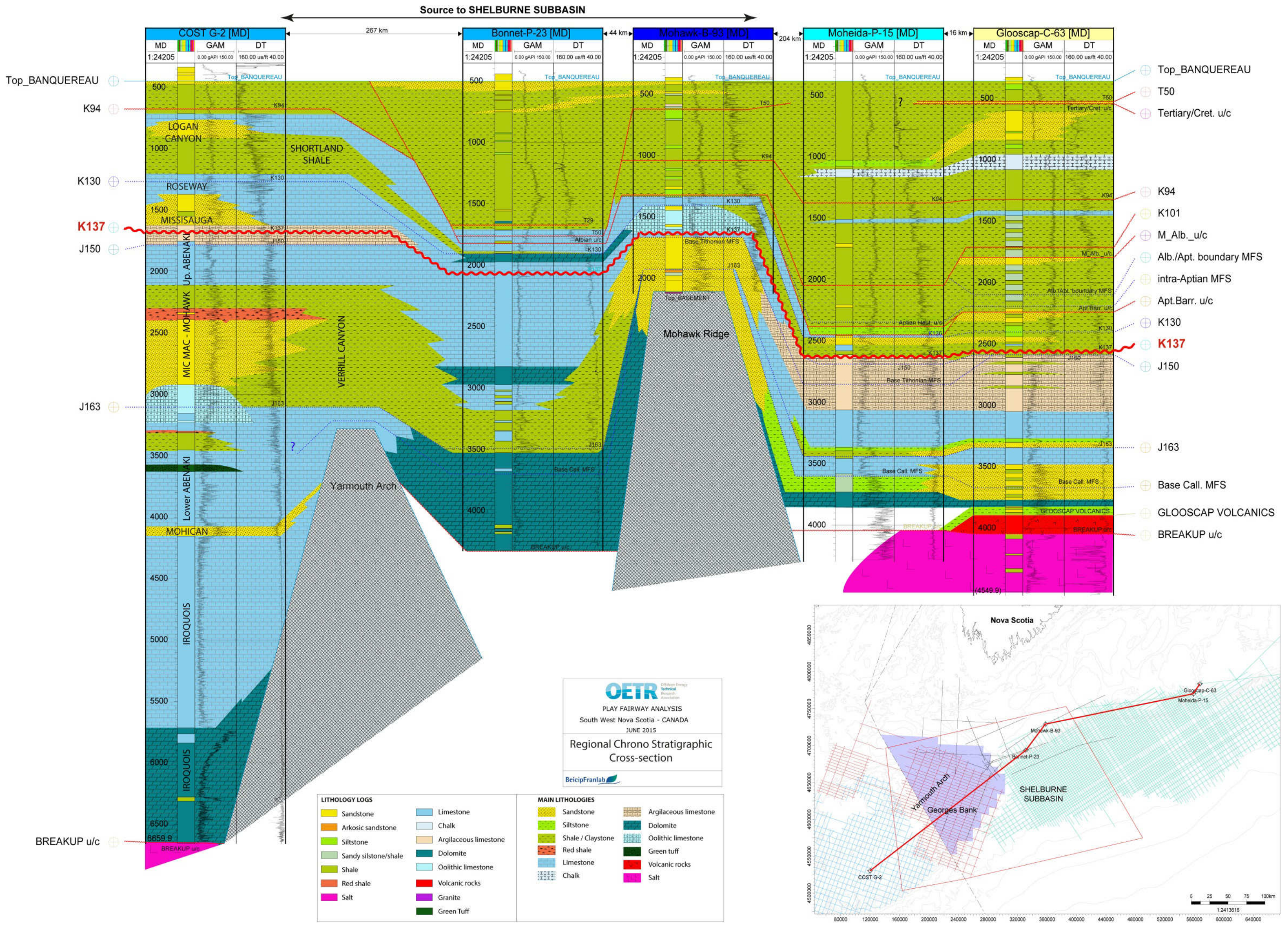


*Figure 15: Well correlation across the margin. The NBCU (**K137**) marks the separation between Jurassic and Cretaceous successions. The geological section shows a thick Jurassic carbonate succession toward Georges Bank, and a thinner mix Clastic – Carbonate interval to the Scotian margin. Note the thick clastic accumulation between J163 and J150 in Shelburne subbasin. It's to be noticed that Cost G2 shows a clastic record similar to Sable subbasin one.*

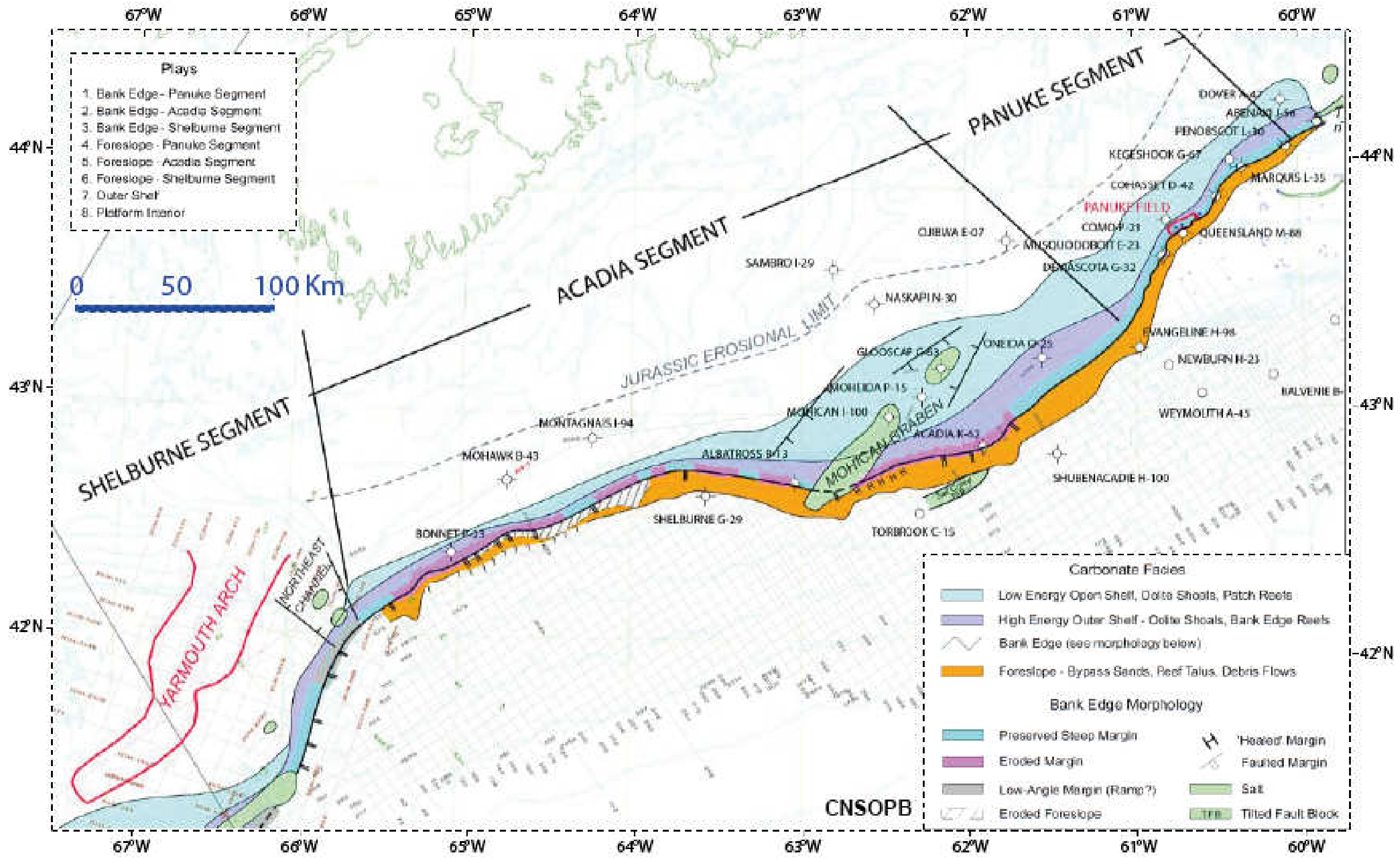


Figure 16: Abenaki Formation Morphology, carbonate facies complex after A. Kidston et al, (2005).

The Scatarie Member is predominantly an oolithic limestone. According to the biostratigraphy, the Scatarie Member is intra Callovian in age (Figure 14). It represents a seaward thickening wedge with deepening-upward transgressive sequences. The formation is about 100 m thick in Bonnet P23 and thickens towards Georges Bank where it reaches its maximum thickness, of about 500 m.

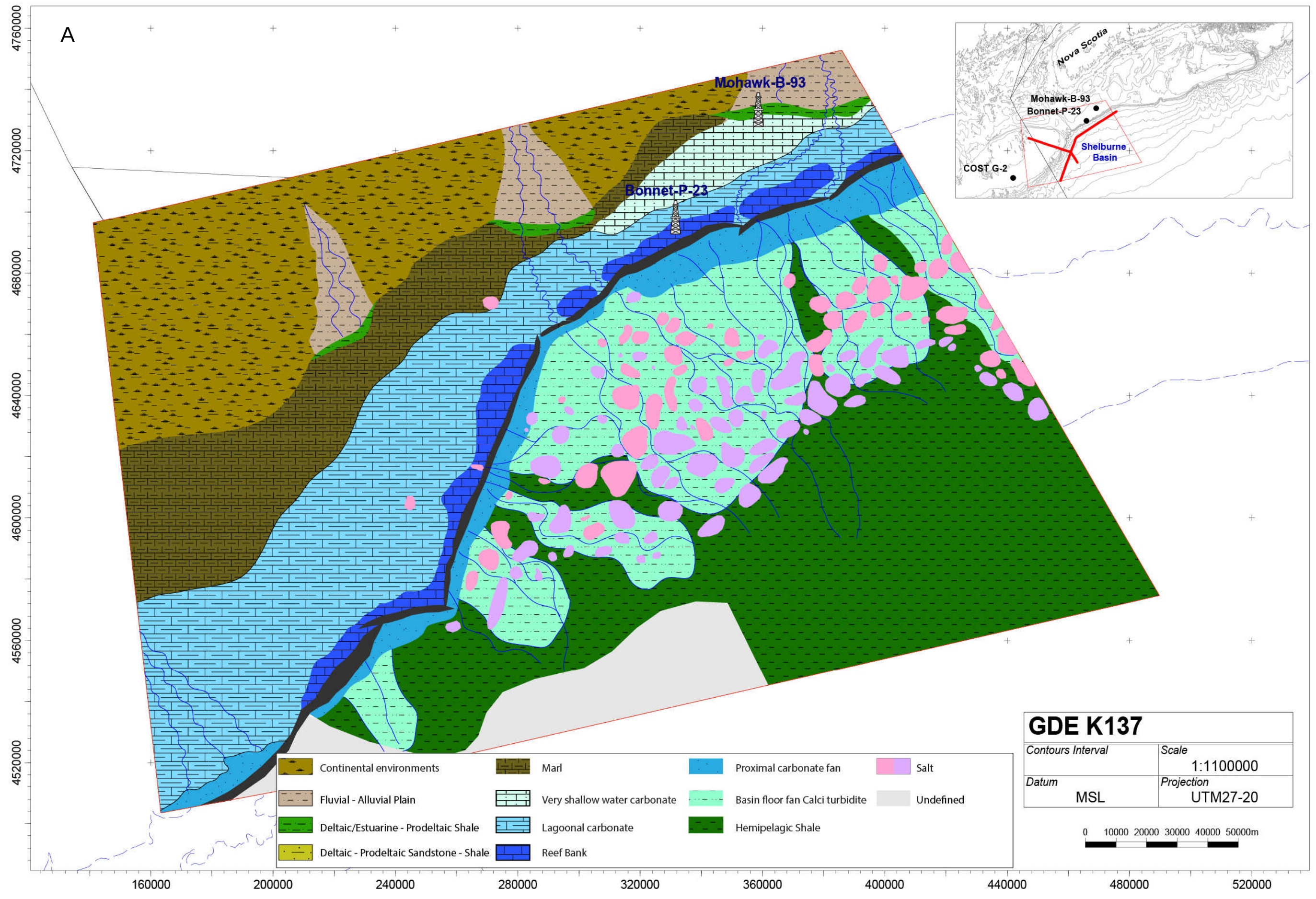
Misaine Member is a shale dominated formation deposited during the Callovian and is the only clastic dominated unit of the Abenaki Fm (Kidston et al., 2005). It correspond to a transgressive facies that overlies the Scatarie Mb. The Misaine Member (up to 250m thick) is composed of dark grey calcareous shales with minor laminated limestone pinching out landward over the platform with interbedded proximal sandstone. Misaine Member is representative of the Callovian regional transgressive flooding event well developed along the Jurassic shelf margin.

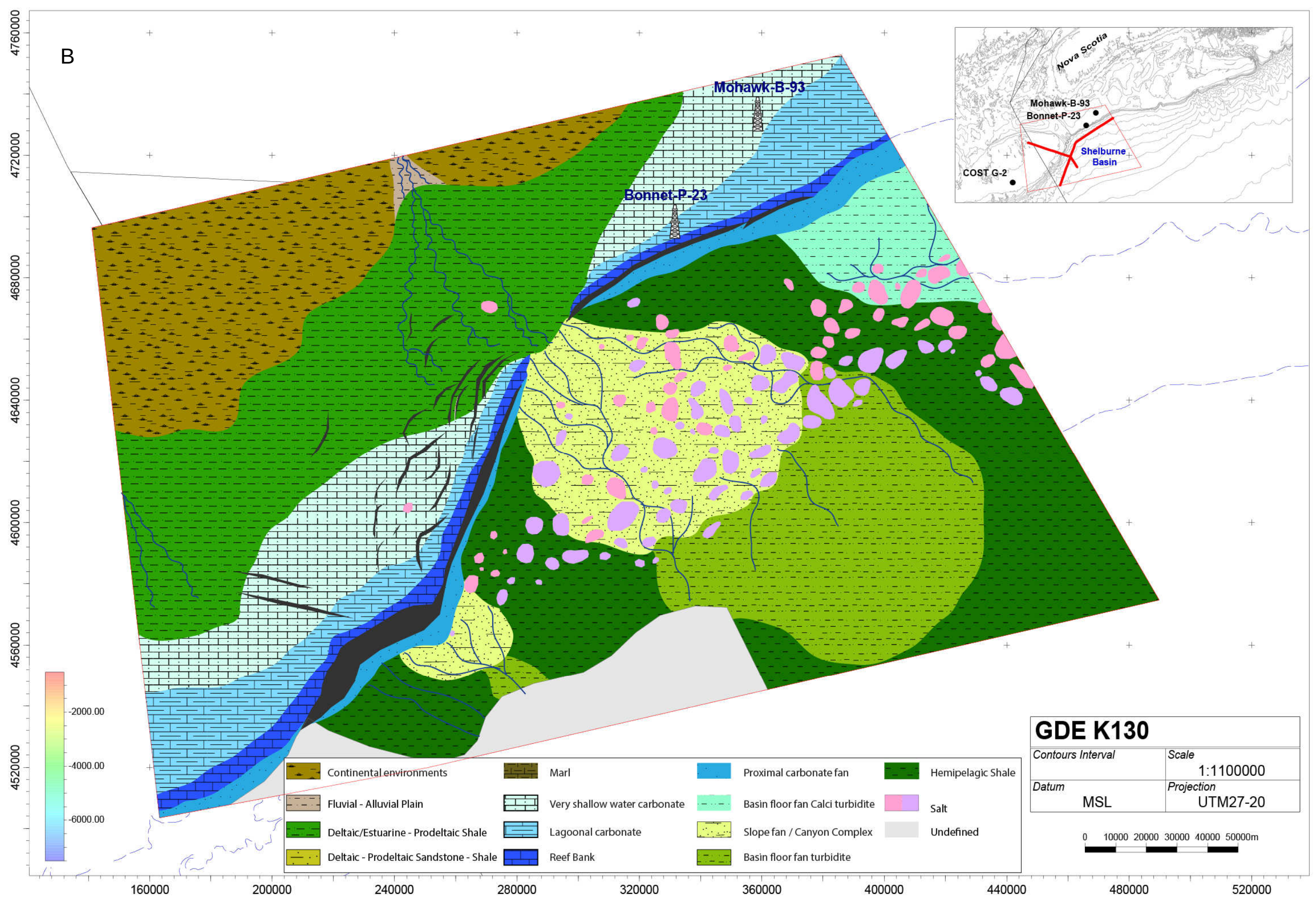
The Baccaro Member is the thickest and best developed carbonate unit of the Abenaki Formation and developed from early Oxfordian to Tithonian. It is composed of numerous aggrading and prograding parasequences of limestones with minor shales and sands intervals. The formation is of variable extension, corresponding on average to a 15 – 20 km wide belt that follows the Jurassic hinge line and defines the seaward limit of the Abenaki platform margin (Figure 16).

Avalon Unconformity and New England Hot Spot

During the late Jurassic a second breakup episode occurred on the eastern Canadian margin related to the separation of Iberia and The Grand Banks. The associated uplift called Avalon Uplift developed beneath the Grand Banks and led to extensive erosion of Jurassic and older sediments. The resulting unconformity is called the Avalon Unconformity (Jansa and Wade, 1975; MacLean et al., 1989; Wade and MacLean, 1990). The event is well recorded across the margin. The Avalon uplift induced a massive erosion of upper Jurassic sequences and a drastic reduction of accommodation space. The impact of the Avalon uplift decreases to Georges Bank where more series are preserved (Figure 21; PL 2.7).

In the mean time, volcanism related to hot spot activity started in the New England/Quebec area (see also PL 2.7). The hot spot called New England hot spot or more accurately Monteregian hot spot is the origin of the New England seamount (Duncan, 1984; Sleep, 1990). The hot spot crossed New England Province and Georges Bank during the Early Cretaceous and built the first seamount, the Bear seamount, around 100 Ma, i.e. during the Albian period (Sleep, 1990). The hot spot impact on the whole petroleum system is still to be determined, although significant uplift and heat flow anomaly should be expected.





EARLY CRETACEOUS SEQUENCE (BERRIASIAN - BARREMIAN) K137-K130

The early Cretaceous period corresponds to the separation of Newfoundland from Europe which is at the origin of the Avalon uplift and subsequent regional unconformity (Figure 8). Both seismic and well data show a southward attenuation of the unconformity. The presence of J150 (Tithonian MFS) on Georges Bank but not on the southwestern Scotian Shelf support this observation.

Similarly to the Callovian – Kimmeridgian interval, this sequence is characterised by a mixed carbonate – clastic system (Figures 15, 17 and 20; PL. 3.3.1, 3.3.2 and 5.2.10 to 5.2.13). The sequence starts with a wide spread carbonate interval, from marl sediment on Georges Bank to oolitic limestone on Mohawk ridge. During the late Valenginian early Hauterivian clastic sedimentation occurs on Georges Bank leading to the formation of a large delta (Figure 17; PL 3.4.1 to 3.4.3). On the southwestern part of the Scotian Margin limited clastic input is observed on Mohawk ridge, sedimentation remains carbonate dominated with oolitic limestone observed on Mohawk ridge and dolomite and limestone at the shelf edge (Figure 17). Because of deltaic formation this sequence is thicker on Georges Bank than the southwestern Scotian margin. This Early Cretaceous sequence ends with the Hauterivian MFS (K130). Clastic succession corresponds to Missisauga eq Fm whereas the carbonate succession corresponds to Roseway Fm (Figures 15 and 20). Downslope deposits correspond to the upper Verrill Canyon Eq. Fm.

Identication

- Number of exploration wells reaching the lower Cretaceous Fms: 5 wells (PL. 3.2.12, 3.3.1 and 3.3.2; Enclosure 3.3 and 3.4)
- Formation/Members: **Missisauga, Roseway** and **upper Verrill Canyon** eq. Formations.
- Age: **Valanginian – Hauterivian (K137-K130)**
- Regional top sequence seismic horizon: **Intra Hauterivian MFS (K130).**
- Chronostratigraphic cross-sections (PL. 3.2.12).
- Lithostratigraphic cross-sections (PL. 3.3.1 and 3.3.2); Geological Composite Well Logs (Enclosures 3.3 and 3.4).
- Architectural cross-sections (PL.3.4.1 to 3.4.3).

Description

Missisauga and upper Verrill Canyon eq. Formation

The Missisauga Fm is well developed on Georges Bank area but not on La Have platform (Figures 10, 12, 15; PL. 3.3.1 and 3.3.2). Missisauga Fm is linked to the presence of a wide spread deltaic system on Georges Bank called the Shelburne delta that lasts until the Cenomanian. This large deltaic system provide siliciclastic turbidites to the Shelburne subbasin. Timing and location of the Shelburne delta correlates with the crystalline basement uplift which provides coarse-grained fluvio-detaic sediments to the margin (Pe-Piper & MacKay, 2006). The resulting sedimentary formation comprises fluvial, deltaic sands and derivative shelf sediments up to the shelf edge (Figure 17). Basinward, canyons and valleys incise the slopes and basin floor fan systems develop on the rise. Sediment distribution is primarily controlled by canyons location and morphology and salt tectonic (Figure 17). Due to limited accommodation space, the Shelburne delta is not as thick as during the Callovian – Kimmeridgian stage. As a consequence, most of the sediment is transferred to the Shelburne subbasin leading to well developed turbidite systems.

Roseway Unit

The Roseway unit conformably overlies the Baccaro Member (Kidston et al., 2005). It may be the shallow water equivalent to the deeper water transgressive Artimon Member and corresponds to a force regressive succession of mixed shallow water oolitic limestones, sandstones, siltstones and shales (Kidston et al., 2005; Wade, 1977; Wade and MacLean, 1990). The Roseway Unit is considered in the literature as part of the Abenaki Fm, although it is early Cretaceous in age (Kidston et al., 2005; Wade and MacLean, 1990). Roseway unit is restricted to the La Have Platform and is found in Mohawk B93 and Bonnet P23 wells (Figures 10 and 12). The Roseway unit is the lateral equivalent of the fluvial-deltaic-strand plain successions of the Missisauga Formation (Kidston et al., 2005.) and last until the Hauterivian MFS.

Figure 17: A) GDE map at the Near Base Cretaceous Unconformity (NBCU – K137); B) GDE map at the Hauterivian MFS (K130). The K137 - K130 interval corresponds to the middle Missisauga / Roseway formations. This interval occurs during the Avalon Uplift and the arrival of the New England hot spot. This time frame corresponds to the reappearance of clastic input which increases progressively through time, alternating with carbonate sedimentation. Sources focused mostly between Georges Bank and Nova Scotia. Calciturbidites are recorded offshore Mohawk and Bonnet, whereas siliciclastic sediments predominates offshore Georges Bank.

THE BARREMIAN – CENOMANIAN SEQUENCE K130-K94

The late early Cretaceous and Cenomanian period corresponds to a drastic change in sedimentary succession with a switch from a carbonate dominated margin to a clastic dominated margin (Figures 15 and 20; PL. 3.3.1 to 3.4.3). At the start of the Barremian, Georges Bank basin and La Have platform are dominated by carbonated successions corresponding to the **Roseway Member** which continue to growth until the **Intra Aptian mfs** (Figures 20). By the early Barremian, carbonate growth stops on Georges Bank and decreases progressively to La have Platform until the Aptian. Carbonate sedimentation on Georges Bank is replaced by prodeltaic shaly succession at first and by the sandstone succession of the Shelburne delta by mid-Aptian that feeds deep water turbidites (Figures 17 to 20; PL. 3.4.1 to 3.4.3). Clastic input increases through the late Aptian to mid Albian across the margin, with thick sandstone accumulation in Georges Bank and south of Shelburne subbasin and predominantly shale succession for the rest of the margin (Figures 15 and 20). The clastic accumulation is interrupted during the mid-Albian by a short interval of carbonate accumulation essentially developed on Georges Bank.

By the late Albian a major unconformity is observed called the **late Albian unconformity (K101)**. This unconformity has a variable impact on sedimentation across the margin, with a minimum impact on Georges Bank and more or less well preserved early Cretaceous sediment, but large impact on La Have Platform with most of the early Cretaceous missing. After K101 a global increase of shale proportion in the basin is observed. The Shelburne delta activity continue until the Cenomanian and because of limited accommodation space on the shelf, a large part of the sediment is transferred to the basin. In the mean time a wide by-pass area developed on the slopes offshore La Have platform. At the end of the Cenomanian another major unconformity takes place called the **Cenomanian – Turonian unconformity (K94)**, but has a lesser impact on sedimentation than K101.

The constant increase of clastic sediment with a paroxysm during the Albian – Cenomanian is consequent to the regional uplift that started at the late Jurassic early Cretaceous resulting from the Avalon uplift and New England seamount hot spot. Besides an increase of terrain altitude and watershed slopes that has as a consequence an increase of sedimentary influx, a major rerouting of the St Lawrence ancestor and neighboring rivers to the Shelburne subbasin occurred during the late Hauterivian – early Aptian until the late Cenomanian (Tsikouras et al., 2011; Stradhee, 2012) (Figure 18). This shift in sediment source adds to the already increasing regional influx and therefore accentuates shelf and slope erosion and deep water sedimentation.

Figure 18: Map showing proposed paleogeography of Atlantic Canada during the early Cretaceous (from Stradhdee, 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, thus Shelburne subbasin. (For further information, see Pe-Piper et al., 2011; Tsikouras et al., 2011)

Identication

- Number of exploration wells reaching the Aptian - Albian Sequence : 5 wells (PL. 3.2.12, 3.3.1 and 3.3.2; Enclosures 3.3 to 3.4)
- Formations: **Logan Canyon** eq .Fm; **Shortland Shale** eq. Fm; **Naskapi Member**
- 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. 3.2.12 and 3.3.1)
- Lithostratigraphic cross-sections (PL. 3.2.12 and 3.3.2) and Geological Composite Well Logs (Enclosures xx to xx)
- Architectural cross-sections (PL. 3.4.1 to 3.4.2)
- Age: **Barremian – Cenomanian**

Description

Logan Canyon and Shortland Shale eq. Fms

Logan canyon and Shortland shale Fms span the entire early Cretaceous. The Logan Canyon Formation is an upward fining trend similar to the Missisauga Fm. It has been subdivided into four members, two of which are shale dominated (**Naskapi and Sable Shales**); the two others are sandstone dominated (**Cree and Marmora members**) (MacLean and Wade, 1993) representing alternatively transgressive and regressive facies. It is generally interpreted to have been deposited in an estuarine and shallow marine clastic shelf environment during a long term transgression from Aptian to Cenomanian that culminated during the Late Cretaceous. The mudstone and chalk corresponding to a global rise in sea level (Weston et al., 2012). The Logan Canyon eq. Fm grade distally to **Shortland Shale**, a slope and deep water shale facies. In the Shelburne Basin Naskapi and Cree members equivalent are observed.

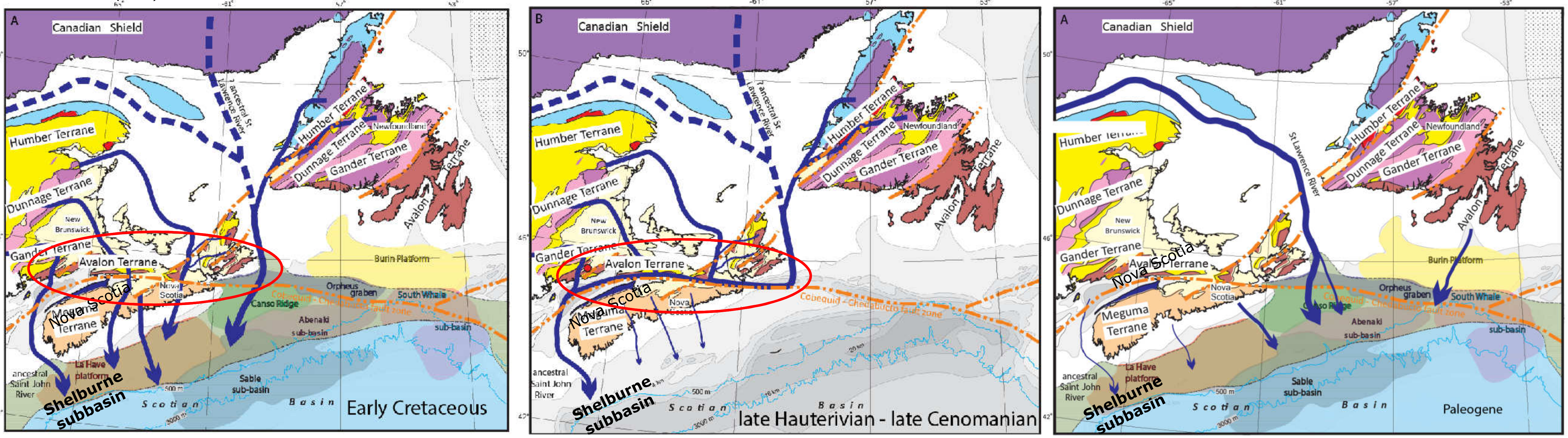
Cree Member eq.

The Cree Member is late Aptian to late Albian. Cree Member eq. is predominantly sandy and consists of interbedded sandstones and shales with minor siltstone. Cree Member eq. is well represented on Georges Bank because of the Shelburne delta.

Naskapi Member eq.

The Naskapi Member and lateral eq., starts after the intra Aptian MFS, which is characterized by a thick dark brown to black shaly unit separating the top Upper Missisauga or Roseway from the Logan Canyon eq Fm or Shortland shale eq. Naskapi Member is barely present on the margin with 16 m of shale observed in Mohawk B93.

From Strathdee (2012)



THE LATE CRETACEOUS TO EOCENE SEQUENCE K94-T50

Identication

- Number of exploration wells reaching the Late Cretaceous to Eocene Sequence: 4 wells (PL. 3.2.12, 3.3.1 and 3.3.2; Enclosure 3.3 and 3.4)
- Formations: **Dawson Canyon**, **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. 3.2.12, 3.3.1)
- Lithostratigraphic cross-sections (PL. 3.2.12, 3.3.2) and Geological Composite Well Logs (Enclosures 3.3 and 3.4)
- Architectural cross-sections (PL. 3.4.1 to 3.4.3)

Description

Dawson Canyon Formation

The Dawson Canyon eq Formation consists of thick marine shales intersected by chalk and limestone layers near the early Turonian. The formation is found all across the Scotian Shelf, but the sequence of deposition appears to be diachronous (PFA, 2011). The Wyandot Formation seems to be absent in the Shelburne subbasin and as a consequence Dawson canyon Formation is topped by the Ypresian Chalk.

Ypresian Chalk

The Ypresian Chalk is an early Eocene Formation. It's a wide spread formation 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 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 wide spread margin collapse associated with intense erosion that drastically increased the impact of the Ypresian unconformity on pre-existing sedimentary succesions.

LATE EOCENE TO PRESENT SEQUENCES

Banquereau Fm

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

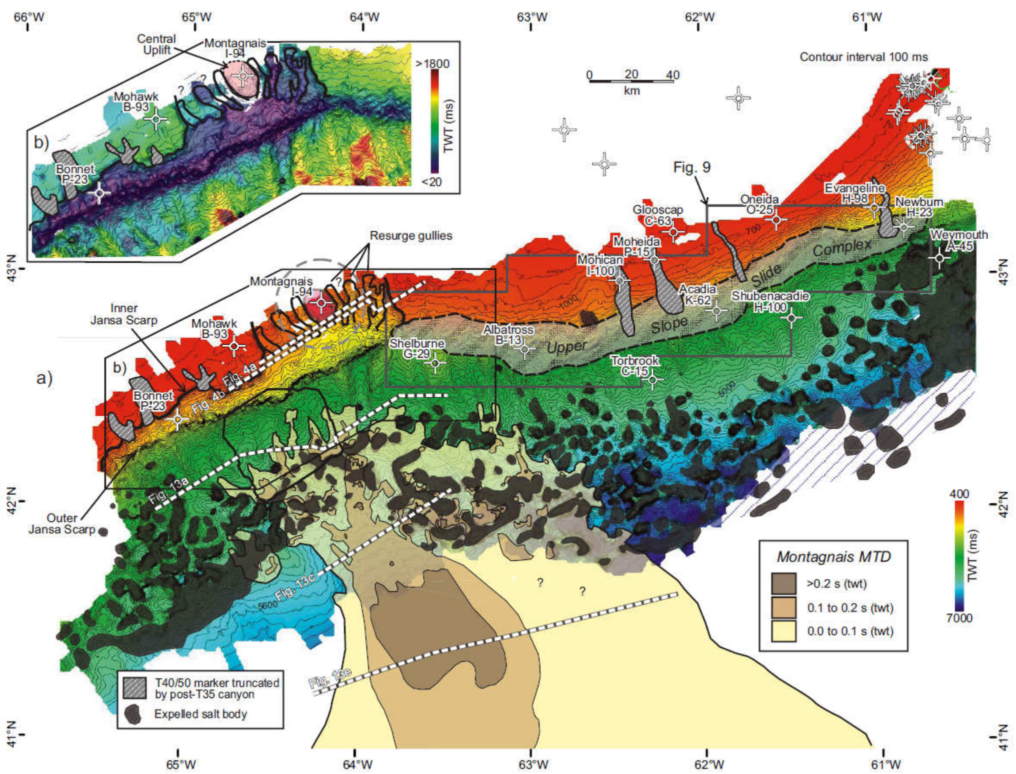


Figure 19: Time-structure map (*a*) and Time-thickness map (b) of the T50-40 marker, showing the location of the Montagnais Impact crater in the southwest and related mass-transport deposit (MTD) (*From Deptuck and Campbell, 2012*).

The Montagnais impact is within the study area and had a significant impact on sediment preservation on the shelf and slope.

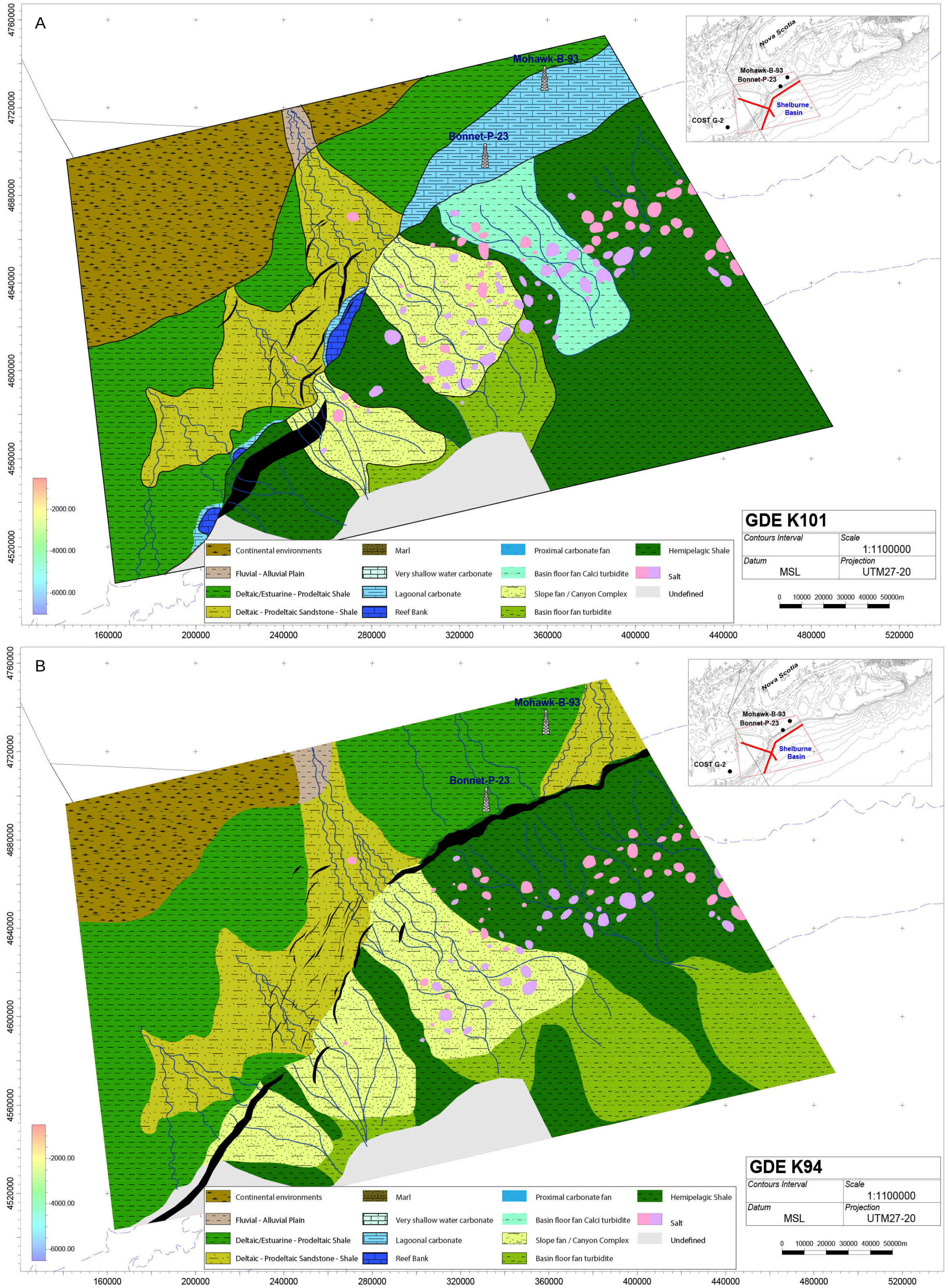


Figure 20: A) GDE map at the Albian unconformity (K101); B) GDE map at the Turonian – Cenomanian unconformity. The K101 – K94 interval corresponds to the Logan Canyon/ Shortland shale Fms. This interval occurs at the end of the Avalon Uplift and New England hot spot event. During this time frame well developed deltaic systems formed on the shelf and well developed basin floor fan turbidite systems, slope valley and channel complexes.

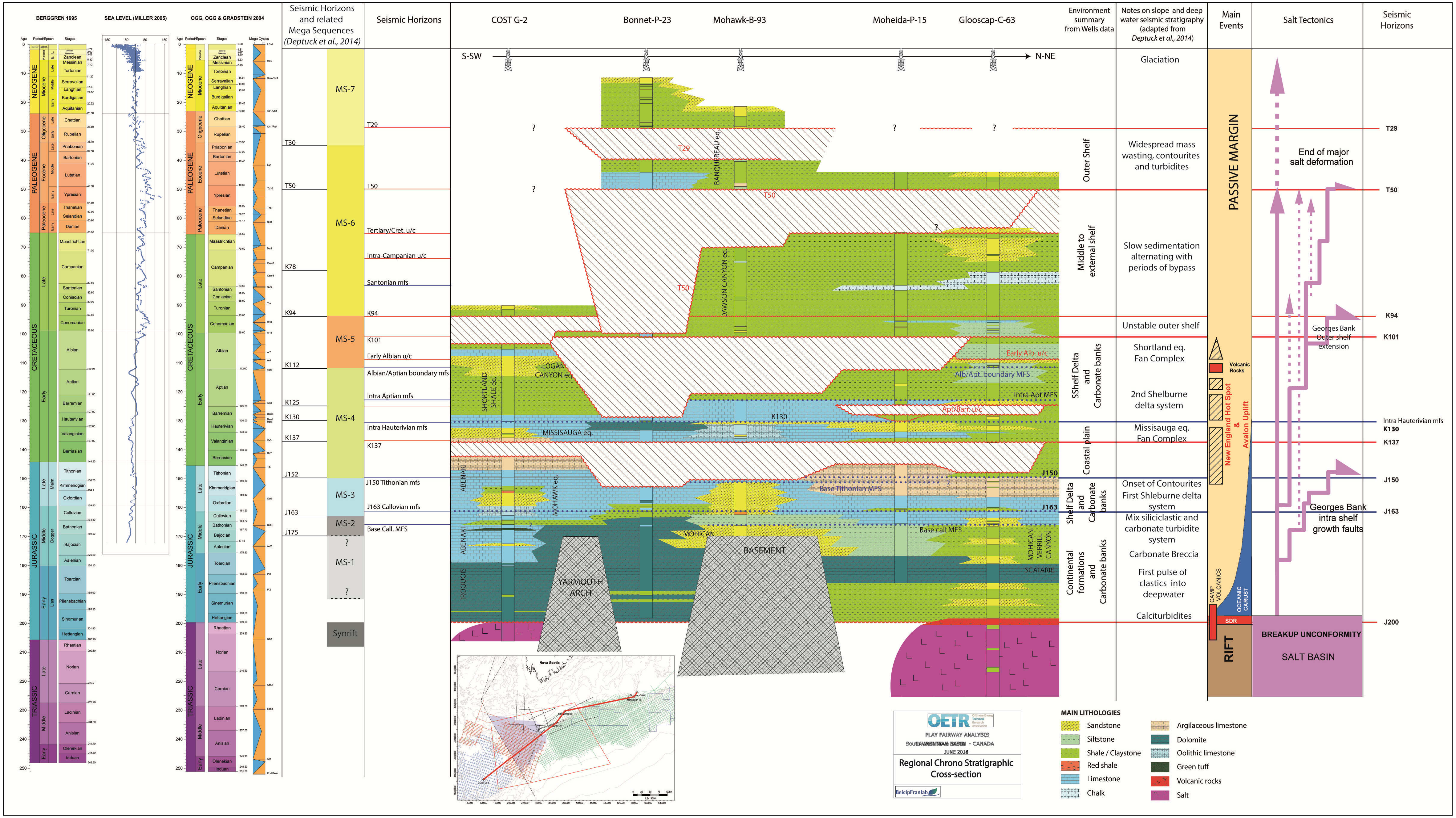


Figure 21: Chrono – lithostratigraphic panel showing lithological correlation through time in perspective of geological events. The correlation panel shows the timing, duration and lateral changes of sedimentary processes as well as successive erosive events. Wells correlation shows that the Cretaceous is not well preserved on the southwestern part of the Scotian margin, mostly due to the T50 and K101erosive events. The Tithonian MFS (J150) is largely absent in Bonnet and Mohawk area, but observed in Cost G2, highlighting a lower impact of the K137 unconformity near Georges Bank. The panel illustrates quite well the lateral variation of facies across the margin through time. Thus, thick carbonate accumulation are observed during the Jurassic in Georges Bank and Shelburne subbasins and whereas for the same time interval the margin tends to be clastic dominated to the North near Glooscap (Mohican sub basin). Influx of clastic sediment is significant in the mid – late Jurassic, particularly in Shelburne and Georges Bank subbasins.

During the early Cretaceous (K137 – K101), carbonate intervals are predominant around Bonnet and Mohawk wells whereas they are interbedded within sandstone and shale on Georges Bank due to the influence of the Shelburne delta. The K101 erosion significantly removed early Cretaceous sediment around Bonnet and Mohawk, whereas Clastic succession are well preserved on Georges Bank area.

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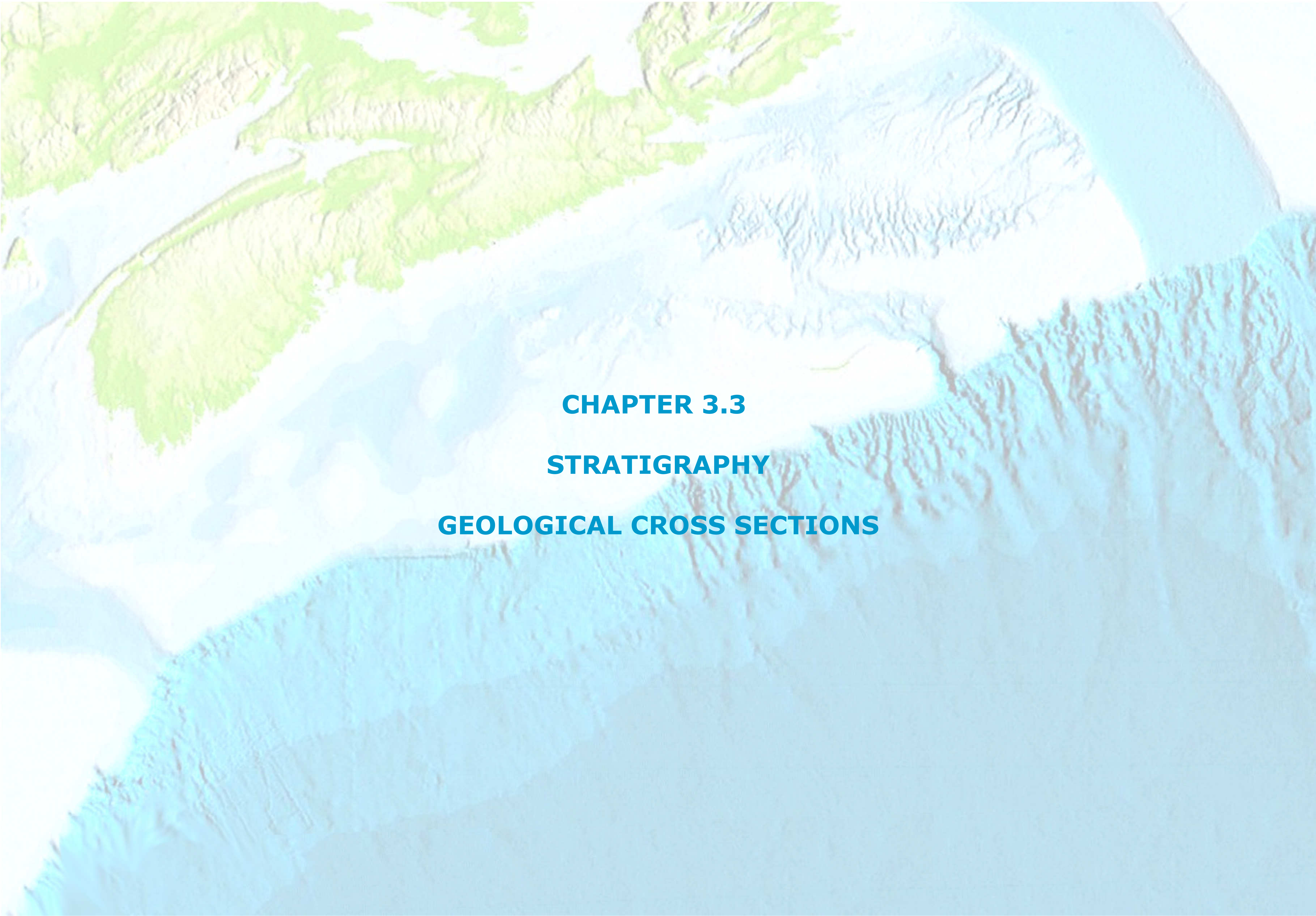
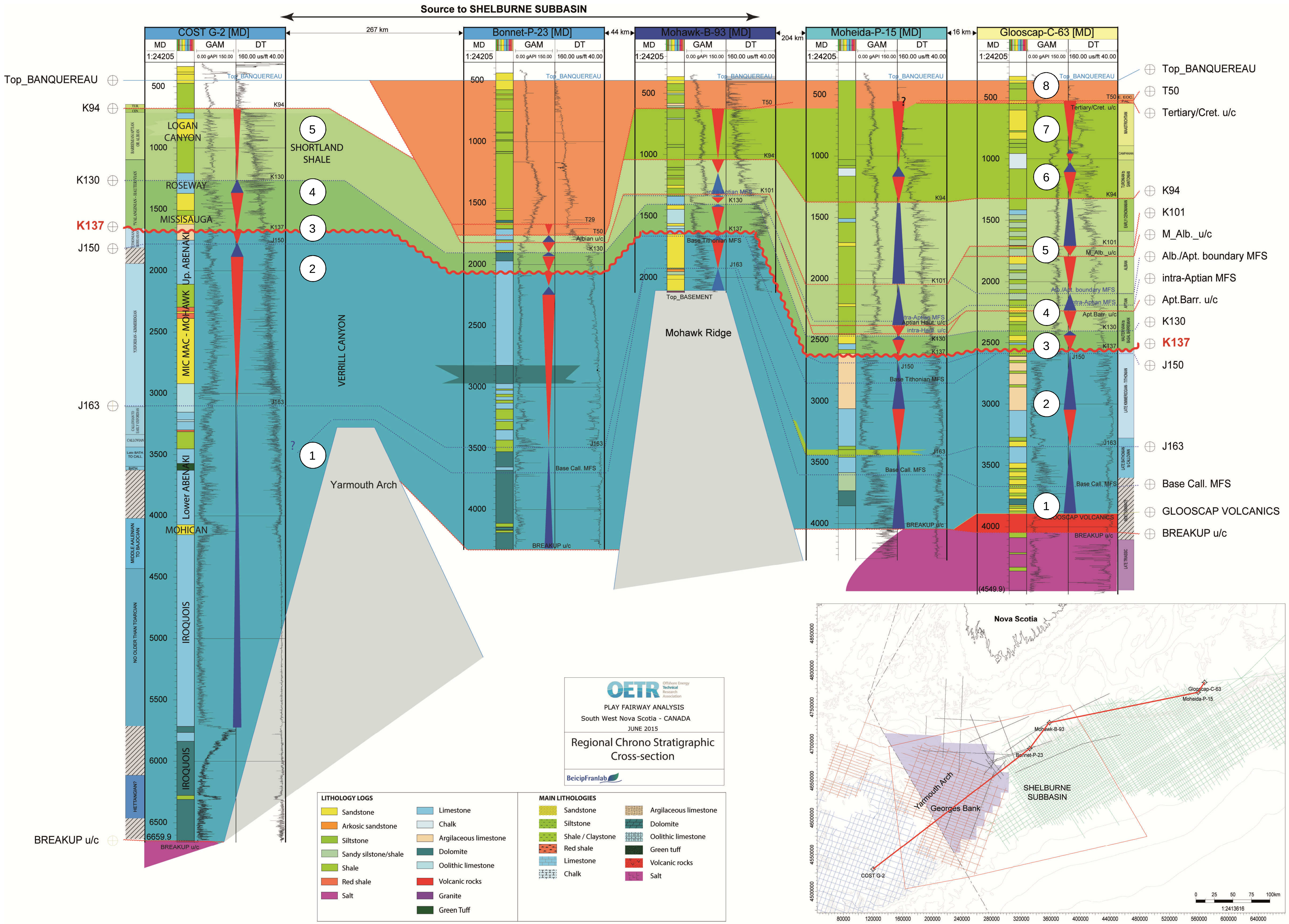


CHAPTER 3.3

STRATIGRAPHY

GEOLOGICAL CROSS SECTIONS



Triassic sequence (syn-rift)

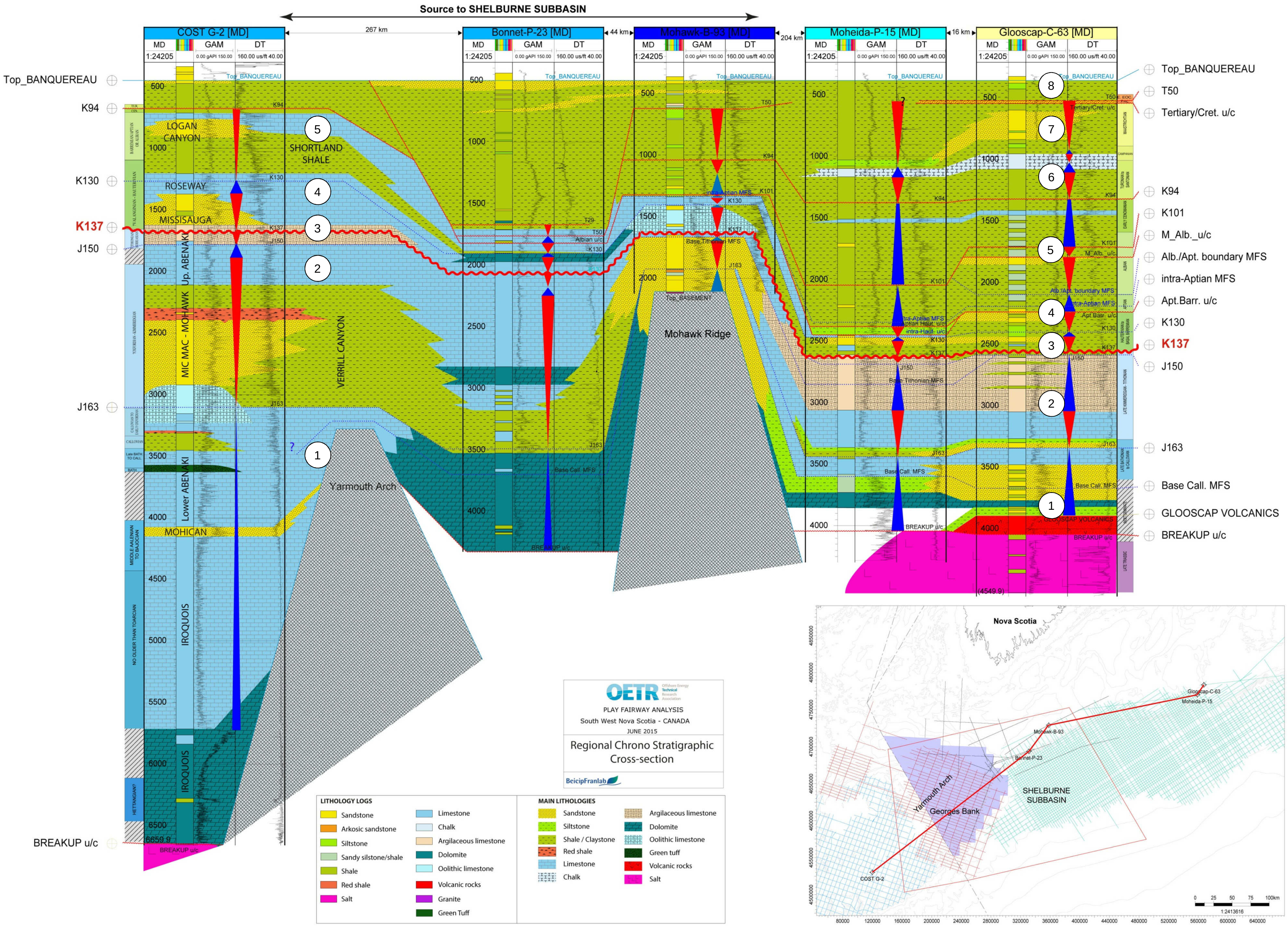
The top part of the syn-rift sequence is of Late Triassic age. It is observed in Glooscap C-63, where it contains siliciclastics and evaporites corresponding to fluvio-lacustrine conditions. The syn-rift sequence is overlain by the break-up unconformity and basalts.

Hettangian-Valanginian sequences (Sequences 1 to 3)

The first post-rift sediments deposited are dated of Hettangian age (Cost G2) and correspond to the lower part of the Iroquois Fm. During the Bajocian, a transgressive sequence with non-marine siliciclastics grades into Callovian shallow-marine oolitic carbonates. During the Late Callovian, the carbonate platform is drowned and marine shales and sandstones are deposited. Carbonate sedimentation reinitiates at the Callovian-Oxfordian boundary with the development of an oolitic carbonate ramp, which subsequently evolved into a reefal platform during the Oxfordian (Bonnet P-23). Beyond the reef margin, shales accumulated in a deep open-marine environment. The top of the Late Jurassic deposits are eroded by the Berriasian-Valanginian unconformity, recognized biostratigraphically across the margin.

Valanginian-Aptian sequence (sequence 4)

The demise of the carbonate platform starts during the Late Jurassic and increases during the Early Cretaceous. Shallow-marine siliciclastics derived from Mohawk and Shelburne. Away from these siliciclastic inputs, shallow-marine carbonate sedimentation continued (Bonnet P-23).



Aptian-Cenomanian sequence (sequence 5)

The sequence is identified on La Have Platform. Away from significant sand sources, shallow water sedimentation is predominantly argillaceous. The sedimentation rate is very low both in the deep water basin and on the remnant shallow-water carbonate platform (Bonnet P-23). The Cenomanian unconformity is recognized across the margin.

Turonian-Campanian sequence (sequence 6)

As observed in the Central and Eastern Scotian Shelf, 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 starts 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)

Chalk sedimentation is still predominant over the Southwest part of the Scotian Margin, except around Glooscap C-63, where shales and sands are present derived from a local deltaic system. The sequence is deeply eroded by the Eocene unconformity and the Montagnais meteorite impact at 50.50 ± 0.76 Myrs. The largest and deepest erosion is observed in Bonnet P-23, where Late to even Early Cretaceous sediments are eroded and transfer into the adjacent basin. The Eocene unconformity is overlain by the Ypresian chalk.

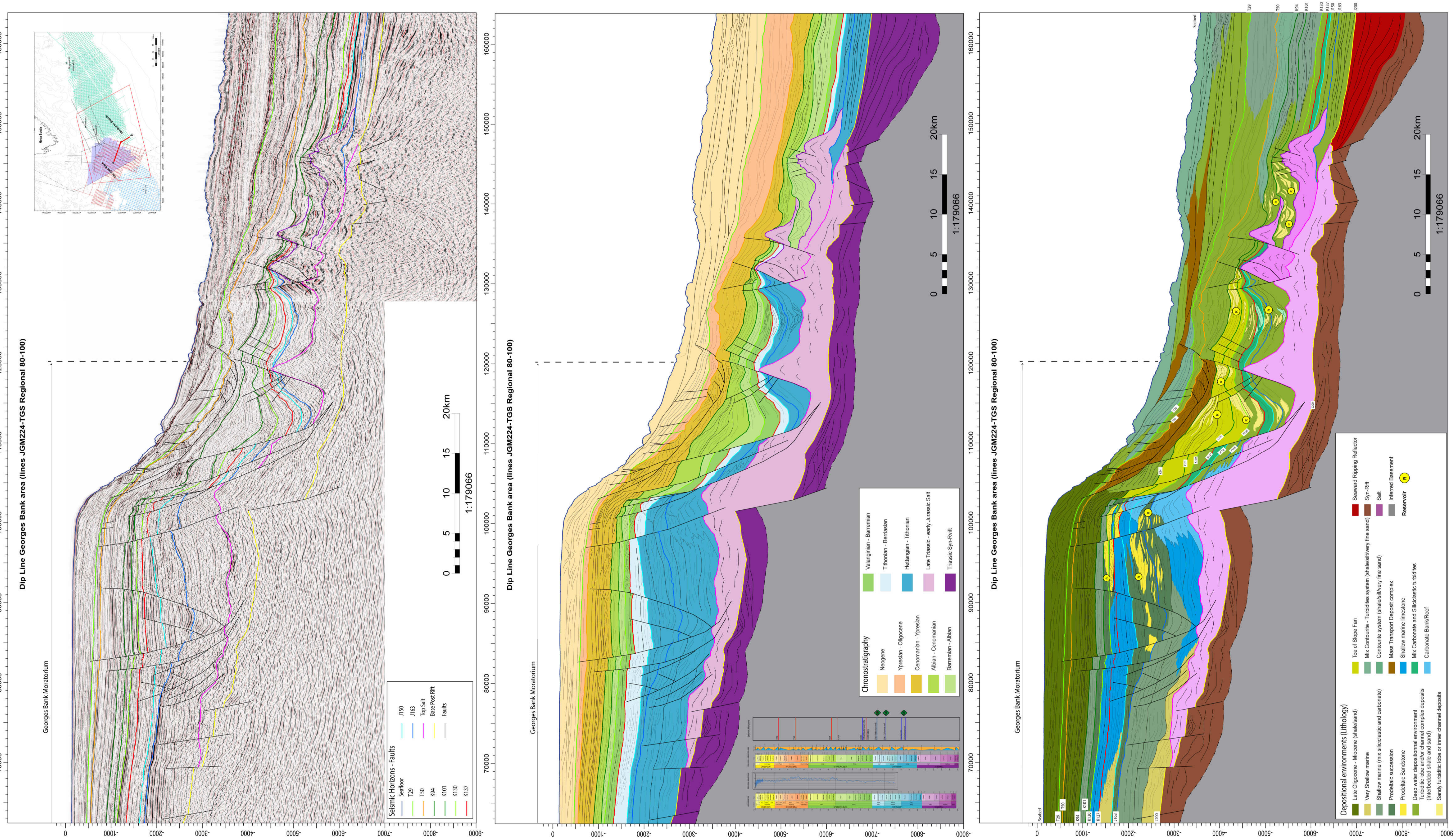
Lutetian-Priabonian sequence (sequence 8)

This sequence, documented at the top of the dated section in wells, records widespread open-marine shales preserved below the Oligocene unconformity.

CHAPTER 3.4

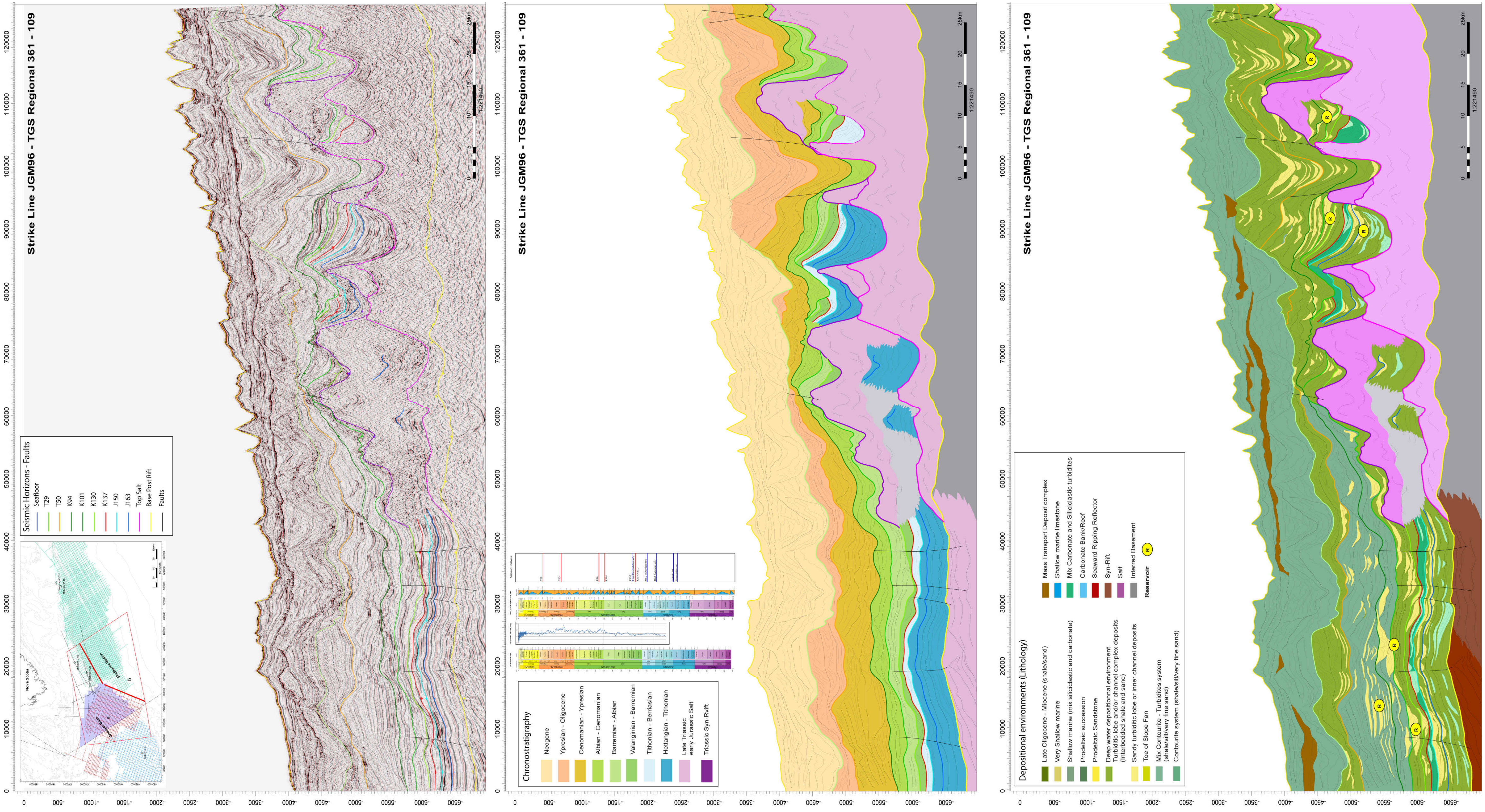
STRATIGRAPHY

SEISMIC STRATIGRAPHY



The dip section illustrates the architecture of this part of Georges Bank margin since J200 (Breakup Unconformity).

The deepest part of the cross-section shows the autochthonous and allochthonous salt identified above basement. The salt is overlapped by thick early to middle Jurassic carbonate sediments (J200 - J163). This series is essentially composed of carbonate banks until about J163, time around which deltaic and prodeltaic sediments prograde on the shelf and feed an early turbidite systems on the basin slope and rise. This interval corresponds to the development of an early Shelburne delta system. Near top Jurassic the sedimentation is dominated by carbonate sediments and marine shale related to the transgressive trend. Calciturbidites are inferred to be significant in deep water during the early to mid Jurassic as well as during the J150 – K137 interval. Sediment accumulation during the Cretaceous is dominated by prodeltaic sediment interbedded with limestone on the shelf, whereas the basin is dominated by clastic turbidites and marine shale. The late Cretaceous until the base Paleocene is composed of chalk and marl sediments. The Chronostratigraphic transect (2nd line) shows thick Jurassic succession on the shelf, whereas Cretaceous succession are thicker downslope due to limited accommodation space on the shelf and extensive base of slope deformation related to salt movement. The Lithostratigraphic transect (3rd line) highlight the well developed Shelburne delta through time, and illustrates the change in accommodation space on the shelf and slope from the Jurassic to the Cretaceous.



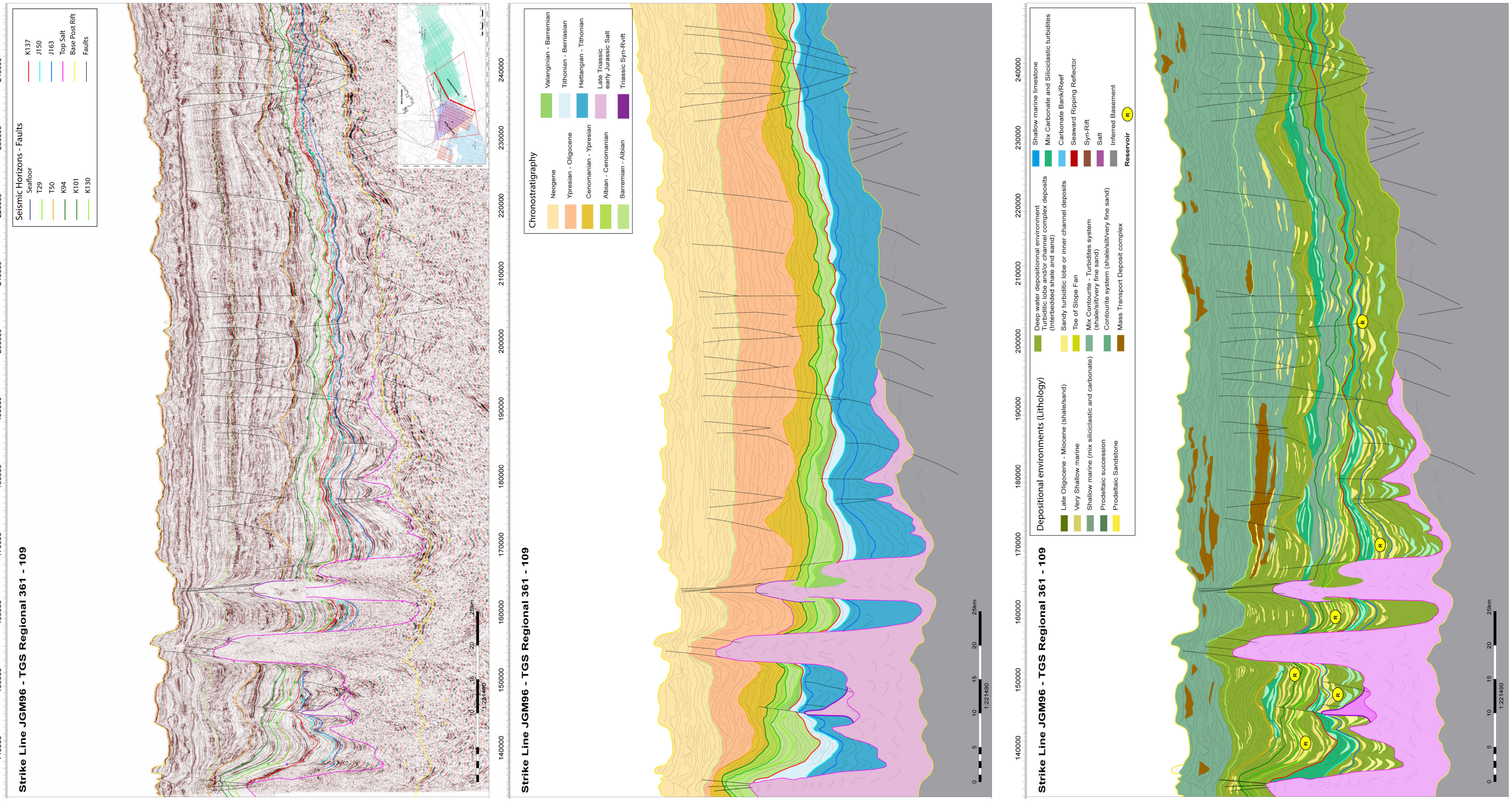
Part one of the strike section that illustrates the proximal offshore architecture of the entire Shelburne Subbasin since J200 (Breakup Unconformity)

Salt deformation is well observed here with formation of intra salt mini basins and overhanging salt sometimes sealing the mini basins. The early Jurassic interval is at first composed of marine shale and calciturbidites until about J163, time around which an early turbidite systems formed fed by the Shelburne delta system. The early calciturbidites are inferred to be related to mix of breccia and carbonate MTDs. Near top Jurassic the sedimentation is dominated by calciturbidites and marine shale. Sediment accumulation during the Cretaceous is dominated by clastic turbidites and marine shale. During the Jurassic and Cretaceous the salt deformation controls the sediment distribution across the basin. The late Cretaceous until the base Paleocene is composed of chalk and marl sediments.

The Chronostratigraphic transect (2nd line) shows that intra salt mini basin record different sedimentary succession. Sometimes successions from Jurassic to Cretaceous, sometimes only Cretaceous or even late Cretaceous to Paleogene. Some mini basins are sealed by overhanging salt walls.

Architectural CROSS-SECTION: Strike transect part 1 (lines JGM 96)

STRATIGRAPHY



Part two of the strike section that illustrates the proximal offshore architecture of the entire Shelburne Subbasin since J200 (Breakup Unconformity)

Observations made here are very similar to the first part of the transect, with intra salt mini basins showing thick sedimentary successions but of different timing. Well developed Jurassic and Cretaceous turbidite systems with large stacked channels and channel levee complexes are observed within intra salt mini basins. Out of the salt area, turbidites tend to spread out and formed proximal to mid turbidite lobes. Thick Jurassic and Cretaceous turbidites accumulation are observed in the basin. Calciturbidites are abundant in the lower Jurassic and the J150 - K137 interval. Jurassic turbidite systems seem to be more proximal than the Cretaceous ones. Miocene interval shows well developed calciturdidite systems which could represent also interesting reservoirs. Off the salt area carbonate and clastic sediments originate essentially from LaHave Platform (see GDE maps for sediment input).