CHAPTER 4

STRATIGRAPHY

Objectives

Chapter 4 has for objective to provide the gross geological framework of the Laurentian Basin in integrating new results from biostratigaphy, sequence stratigraphy and sedimentary environment. Based on 4 wells, the geological formations from early Triassic to Pliocene in age are described in regard to the main tectono-sedimentological sequences. This succession encompasses the late Triassic to Mid Jurassic sequence (200-163 Ma), the Mid to Late Jurassic sequence (163–150 Ma), the Lower Cretaceous sequence of the Missisauga delta (150 to 130 Ma), the Mid-Upper Cretaceous of the Logan Canyon sequence (130 to 94 Ma) and the Upper Cretaceous – Tertiary sequence. Ages of the geological formations through the basin were defined by biostratigraphic markers, some of them correspond also to regional seismic horizons.

An updated Stratigraphic Chart, Geological Composite Well Logs, lithostratigraphic and chronostratigaphic cross-sections are produced meanwhile the architectural aspect of the main sedimentary sequences are designed along seismic cross-sections.

Stratigraphy framework overview

The Laurentian Basin contains Mesozoic-Cenozoic sedimentary rocks up to 15km thick that were deposited during the rifting of Pangea and the North Atlantic ocean opening. The earliest basin infilling occured during the **Triassic rifting** and consists of red continental clastic and evaporite deposits. During the **Early Jurassic rift** basins were gradually filled by clastic and carbonate sediments with the transition to seafloor spreading. Fully marine conditions developed by **Mid to Late Jurassic** leading to the formation of alluvial plain, deltaic and carbonate environments. The **Early Cretaceous** was dominated on the shelf by deltaic progradation and shelf clastic deposits as a consequence of the Avalon uplift. **Late Cretaceous/ Early Tertiary** sedimentary deposits are dominated by transgressive shales, sporadic influx of deltaic sands, limestone and chalk units. 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). **Mio-Pliocene** formations are overlained by unconsolidated glacial till, glaciomarine silts and marine sediments that were deposited during the Quaternary.

INTRODUCTION – STRATIGRAPHY

Objectives

The objective of Chapter 4 is to extend the Mesozoic-Cenozoic stratigraphic framework of the Scotian margin to the Laurentian Basin in order to better constrain our understanding of age and sequences of major geological events that controlled the sedimentary infill of the basin thus the petroleum system. This results in the following:

- A lithostratigraphic overview of the Laurentian Basin based on facies and lithological interpretation at well, for 8 relevant stratigraphic surfaces delimited by 9 key seismic horizons
- A second order sequence stratigraphic breakdown for each studied well illustrating major stratigraphic sequences (Plates 4.3.1 and 4.3.2)
- A stratigraphic and lithostratigraphic chart for the Laurentian Basin (PL 4.4.1 and 4.4.2) adapted from the Scotian Margin stratigraphic chart presented in Figure 2
- A stratigraphic and lithostratigraphic interpretation of 2 key seismic transects for 2D petroleum system modeling (Temis Suite 2008® software).

Well database and methodology

The Well database consists of a selection of 4 key wells (Table 1) distributed over the Northeastern Scotian shelf and slope and Southeastern shelf of Newfoundland (Figure 1). These 4 wells are used as a basis to define the lithostratigraphy and sequence stratigraphy of the Laurentian Basin.

The Geological Composite Well logs are presented in Enclosures 4.12 to 4.15. They display a (1) logs suite (GR, NPHI curve, RHOB); (2) a lithological column from both lithofacies and cuttings; (3) biostratigraphic surfaces; (4) formation tops; (5) HC occurrences; (6) sequence stratigraphy breakdown and (7) depositional environments.

- *Wells Lithology and Petrophysics*

The lithological interpretation was carried out on the 4 key wells and shown in their respective composite log. For each well, lithologies are obtained from final well reports and petrophysical analysis. Such information includes qualitative log interpretations, mud reports, geological mud logs, existing composite well logs, and master logs.

Petrophysical analysis was run for 3 out of 4 wells (Bandol-1, East-Wolverine G-37, Heron H-73) in order to constrain the GDE maps. 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. It has to be mentioned that final lithologies could not be automatically computed from logs due to missing log intervals.

- *Biostratigraphy in wells*

New quantitative biostratigraphic analyses of the 4 wells were carried out to support the sequence stratigraphy and seismic correlations across the Laurentian Basin.

The biostratigraphic interpretation for each well provides the timeframe and stratigraphic age references (datum) to construct the sequence stratigraphic breakdown.

- *Sequence stratigraphic breakdown and depositional environment in wells*

Sequence stratigraphic breakdown is performed on the 4 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 is 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 11 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 Laurentian Basin scale through seismic mapping and wells correlation. Results from biostratigraphy, sedimentology and seismic integration highlight the main sedimentary infill stages of the margin.

- *Wells correlation*

Although wells correlation at the Laurentian Basin scale provides a broad picture of the petroleum system, the geological complexity of the margin cannot be addressed through the interpretation of 4 wells . Therefore, the stratigraphic analysis of the Laurentian Basin was extended to the Scotian Basin in adding 3 wells from the 2011 PFA study. These wells are used to constrain the stratigraphic and lithostratigraphic correlations across the margin.

Content

Chapter 4 includes the following:

- A Lithological and stratigraphic overview of the Laurentian Basin resulting from wells description and supported by the updated stratigraphic Chart of the Scotian Margin (Figure 2). This overview sets up the sedimentological setting that will be used in the current PFA.
- A Biostratigraphic summary of calibrated formation tops and their integration into the stratigraphic chart (Figure 2; Plates 4.1.1 and 4.1.2)
- 2 well correlation plates illustrate the vertical and lateral variation of sedimetary facies and depositional environment through time (PL 4.3.1 and 4.3.2.)
- 2 Chronostratigraphic and lithostratigraphic sections display the stratigraphic sequences in time highlighting the impact of geological events on sequences thickness, spatial distribution of depositional sequences and time-gaps (Plates 4.4.1 and 4.4.2)
- 2 Seismic sequences and facies analysis performed on 2 key seismic transects (Plates 4.5.1 to 4.5.4) showing the 2D geometry of the full sedimentary system and successive depositional sequences in response to geological envents such as salt tectonic, uplift, source shift etc....

Well	KB (m)	Water Depth (m)	TD (m)	Formation at TD	Stratigraphy	Study
BANDOL-01	23	93	4046	Abenake	Callovian	Present study
EAST WOLVERINE G-37	31.6	1890.6	6857	Verrill Canyon	Bathonian	
EMERILLON C-56	29.9	120	3276.6	Mohican	Bajocian	
HERON H-73	25.9	105	3658	Salt	Pliensbachian	
COHASSET L-97	32.9	21.6	4872	Iroquois	Bajocian	2011 PFA
DAUNTLESS D-35	31.4	69.2	4741	Baccaro	Oxfordian	
SOUTH GRIFFIN J-13	39.6	63.4	5911	Mic-Mac	Oxfordian	

Table 1: List of the 4 wells selected for the stratigraphic study and 3 additional wells from the 2011 PFA study used as reference wells

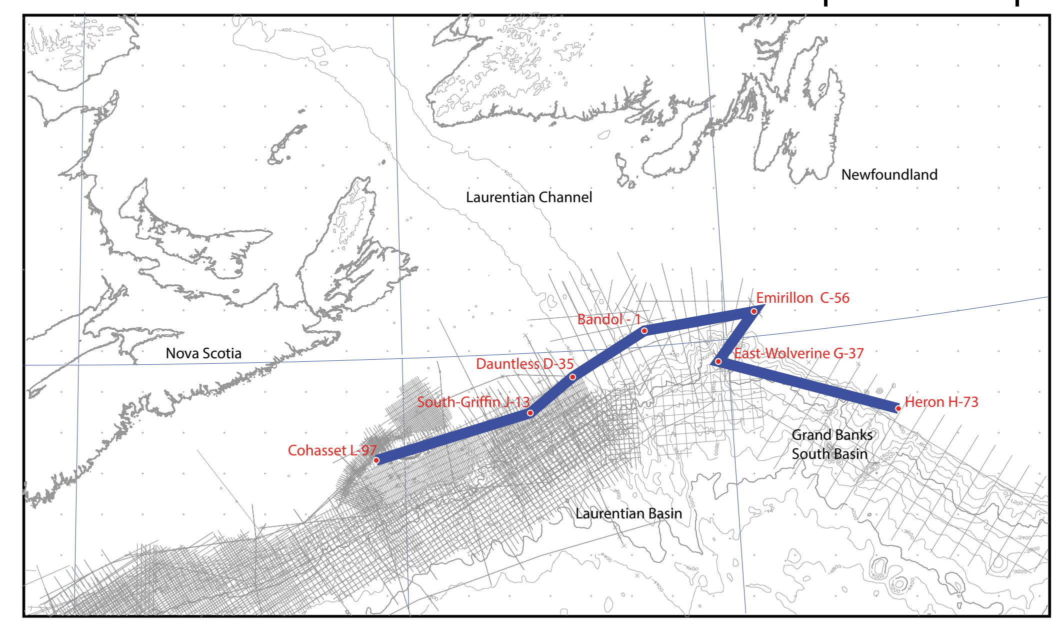


Figure 1: Wells and transect location across the Scotian Margin

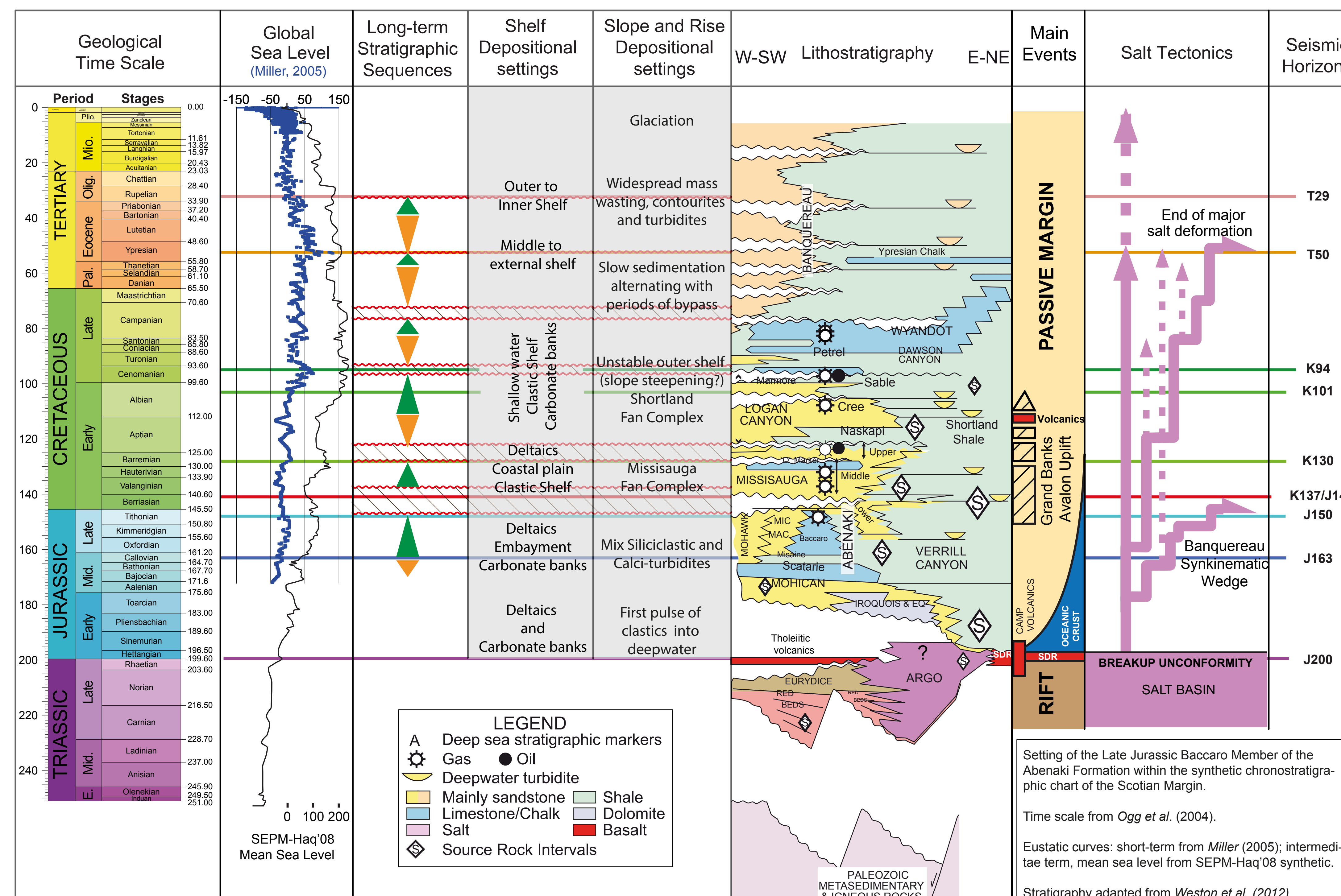
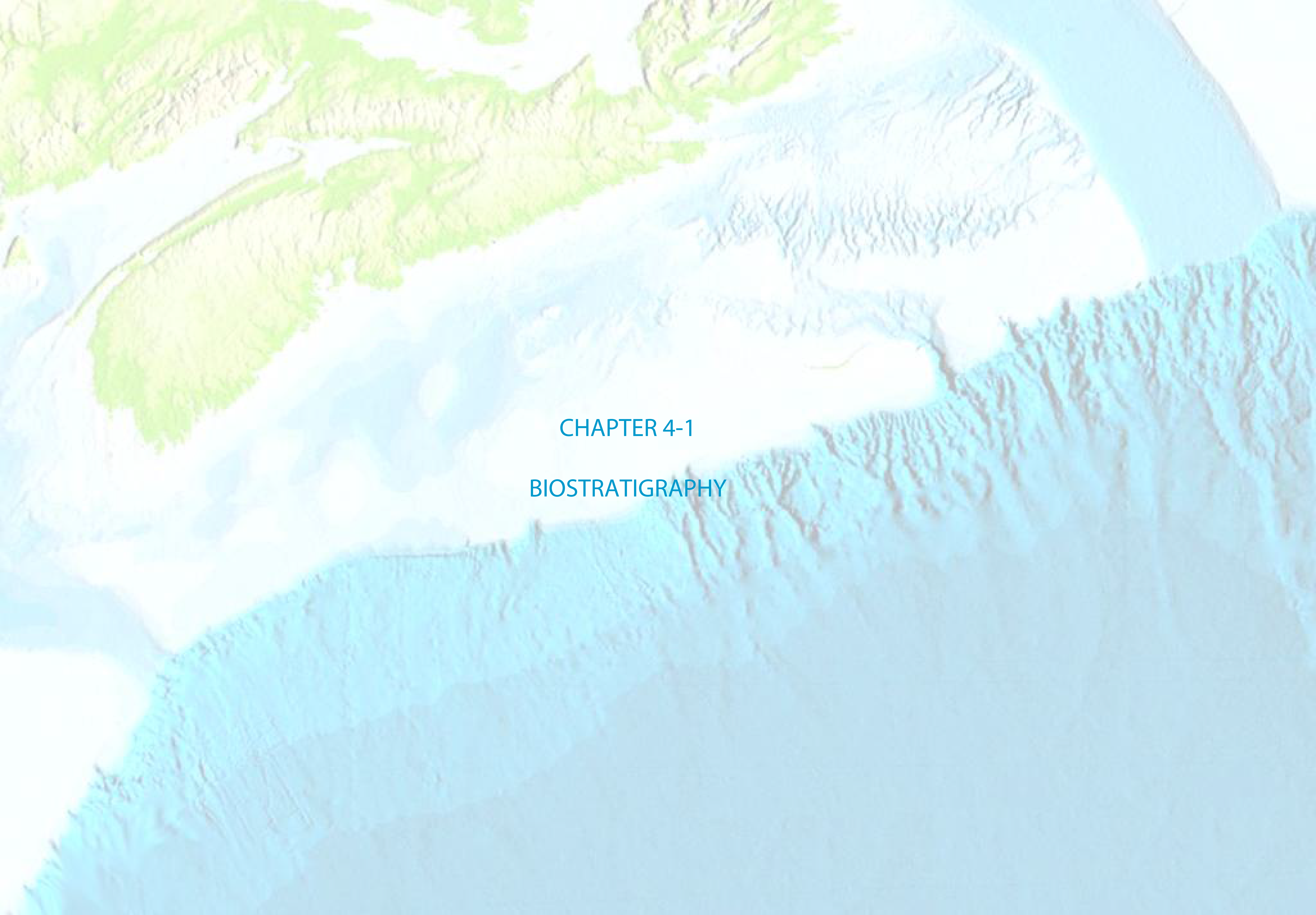


Figure 2: Stratigraphic Chart of the Scotian Margin (Eastern Canada)



CHAPTER 4-1

BIOSTRATIGRAPHY

This chapter summarizes the results of a biostratigraphic study of 4 wells from the Laurentian Basin, which was designed to calibrate the seismic mapping with that of the eastern part of the Scotian Margin. The results from these 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)*. Numerical ages reference Gradstein *et al.* (2005) to be compatible with this previous study. The new samples analysed biostratigraphically and the disciplines of the biostratigraphic data reviewed are outlined in Table 2 and a fuller summary of the results of the study is included in Enclosures. For well locations in the Laurentian Basin, see Pl. 4 Stratigraphy– Introduction. Summary charts showing the stratigraphic breakdowns of these 4 wells are provided in Enclosures 4.1 to 4.4 and tabulated in Table 3, while range charts showing the biostratigraphic data from new analyses undertaken in this project are included in Enclosures 4.5 to 4.9.

The biostratigraphic data evaluated consisted mainly of pre-existing data of various vintages, which was supplemented by targeted new analyses (see Table 2). Data comprised:

- integration of internal GSCA data and reports dating from the 1970's and 1980's, mainly consisting of 'top' occurrences of palynological and micropalaeontological species (Emerillon C-56 and to some extent Heron H-73)
- recent industrial reports that included quantitative data and full range charts (Bandol-1 and East Wolverine G-37);
- new quantitative analyses undertaken for this project (Bandol-1, East Wolverine-1 and Heron H-73);
- a review of pre-existing palynological preparations held at the C-NLOPB (Heron H-73) and C-NSOPB (Emerillon C-56).

Because of the variations in data type, some interpretations provide broader stratigraphic resolution and the picks for the relevant biostratigraphic surfaces are less confident (e.g. Emerillon C-56) than in others (e.g. Bandol-1, East Wolverine G-37).

Within the Scotian Margin PFA, 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)

The majority of these, plus other regional biostratigraphically distinct surfaces, have been recognised within the 4 well sections studied from the Laurentian Basin (see Enclosures 4.1 to 4.4 and Table 4). Their occurrences with the wells have been checked by seismic correlation to wells in the original Scotian Margin PFA study, particularly Dauntless D-35. Notable differences from the wells in the Scotian Margin are:

- The Tithonian MFS and the majority, if not all, of the Late Jurassic section is absent from all 4 new well sections due to erosion beneath the 'Near Base Cretaceous' or older Cretaceous/Late Jurassic unconformities. These are amalgamated within the 'Avalon Unconformity' of the Grand Banks and NE Scotian Margin;
- A wedge of earliest Cretaceous (?Berriasian) aged sediments is present beneath the 'Near Base Cretaceous Unconformity' in the East Wolverine G-37 well, and it is these earliest Cretaceous sediments that overlie the Middle Jurassic in East Wolverine G-37;
- Within East Wolverine G-37, a major flooding surface of Bathonian age is recognised and termed 'Bathonian MFS J166'. This is tentatively correlated into Emerillon C-56 and may be comparable to the 'Bathonian/Bajocian MFS' recognised in Cohasset L-97 (Weston *et al.*, 2012);
- Within Heron H-73, shallow marine sands of Bajocian age unconformably overlie claystones with a high gamma ray log signature of Early Toarcian age. These are underlain by a section of interbedded claystones and limestones of Late to late Early Pliensbachian age;
- Within Heron H-73, the Pliensbachian claystones and limestones are underlain by dolomites and then evaporites (salt) in which the well reaches T.D. These deepest sediments are not so well constrained biostratigraphically, but the palynofloras imply an age no older than Late Hettangian within the salt;
- Deposition of the Early Toarcian to Pliensbachian sediments in Heron H-73 took place under open marine conditions close to a marshy coastal plain. Palynofloras derived from the dolomites and salt imply deposition under shallow marine conditions close to a marshy coastal plain.

Well Name	New Samples Analysed			Biostratigraphic Data Reviewed	Interval
	Micropalaeo	Nannopalaeo	Palynology		
Bandol-1	64	64	0	P	1000-4045m
East Wolverine G-37	0	23	0	M, N, P	2920-6857m
Emerillon C-56	0	0	0	M, P	1430-10750ft
Heron H-73	0	16	77	M, P	1550-11970ft
DSDP 547B	0	6	4	M	847.55-905.2m

M = micropalaeontology
N = nannofossils
P = palynology

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

Bandol-1	
Top Depth (m)	**Age**
1060-1388	Miocene, ?Late Miocene
1388-1644	Paleocene (?-top Cretaceous)
1644-1784	Early Campanian to Coniacian
1784-1890	Middle (?to Early) Turonian
1890-1952	Middle to Early Cenomanian
1952-2050	?Middle to Early Albian
2115-2328	Aptian
2328-2642	Hauterivian (-?Valanginian)
2642-2905	Callovian
2905-4045 T.D.	Middle Jurassic, ?Callovian

East Wolverine-1	
Top Depth (m)	**Age**
2920-2985	Late Miocene, Tortonian
2985-3462	Middle to Early Miocene
3462-3908	Oligocene
3908-4032	Late Eocene
4032-4190	Middle Eocene
4190-4200	Early Eocene
4200-4205	Paleocene
4205-4227	Maastrichtian to Campanian
4227-4250	Middle to Early Cenomanian (?to latest Albian)
4250-4390	Albian, ?intra-Albian
4390-4578	Aptian
4578-4867	Early Hauterivian to Valanginian
4867-5149	Early Cretaceous (?Berriasian/Valanginian)
5149-5550	Callovian
5550-6620	earliest Callovian to Bathonian
6620-6730	?Middle Jurassic
6730-6857 T.D.	Indeterminate

Emerillon C-56	
Top Depth (ft)	**Age**
1430-2566	Miocene to ?Oligocene
2566-3014	?Late Eocene
3014-3634	?Middle to Early Eocene
3634-3746	Late Paleocene
3746-3792	Late Maastrichtian
3792-5426	Campanian to Turonian
5426-5582	Cenomanian to ?Late Albian
5582-5845	Albian
5923-6482	Aptian
6482-6847	Barremian-?Hauterivian
6847-7755	(?Early Oxfordian)/Callovian to Bathonian
7755-10625	Callovian to Bajocian
10780	?Early Jurassic

Heron H-73	
Top Depth (ft)	**Age**
1550-4110	Miocene
4110-5378	Oligocene
5378-5792	Eocene
5792-7598	Campanian to Turonian
7598-7778	Cenomanian to Late Albian
7778-8072	Early Cretaceous, ?Aptian
8072-9998	Oxfordian to Bajocian
9998-10260	Early Toarcian
10260-11100	Pliensbachian
11100-11970 T.D.	Early Jurassic, no older than Late Hettangian

Unconformity surfaces

Table 3: Summaries of the stratigraphic breakdowns in the 4 wells reviewed/analysed in this study

Event	Bandol-1 (m)	East Wolverine G-37 (m)	Emerillon C-56 (ft)	Heron H-73 (ft)
Intra-Oligocene Unc. (T29)	1388	3695?	2566?	4928?
Top Ypresian Chalk	Truncated beneath Unc.	4189	-	5710
Ypresian Unc. (T50)	Truncated beneath Unc.	4193	3634?	5792
Tertiary Cretaceous boundary	1640?	4205	3746?	Truncated beneath Unc.
Intra-Campanian Unc.	1644	-	3792	-
Santonian MFS	1654	-	4686?	6420
Turonian/Cenomanian Unc. (K94)	1890	4227	5426	7598
Late Albian Unc. (K101)	1952	4250	5582?	7778
Albian/Aptian boundary MFS	2082?	4398	-	-
Intra-Aptian MFS	2287	4482	6438?	-
Aptian/Barremian Unc.	2328	4578	6482	-
Intra-Hauterivian MFS (K130)	2516	Truncated beneath unc.	-	-
Near Base Cret. Unc. (K137)	2642	4867?	6847	-
Cretaceous/Jurassic Unc. (K147)	-	5149	-	8072
Top Callovian MFS	2669	-	-	-
Base Callovian MFS (J163)	2808	5550	7062?	9070?
Bathonian MFS (J166)	-	6611	9610?	-
Bajocian/Toarcian Unc. (J170)	-	-	-	9998
Top Salt	-	-	-	11478

Table 4: Surfaces recognised in the 4 wells from the Laurentian Basin. New surfaces recognised in this study are highlighted in red. Seismic horizon numbers are given in parentheses for relevant surfaces.

* 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.

In addition to the 4 wells studied from the Laurentian Basin, new nannofossil and palynological analyses were also undertaken from the Early Jurassic section of DSDP Site 547B on the Mazagan Plateau of Morocco; targeted at those cores that gave the highest TOC values. The aim of these analyses was to clarify the ages and depositional settings of potential source horizons of Early Jurassic age in the Heron H-73 well in comparison to the well-documented Early Jurassic potential source horizon in DSDP 547B. The plate reconstruction by Andrew MacRae (SMU, Halifax) using the rotation poles of Labails *et al.* (2010) and Sibuet *et al.* (2012) and rendered with GPlates (see full references in Annexe 1) shown in Figure 4 highlights the relative positions of the Heron H-73 well and DSDP 547B site at ~183Ma (Pliensbachian – Toarcian).

Range charts showing the new biostratigraphic data produced from DSDP 547B samples in this study are included in Enclosures 10 and 11). These data indicate that the samples analysed from cores 15-22 from DSDP 547B (847.55-905.02m) are older than the claystones and limestones present below the Bajocian/Toarcian Unconformity in the Heron H-73 well.

Figure 3 highlights the difference in age between the two sections:
- samples 10 020-10 190 ft in Heron-H 73 are Early Toarcian (around, or slightly older than, the 'Toarcian Oceanic Anoxic Event');
- samples 10 290 -11060 ft in Heron H-73 are Late Pliensbachian;
- sample 11 100 ft in Heron H-73 is late Early Pliensbachian; this is the same age as the youngest core sample analysed from DSDP 547B (core 15 at 847.55 m);
- samples from core 20 (891.11-893.39 m) in DSDP 547B are Early Pliensbachian to Late Sinemurian, probably Late Sinemurian below 892.30 m;
- the sample at 905.2 m in DSDP 547B yields a nannofossil assemblage restricted to the Early Pliensbachian to Late Sinemurian, but the co-occurrence of Early Sinemurian nannofossil and miospore markers in this sample may suggest proximity to the Late/Early Sinemurian boundary.

The Early Toarcian to Late Pliensbachian sediments in Heron H-73 were deposited under open marine shelf conditions and the palynomorph assemblages recovered indicate deposition close to a marshy coastal plain. The Early Jurassic dolomites and salts present below 11 100ft in Heron H-73 yield rich palynofloras characteristic of deposition in a shallow marine environment that was also close to a marshy coastal plain.

From our studies, it is evident that the Early Pliensbachian to Late Sinemurian sediments in the DSDP 547B cores were also deposited in an open marine shelf setting close to a marshy coastal plain. The deep water (outer shelf/upper bathyal) environment of deposition suggested for these cores in the DSDP volume (Hinz, Winterer *et al.*,1984*) is not corroborated by the data recorded from this study. The micropalaeontological recoveries recorded from the DSDP 547B samples in Riegraf, Luterbacher & Leckie (1984; in Hinz, Winterer *et al.*, 1984) are similar to those recorded in internal GSCA data from the Early Jurassic section of Heron H-73 and are typical of deposition in an open marine shelf environment. The nannofossil assemblages recorded from the new samples analysed are generally rich and diverse, indicating open marine conditions of deposition. The palynofloras are strongly dominated by the gymnosperm pollen *Classopollis torosus*, including abundant tetrads of this form. *C. torosus* inhabited marshy coastal plain settings and tetrads of this species would have been broken up if they had been subject to extensive transport. It is therefore concluded that the sediments analysed from the DSDP 547B cores were deposited close to a marshy coastal plain in an open marine shelf setting (similar to that envisaged for the Early Jurassic sediments in Heron H-73).

* Hinz, K., Winterer, E.L. *et al.* 1984. *Init. Repts. DSDP*, vol. 79, Washington, 934pp.

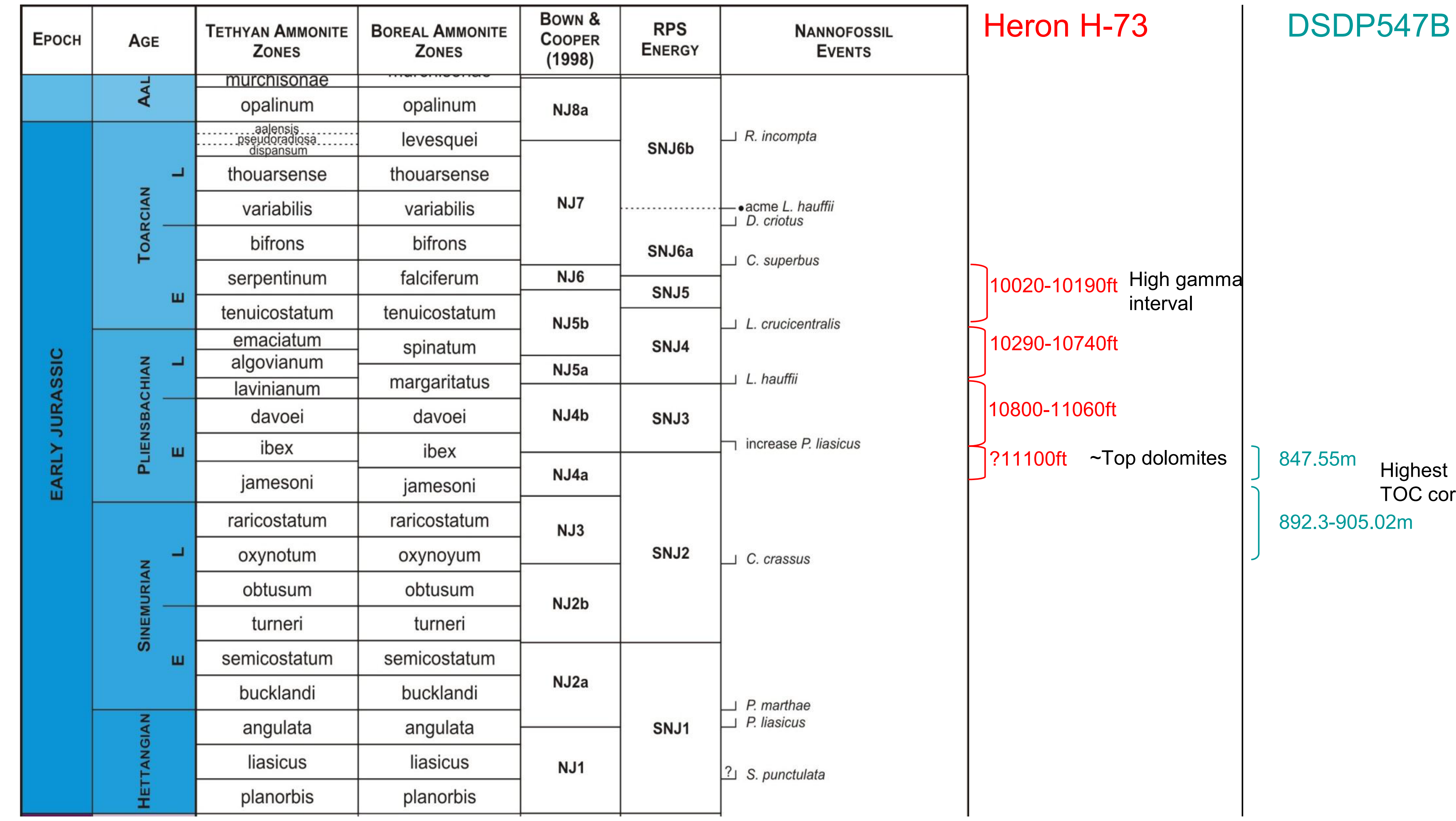


Figure 3: Correlation of Early Jurassic ages with ammonite and nannofossil zonation schemes showing the representation of these ages within Heron H-73 and DSDP 547B samples analysed.

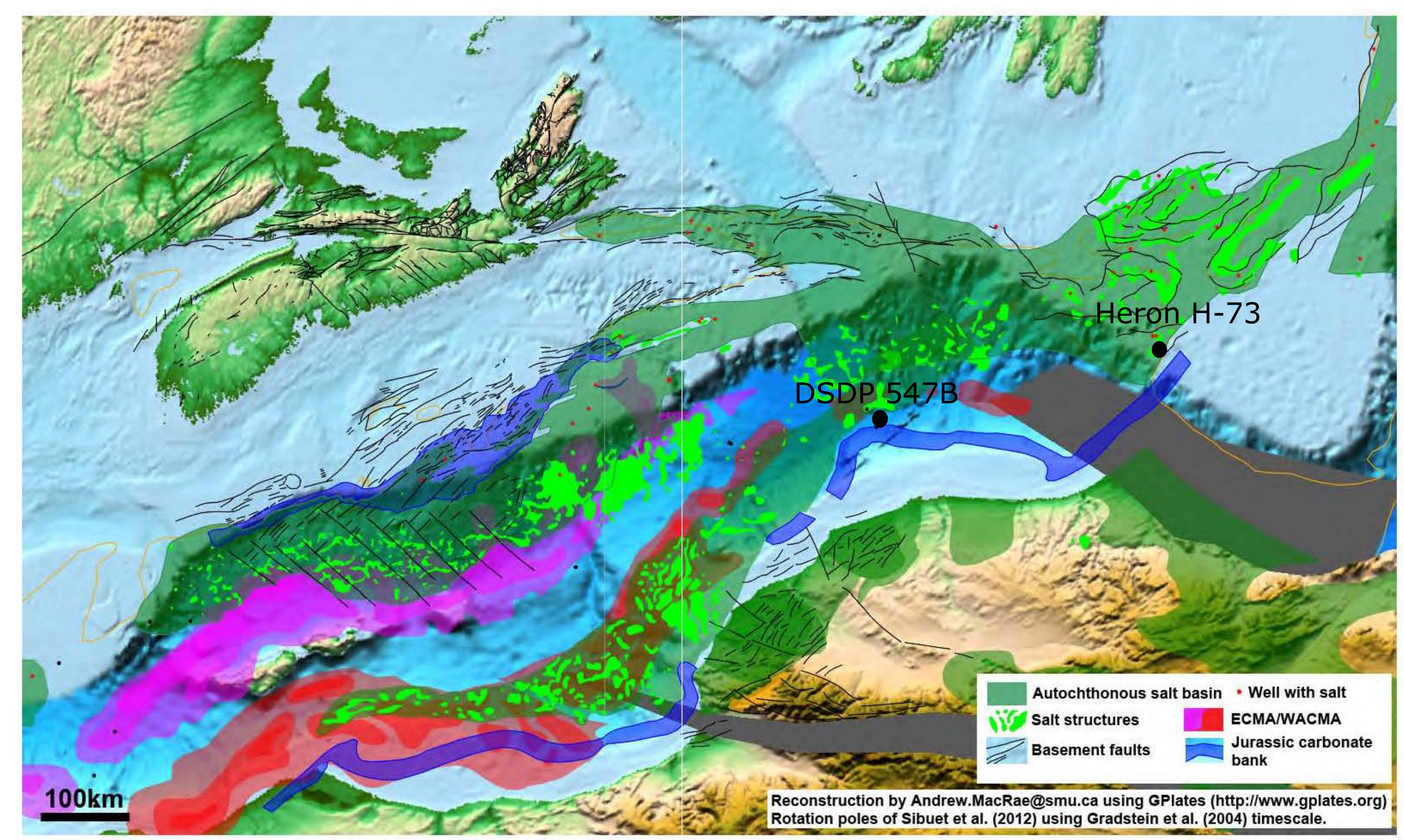
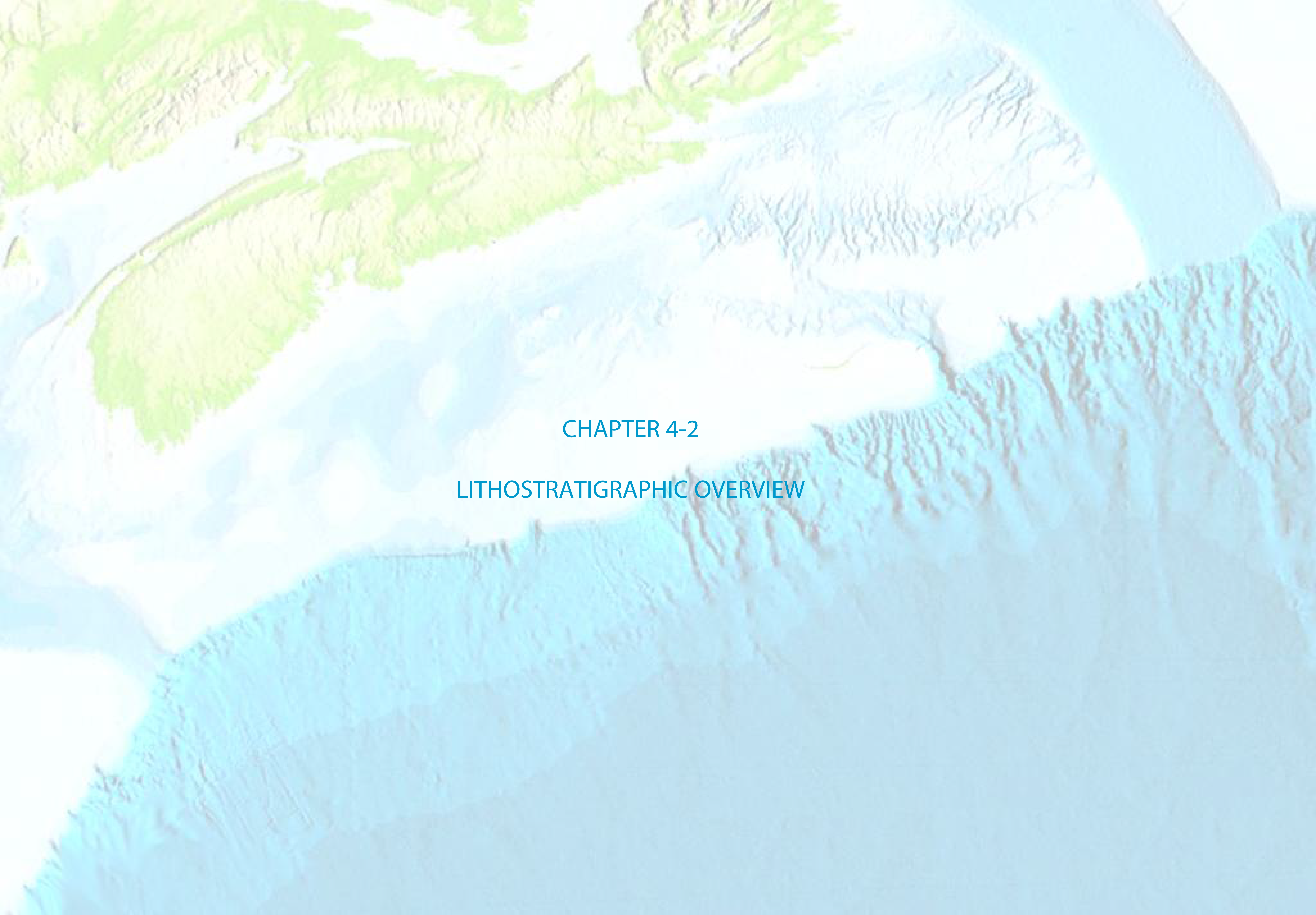


Figure 4: Plate reconstruction at ~183Ma (Pliensbachian - Toarcian), showing the positions of the Heron H-73 and DSDP 547B wells (Andrew MacRae, SMU, Halifax using the rotation poles of Labails et al., 2010 and Sibuet et al., 2012 – see Annexe 1 for full references)



CHAPTER 4-2

LITHOSTRATIGRAPHIC OVERVIEW

Stratigraphic Overview

Generalized stratigraphy of the Central Scotian Shelf

The Scotian Basin contains Mesozoic-Cenozoic sedimentary rocks, up to 15 km thick in place that were deposited during the rifting of Pangea and the opening of the North Atlantic. The earliest basin infill occured during the Triassic rifting, and consists of red continental clastics sediment and evaporites. During the Early Jurassic rift basins were gradually infilled by clastic and carbonate sediments. Fully marine conditions developed by Mid to Late Jurassic, leading to a set of alluvial plain, deltaic, and carbonate environments. Consecutive to the Avalon uplift 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 sand, 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 overlained by unconsolidated glacial till, glacio-marine and marine sediments that were deposited during the Quaternary.

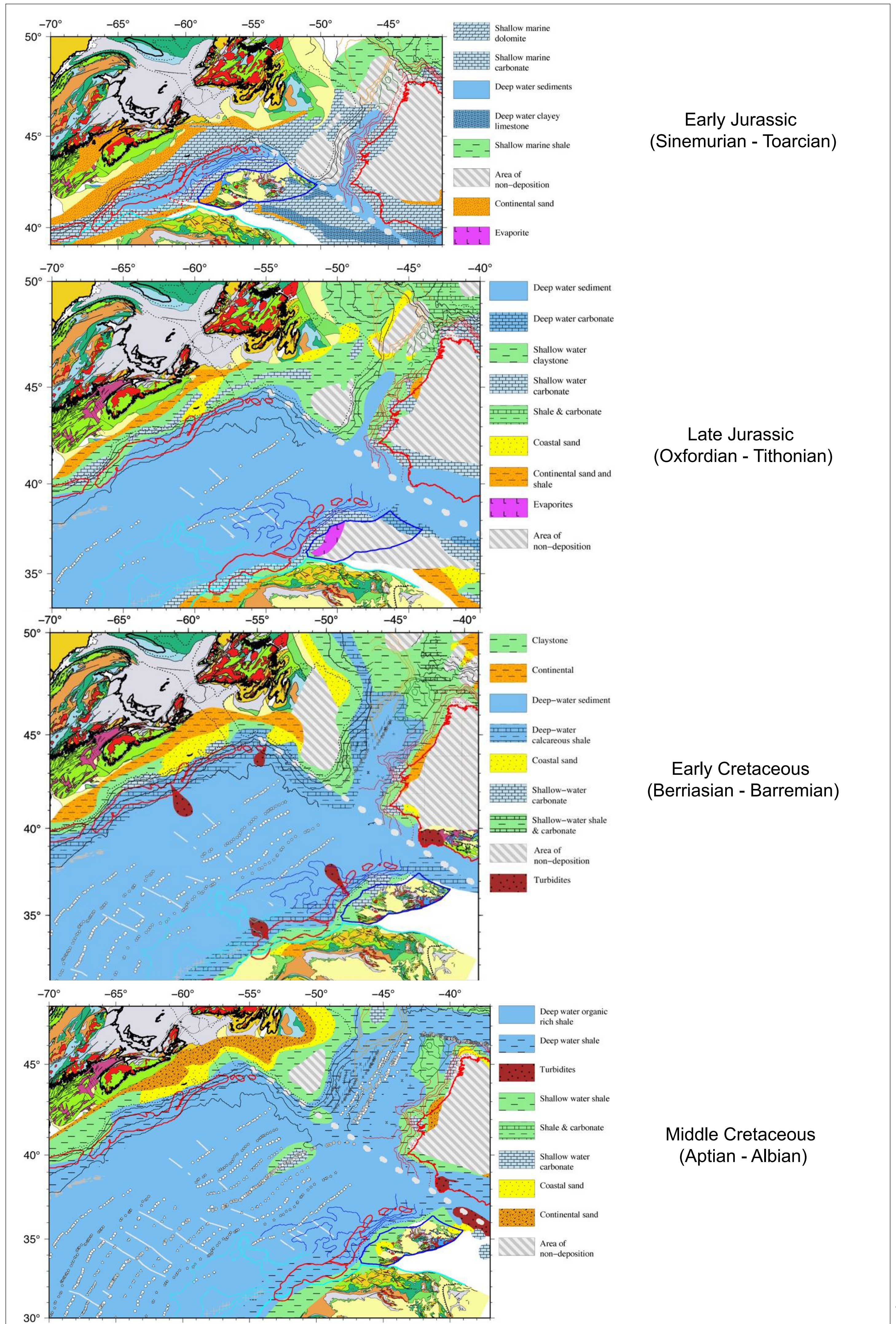


Figure 3: Paleogeography of Eastern Canadian Margin from Early Jurassic to Middle Cretaceous (*Sibuet et al., 2012*)

Top Formation	Stratigraphic surface	Stage	Equivalent formation	Bandol-1	Emerillon C-56	East-Wolverine G-37	Heron H-73
T29	Unconformity	Rupelian	Banquereau	1388 m	782 m	3695 m	1502 m
T50	Unconformity	Ypresian	Dawson Canyon Petrel Wyandot Ypresian chalk		1108 m	4193 m	1765 m
Intra-Campanian	Unconformity	Campanian		1644 m	1156 m		
Santonian	MFS	Santonian		1654 m	1428 m		1957 m
K94	Unconformity	Turonian		1890 m	1654 m	4205 m	2316 m
K101	Unconformity	Albian	Logan Canyon Shortland Shale Albian Carbonate	1952 m	1701 m	4250 m	2371 m
Early Albian	Unconformity			2058 m	1786 m		
Albian/Aptian boundary	MFS			2082 m		4398 m	
Intra Aptian mfs	MFS	Aptian		2287 m	1962 m	4482 m	
Top Missisauga	Unconformity			2328 m	1976 m	4578 m	
K130/Intra Hauterivian	MFS	Hauterivian		2516 m			
K137	Unconformity	Valanginian	Missisauga	2642 m	2087 m	4867 m	2460 m
J147	Unconformity	Berriasien				5149 m	
Top Callovian	MFS	Callovian	Abenaki/ Verrill Canyon	2669 m			
J163	MFS			2808 m	2152 m	5550 m	2765 m
Callovian FS	FS			2830 m	2185 m	5788 m	2798 m
J166	MFS	Bathonian	Scatarie / Mohican / Iroquois & Eq		2929 m	6611 m	2865 m
J170	MFS	Bajocian					3047 m
J181	MFS	Toarcian					3094 m
J186	MFS	Pliensbachian					3306 m
J188	Top Dolomite	Pliensbachian					3429 m

Table 2: Well formation tops 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 or Carboniferous 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. These series could be present offshore in the deepest troughs observed in seismic sections. No well used in this PFA study reached the basement.

Triassic

Formations: Eurydice and Argo Salt Equivalent (Figure 2)

Heron-H73 is the only well that potentilly scratched the top of the salt formation (PL. 4.3.1 and 4.3.2; Enclosure 4.15; Table 1 and 2), but the interval below the Pliensbachian is not well constrained. No well used in the current PFA reached the Triassic.

Eurydice Formation is well known from other wells along the margin. It corresponds to the oldest synrift sequences related to the Atlantic opening. The formation corresponds to thick series of Late Triassic/ red sandstones, siltstones and shales. Wells, scattered across the margin, have encountered the Eurydice Formation beneath the Grand Banks, Scotian Shelf. In Orpheus and Naskapi Grabens, seismic data indicate a total formation thickness of over 3 000 m (Wade and MacLean; 1990).

Figure 4: Exemple of salt occurence in Heron H-73 (Plates 4.3.1 and 4.3.2; Enclosure 4.4)

Breakup Unconformity - J200

J200 Breakup Unconformity is dated at early Jurassic (200 Ma) and separates the synrift and post rift sequences in the Scotian, Laurentian and South Whale Basin. The unconformity is traced up to the Laurentian Basin and South Whale Basin and coincides with the opening of the North Atlantic Ocean. Seismically the unconformity is characterized by a strong reflection regionally mappable, separating a fairly deformed Upper Triassic sediments and an undeformed lower Jurassic and younger sediments. The Mohican Formation completes the rift infilling and overlap 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 plateforms on the shelf (Figures 5 and 6; PL 4.3.2 , 4.5.2 and 4.5.4). Around Bandol area (Abenaki sub-basin?), a wide delta developed at a river mouth complex system coresponding to the ancester St Laurence River (Figure 6). East of the deltaic area a carbonate plateform extends to the South Whale basin punctually cut off by sets of small deltaic complexes. The slope and rise record the first pulses of clastic and carbonate sediments forming the firsts turbidite deposits (Figures 5 and 7; PL 4.3.1 to 4.5.4).

Recognition from Wells

- Formations/Members equivalent: **Iroquois** (carbonate platform), **Mohican** (clastic sands), **Scatarie** (carbonate platform)
- Number of exploration wells that reached the Early to Middle Jurassic: Iroquois was reached only in Heron H-73; Mohican equivalent is observed in the 4 wells although a large part of the formations are missing due to the impact of the Avalon uplift (PL. 4.41 and 4.4.2; Enclosure 4.12 to 4.15)
- Regional top sequence/seismic horizon: **J163** (Top Scatarie)
- Lithostratigraphic cross-sections (Plate 4.3.2 and 4.4.2)
- Architectural cross-sections (PL. 4.5.1 to 4.5.4)
- Age: **Pliensbachian-Callovian** Description

Along the Laurentian and South Wale basins, the early to middle Jurassic Formations overlie either the breakup unconformity or the Argo salt (PL 8.1 and 8.2).

Iroquois and Mohican Formations cover the timespan between the Pliensbachian and Toarcian. Iroquois Fm is a transgressive formation which consists primarily of dolomite deposited under slightly restricted marine conditions (Figure 5; PL 8.1 and 8.2). The dolomite is topped by limestone until the base Toarcian then shale until the Aalenian unconformity (J170). Iroquois Formation is coeval with the lower part of the Mohican Formation due to coexisting carbonate rims and deltaic formations.

Mohican sandstones and shales form a very thick early to middle Jurassic clastic sequence deposited into sub-basins (Figure 5; PL 4.5.1 to 4.5.4; PL 8.1 and 8.2). The formation is widespread on the Scotian Shelf and tends to decrease toward South Whale basin where carbonate formations tend to be thicker (Figure 5; PL 8.2). The thickest Mohican section observed in wells is in Bandol with a maximum thickness of 1 200 m (Figure 5; PL 4.5.2; PL 8.2).

Mohican Formation is topped by Scatarie and lower Mohawik equivalent Formation covering a timespan from Bajocian to base Callovian (J163).

For the entire early to middle Jurassic time offshore sequences are predominantly muddy turbidites and Hemipelagic muds with interbeded thin turbidite lobes. East-Wolverine G-37 shows the first occurence of deep-water clastic and carbonate turbidites. Seismic data show distal turbiditic lobes.

Hydrocarbon occurrence: HC shows are reported at the top of the dolomite; deltaic sand beds (Emerillon); deep water sand sheets (Figure 5; PL 4.3.1 to 4.5.4).

Figure 5: Stratigraphy of early - middle Jurassic in the Laurentian - South Whale basin along a South-North shelf transect.

Mid to Late Jurassic Sequence (Callovian to Kimmeridgian) - J163 – K137

The late Jurassic period corresponds to the expension of sedimentary environments that started to develop during early - middle Jurassic time.

Bandol and surrounding areas show prominent shaly deposits associated to the development of Callovian-Kimmeridgian carbonate banks. This carbonate sequence is observed East of the Laurentian Basin and thicken to South Whale Basin (Emerillon and Heron). East-Wolverine records donwslope processes with sediment coming from Bandol and Emerillon area. The slope and rise record well developped clastic-carbonate turbidite systems. Sedimentary sequences between Tithonian and Oxfordian are absent from all wells used in this study (Tithonian to Kimmeridgian in East-Wolverine) 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 this part of the margin, but preserved on the lower slope and rise.

Recognition from Wells

- Formations/Members equivalent: **Verrill Canyon** (prodelta, open marine, deep water shales), **Abenaki** (carbonate platform and reef margin)
- Number of exploration wells that reached the mid to late Jurassic : 4 wells (PL 8.2 to 8.4; Enclosure 4.12 to 4.15)
- Regional top sequence/seismic horizon: **J150** (Tithonian MFS); **J147** (Jurassic-Cretaceous unconformity); **K137** (near base Creataceous unconformity)
- Lithostratigraphic cross-sections (PL 4.3.1 to 4.4.2; Enclosure 4.16 to 4.19)
- Architectural cross-sections (PL. 4.5.1 to 4.5.4; Enclosure 4.20 to 4.23)
- Age: **Callovian-Kimmeridgian**

Description

Nor the Mohawk or Mic Mac formation have been observed in the 4 studied wells. For the considered time frame (Callovian to late Jurassic), the sedimentary sequences are mostly composed of shale and claystone for Laurentian Basin (Bandol and Emerillon), few thin mix clastic/calciturbidites beds within East Wolverine (Verrill Canyon equivalent Fm) and limestone units for South Whale basin (Heron; Abenaki equivalent Fm). The Callovian - late Jurassic carbonate succesions are best preserved in Heron where limestone fms are recorded through the Oxfordian.

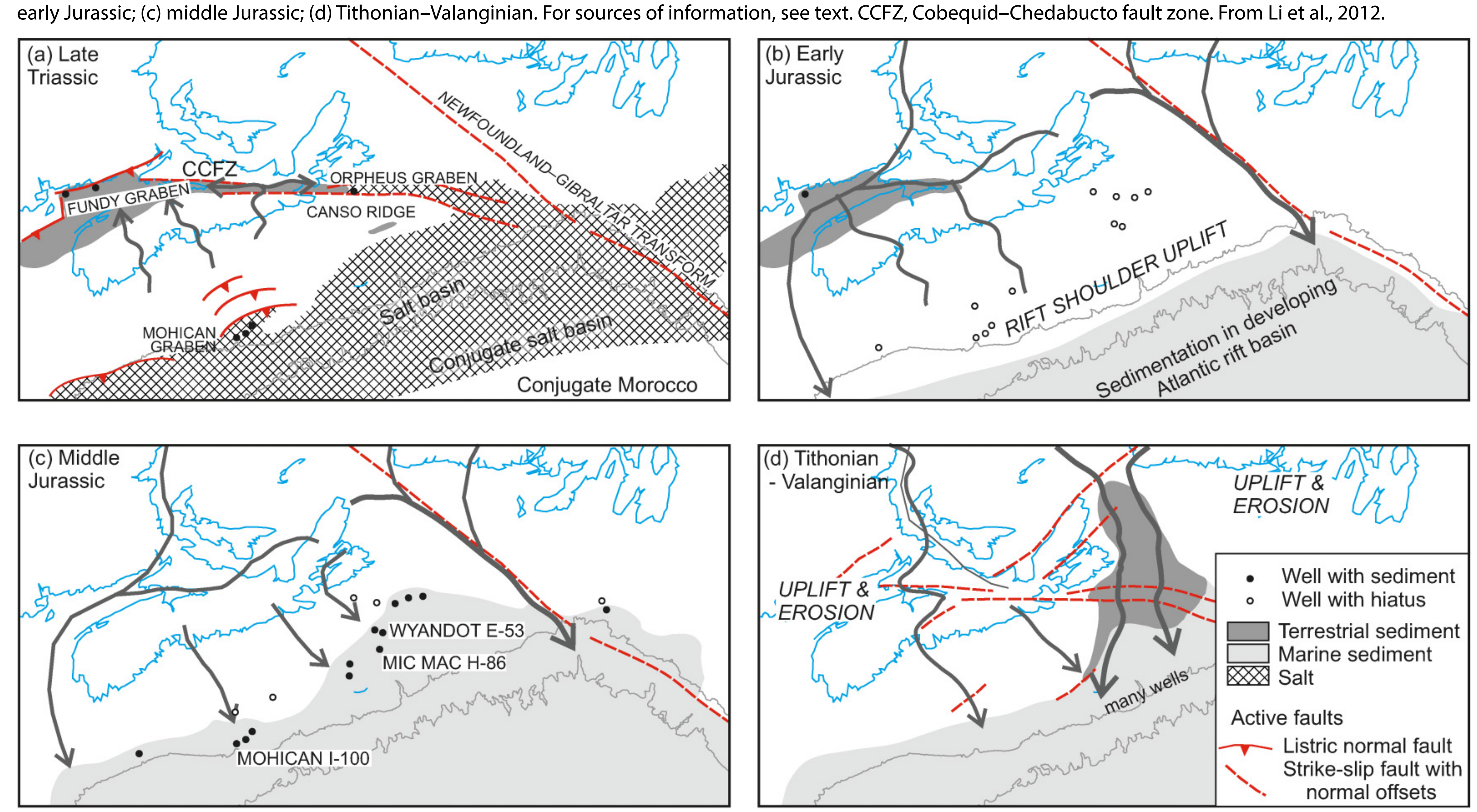
Abenaki Formation

In the studied area the **Abenaki Formation** is a limestone dominated unit. The formation extends up to South Whale basin but replaces by the Verrill Canyon Fm for a significant part of the Laurentian Basin (Figure 5; PL 4.3.2 to 4.4.2). The Abenaki Formation forms an outer shelf carbonate bank complex to the South Whale basin (Figure 9; PL 8.2 to 8.4) and can be subdivided into two sub-Formations: The Scatarie Member and the Misaine Member.

The **Scatarie Member** is predominantly an oolithic limestone. According to the biostratigraphy (Figure 2), the Scatarie Member is intra Callovian in age and includes the base Callovian MFS (Figure 5 and 7; PL 4.3.2 to 4.4.2; Enclosure 4.1 to 4.2). It represents a seaward thickening wedge with deepening-upward transgressive sequences from the southern to the northward depositional edge. Its maximum thickness is reached around Emerillon with a thickness of about 800 m.

The **Misaine Member** is a transgressive facies that overlies the Scatarie member. It is composed of dark grey calcareous shales with minor laminated limestone pinching out landward over the platform (PL 4.3.1 to 4.4.2). The Misaine member is interpreted as representative of the Callovian regional transgressive flooding event, well developed along the Jurassic shelf margin (A. Kidston, 2005).

Figure 6: Map showing structural and geomorphic evolution of the Scotian Basin and its hinterland from the late Triassic to the early Cretaceous: (a) late Triassic; (b) early Jurassic; (c) middle Jurassic; (d) Tithonian–Valanginian. For sources of information, see text. CCFZ, Cobequid–Chedabucto fault zone. From Li et al., 2012.



Verrill Canyon Formation

Verrill Canyon equivalent Formation is reached in East-Wolverine and consists primarily of grey to brown calcareous shale with few thin beds of limestone, siltstone, and sandstone. Verrill Canyon Formation is deposited in prodelta, outer shelf and continental slope settings. This shale dominated unit last through the Early Cretaceous and represents the distal equivalent of the Mohawk, Abenaki, Mic Mac, and Missisauga Formations.

Hydrocarbon occurrence: HC accumulations (oil and gas) are observed in carbonates in top Abenaki limestone in Heron; Near J147 and 137 unconformities in East-Wolverine (Figures 7; PL 4.3.1 to 4.4.2)

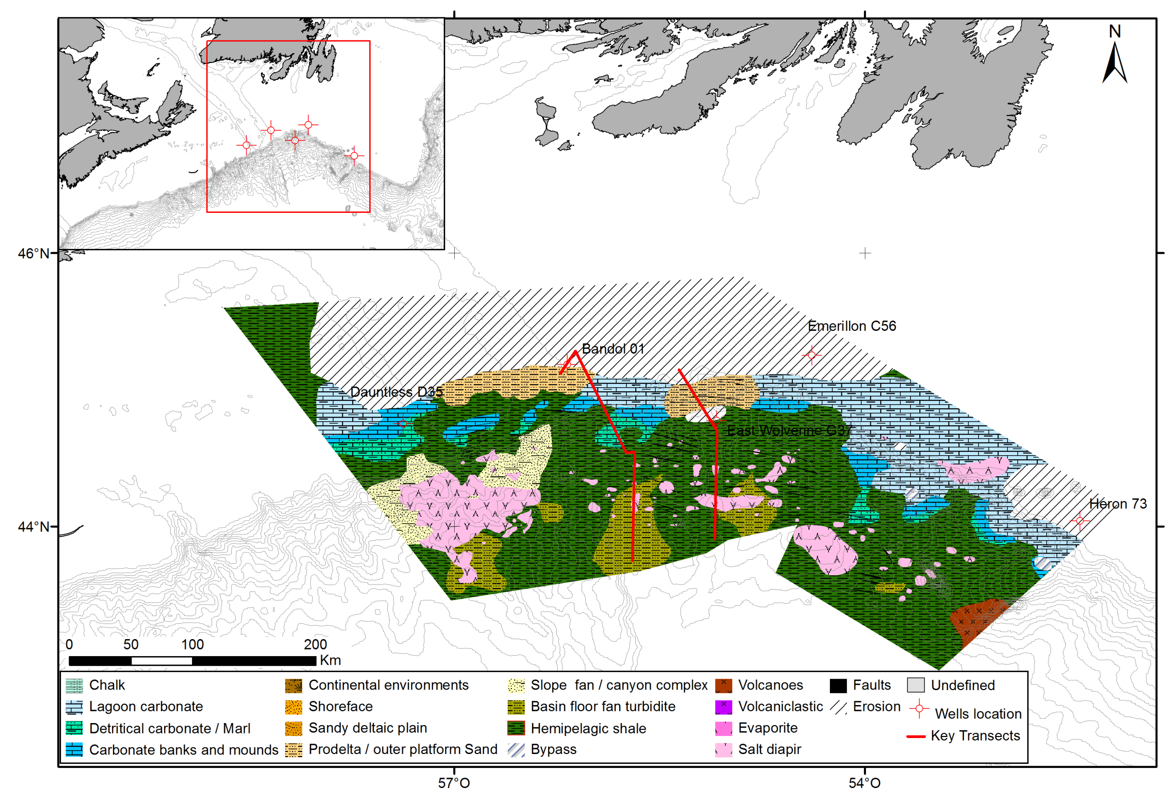


Figure 8: Gross Depositional Environment Map at J150

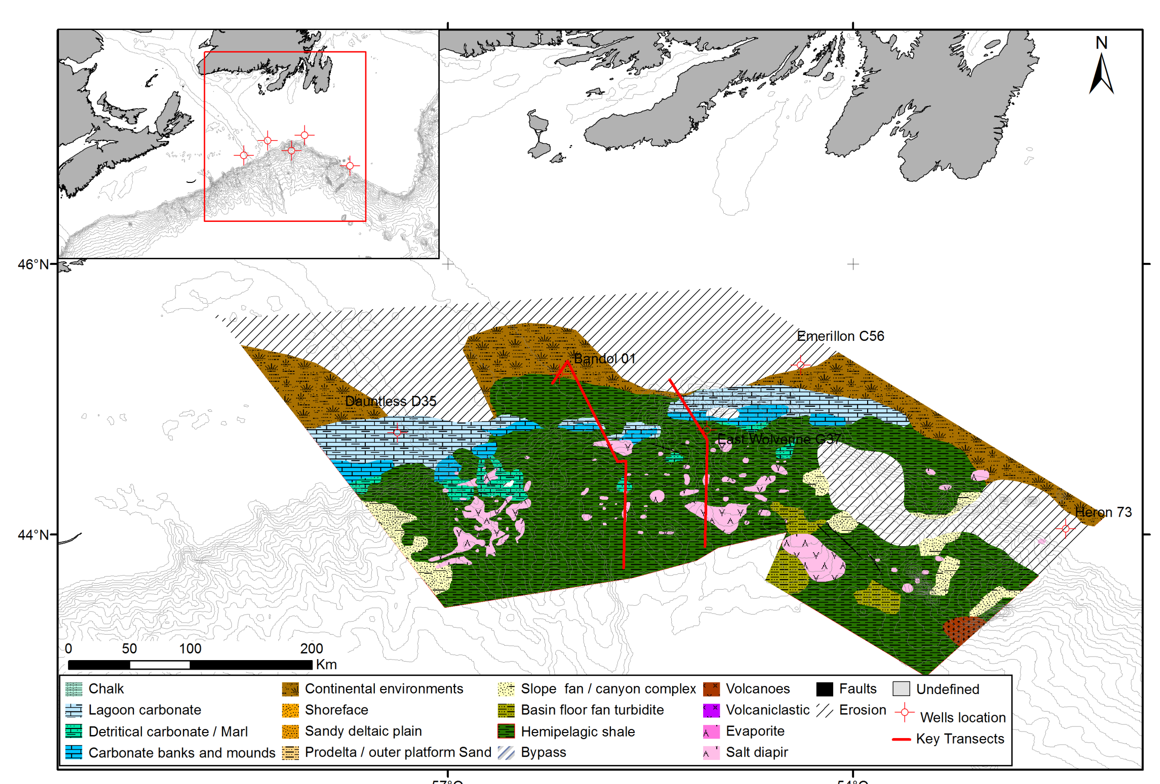


Figure 9: Gross Depositional Environment Map at K137 (Avalon Unconformity)

Figure 7: Correlation between Emerillon and East-Wolverine wells for the Jurassic and Cretaceous intervals showing the upslope downslope of sedimentary successions. For the Jurassic period, Emerillon sedimentary records correspond to the Abenaki succession and East-Wolverine records correspond to Verrill Canyon Fm

Avalon Unconformity

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 from Jeanne d'Arc Basin down to Scotian basin.

In the South Whale Basin the Avalon uplift stage induces a massive erosion of upper Jurassic sequences and a drastic reduction of accommodation space coupled with a tipping of sediment source northward. The impact of the Avalon uplift decreases to the Scotian Basin where more series are preserved (Figure 9; PL 4.3.1 to 4.4.2). In the Laurentian Basin, the Avalon uplift induced a significant erosion of the top Jurassic and additionally rerouted the ancestor Laurentian river to the west-southwest leading to the development of the Missisauga Fms.

Early Cretaceous Sequence (Berriasian - Barremian) J147-K130

The early Cretaceous period corresponds to the separation of Newfoundland from Europe which is at the origin of the Avalon uplift and subsequent unconformity. Both seismic and well data show a southward attenuation of the angular unconformity until Sable sub-basin where it is not visible in the lower Cretaceous strata (Wade and MacLean, 1990, PFA, 2011). This geological interval is characterized by the development of thin sandy interval to the West-Southwest and even thinner sandy units to the east-northeast corresponding to the Missisauga eq Fm (Figure 10; PL 8.4 and 8.5). Downslope deposits correspond to the upper Verrill Canyon eq Fm. This thin lower Cretaceous sequence ends with the Hauterivian MFS (K130)..

Identification

- Number of exploration wells reaching the lower Cretaceous fm: 4 wells (PL. 4.3.1 to 4.4.2; Enclosure 4.12 to 4.15)
- Formation/Members: **Missisauga** and **upper Verrill Canyon** eq Formations.
- Age:
  - Top lower Missisauga: **Berriasian (J147/K137)**
  - Middle Missisauga: **Valanginian-Hauterivian MFS (K137-K130)**
  - Top middle Missisauga: **Intra Hauterivian MFS (K130)**
- Regional top sequence seismic horizon: Intra Hauterivian MFS (**K130**).
- Chronostratigraphic cross-sections (PL. 4.3.1 and 4.4.1).
- Lithostratigraphic cross-sections (PL. 4.3.2 and 4.4.2); Geological Composite Well Logs (Enclosures 4.12 to 4.15).
- Architectural cross-sections (PL.4.51 to 4.5.4).

Description

Missisauga and upper Verrill Canyon eq Formation

In the Laurentian Basin the Missisauga Fm is not as well represented as along the Scotian margin. Missisauga Fm thickness varies significantly from South Whale basin to Sable Basin with a southward thickening trend (Figure 10; PL 8.4 and 8.5). This lateral variability correlates with the crystalline basement uplift which provides coarse-grained fluvio-detaic sediments (Pe-Piper & MacKay, 2006). Resulting sedimentary formation comprises fluvial, deltaic sands and derivative shelf sediments up to the shelf edge.

Basinward, canyons and valleys incise the slopes and basin-floor fan systems develop on the rise (Steel et al, 2003). Sediment distribution is controlled by canyon location and morphology, tectonic impact on topography and salt tectonic (Figure 9). No carbonate has been encountered for this interval in any of the wells used in the present PFA. Nevertheless, along the Sable Sub-basin western rim Missisauga progradations downlap and pinch out onto underlying Abenaki Fm are observed (Cummings, 2004).

Across the margin from South Whale Basin down to Sable basin, sediment thicknesses increase from less than few hundred meters to over 3500 m. In Heron H73 top Missisauga eq Fm corresponds to the late Albian unconformity (K101) suggesting that most of the Missisauga Fm is missing. The total Fm thickness is about 90 m and composed of metric sand beds and thin shale beds. In Emerillon and East-Wolverine the intra Hauterivian MFS is missing. This sequence is topped by the top Upper Missisauga (Figure 7 and 10; PL 4.3.1 to 4.4.2). In Emerillon the Missisauga sequence corresponds to a 80 m thick sandy unit topped by a 35 m thick shaly bed. In East-Wolverine the sequence corresponds to the Verrill Canyon eq Fm and consists essentially of 310 m of shaly deposit interrupted by a few meter thick sand beds. Bandol shows a complete middle Missisauga sequence of 140 m thick composed of a succession of metric sand and shale beds.

Hydrocarbon occurrence: No show have been described for this interval in the wells used in the present PFA

Figure 10: Sedimentary succession recorded during the Cretaceous across the shelf.

The Aptian - Cenomanian Sequence K130-K94

Identification

- Number of exploration wells reaching the Aptian - Albian Sequence : 3 wells (PL. 4.3.1 to 4.4.2 and Enclosures 4.12 to 4.15)
- Formations: **Upper Missisauga** eq Fm; **Logan Canyon** eq Fm; **Shortland Shale** eq Fm; **Albian Carbonate Fm**
- Regional top sequence: Intra Aptian MFS; Albian/Aptian boundary MFS; Early Albian unconformity; Late Albian unconformity (**K101**); Turonian/Cenomanian unconformity (**K94**)
- Chronostratigraphic cross-sections (PL. 4.3.1 and 4.4.1)
- Lithostratigraphic cross-sections (PL. 4.3.2 and 4.4.2) and Geological Composite Well Logs (Enclosures 4.12 to 4.15)
- Architectural cross-sections (PL. 4.5.1 to 4.5.4)

Description

Logan Canyon eq Formation, Shortland Shale eq and Albian Carbonate Fm

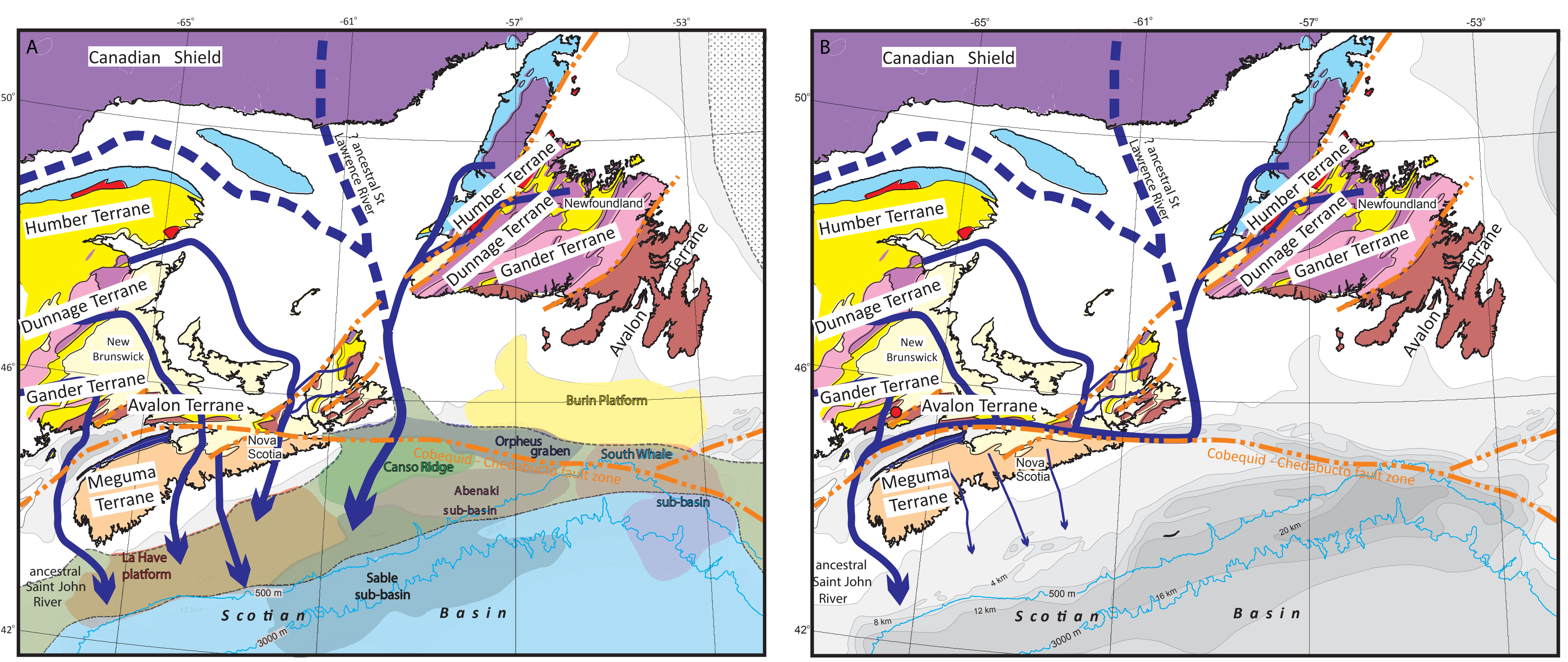
The Logan Canyon eq Fm and lateral and distal related Fms starts after the intra Aptian MFS (Figure 10; PL 4.3.1 to 4.4.2). The intra Aptian MFS is characterized by a thick dark brown to black shaly unit separating the top Upper Missisauga from the Logan Canyon eq Fm. The maximum thickness inferred from thickness map is observed between Emerillon and Heron (PL 8.6 and 8.7).

The Logan Canyon Fm is classically subdivided into four members along the Scotian Margin (Shale dominated Naskapi and Sable Fm; Sandstone dominated Cree and Marmora members) (Wade,1991b; MacLean and Wade, 1993). In the Laurentian and South Whale Basins the distinction between the different members is difficult to make because of the impact of the successive unconformities (Figure 9 and 10; PL 4.3.1 to 4.5.4). Overall, Logan Canyon eq Fm is observed in the 3 wells on the shelf with a thickening trend and shalier deposit near Bandol. Shortland Shale eq Fm is found in East Wolverine where it forms a 330 m thick unit (Figure 7; PL 4.3.1 to 4.4.2).

During Albian times, a 90 m thick preserved limestone unit is observed bordered by the early Albian unconformity and K94 (Figure 7 and 10; PL 4.3.1 to 4.4.2). This carbonate sequence is composed of coarse to fine grained bioclastics, nautiloids, crinoids and other fossil debris as well as calcareous shale and sometimes quartz grit. This suggests a shallow water environment under the influence of a distal estuarine environment. In Heron, the limestone unit is preserved after the late Albian unconformity (K101) suggesting that either carbonate banks form after the unconformity, or more likely no carbonate formation was preserved in Heron because of K101.

Overall, the Logan Fm corresponds to an estuarine and shallow marine clastic shelf environment south of Emerillon which evolved into a carbonate dominated

Figure 11: Map showing sediment sources distribution along the Scotian and South Newfoudland margin. Between early Cretaceous (A) and the late Hauterivian-early Albian the ancestral St Lawrence River migrates southward merging with the ancestral Saint-John River (Strathdee, 2012; modified from Tsikouras et al., 2011)



The Late Cretaceous to Eocene Sequence K94-T50

Identification

- Number of exploration wells reaching the Late Cretaceous to Eocene Sequence: 3 wells (PL. 4.3.1 to 4.4.2; Enclosure 4.12 to 4.15)
- Formations: **Dawson Canyon**, **Petrel**, **Wyandot**, **Ypresian Chalk**
- Age: Dawson Canyon (**Turonian to Campanian**), Petrel Member (**Turonian**), Wyandot (**Santonian-Maastrichtian**), Ypresian Chalk (**Base Eocene**)
- Regional top sequence: Ypresian unconformity (**T50**)
- Chronostratigraphic cross-sections (PL. 4.3.1 and 4.4.1)
- Lithostratigraphic cross-sections (PL. 4.3.2 and 4.4.2) and Geological Composite Well Logs (Enclosures 4.12 to 4.15)
- Architectural cross-sections (PL. 4.5.1 to 4.5.4)

Description

Dawson Canyon Formation and Petrel Member

The Dawson Canyon eq Formation consists of thick marine shales intersected by chalk and limestone layers near the early Turonian. Although the formation is found across the Scotian Shelf, the sequence of deposition appears to be diachronous from Sable Basin to South Whale Basin (Figure 12 and plate 4.3.1 to 4.4.2). To the south-west of the Scotian margin, the formation is restricted to the Turonian (See PFA 2011), whereas in the South Whale Basin it extends through the Campanian. This last observation is consistent with what has been described for Grand Banks of Newfoundland where the Dawson Canyon eq Fm lasts until the Campanian (Grant and MacAlpine, 1990). Based on wells used for this PFA study, Dawson Canyon eq Fm and Petrel member are found across the Scotian Margin up to the Grand Banks. Dawson Canyon Fm tends to increase to the South Whale Basin where it reaches a preserved thickness of about 550 m, whereas Petrel member tends to decrease from 230 m in Bandol to 100 m in Heron. In Emerillon the Dawnson Canyon eq Fm forms a 140 m thick unit between the Petrel and Wyandot Fms. The Dawson Fm and Petrel member are totally absent from East-Wolverine where only a small part of Wyandot is preserved.

Wyandot Formation

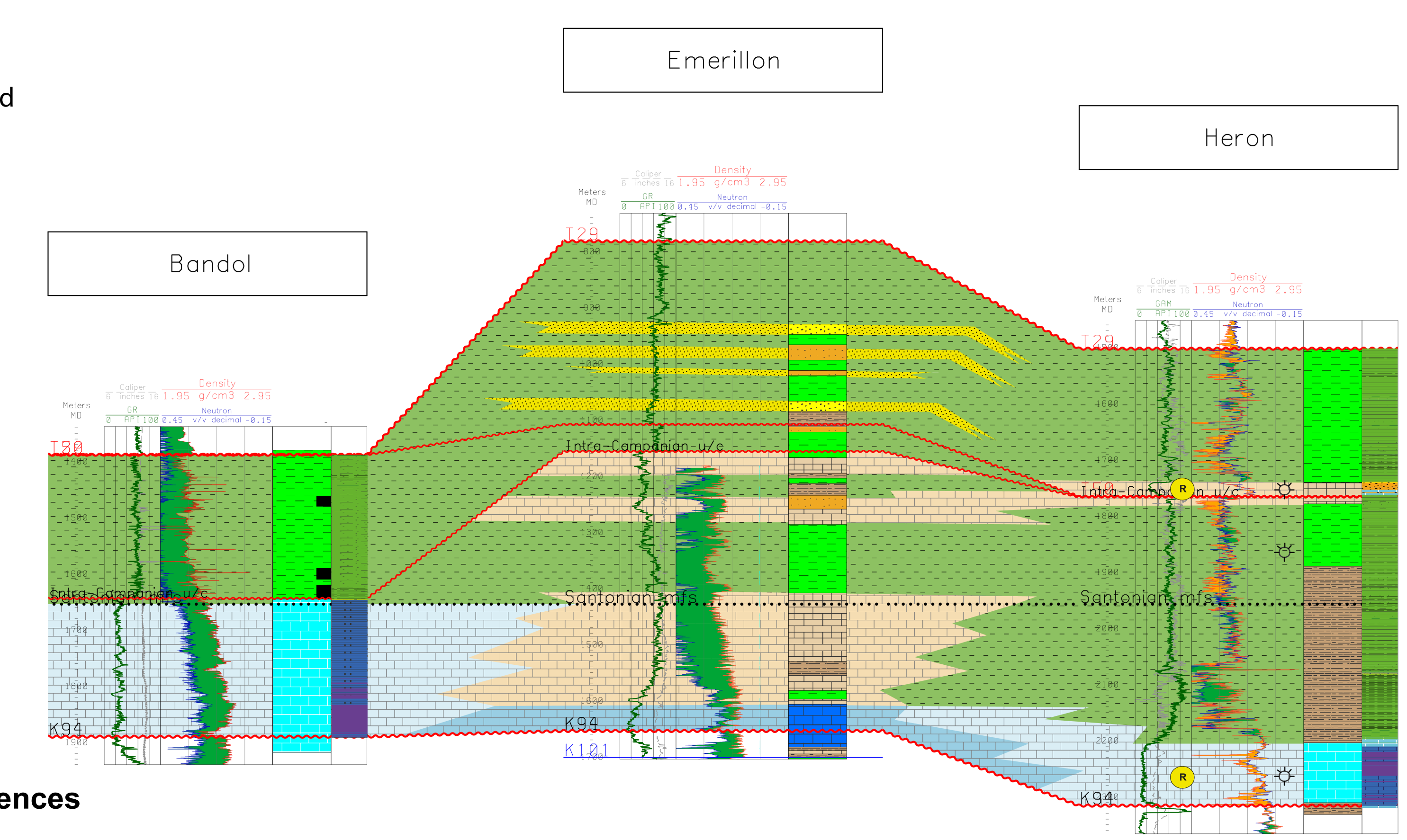
The Wyandot Formation is composed of chalk, marl and limestone (Figure 12; PL4.3.1 to 4.4.2). Formation thickness ranges from few metres in Bandol to about 250 m in Emerillon. In the latest, Wyandot corresponds mostly to marl deposits characteristic of back reef and lagoonal environment, which is coherent with the development of large reef mounds and platforms. Overall the formation is more preserved and developed to South Whale Basin. Near the outer shelf and slope, top Wyandot Formation is often marked by an unconformity overlain by Tertiary sediments. In East-Wolverine, Wyandot Fm is only few meters thick..

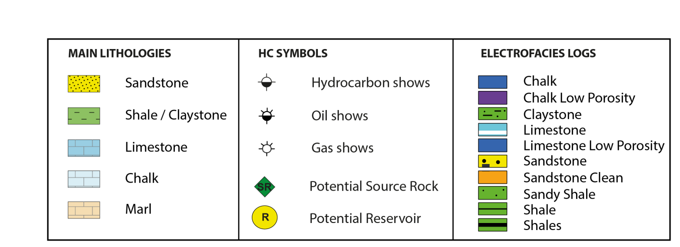
Ypresian Chalk

The Ypresian Chalk is an early Eocene Formation and composed of chalk. Around the St Laurent river outlet, the formation is nearly absent and for the rest of the margin disrupted by numerous Tertiary unconformities (Figure 12; PL 4.3.1 to 4.4.2). When preserved the chalk unit is about 100 m thick and is interpreted as formed in a deep water environment. In Emerillon the same interval corresponds to a silt-shale unit indicating a more proximal depositional environment.

Hydrocarbon occurrence (Figure 12; PL.4.3.1 to 4.4.2): Gas shows are observed at the top of the chalk for Heron; O&G shows are observed along the T50 unconformity south of Laurentian Basin.

Figure 12: Sedimentary succession recorded between the late Cretaceous and Eocene





Late Eocene to Plio-Miocene sequences

Banquereau and Laurentian Fms

Sedimentary successions between top Ypresian and latest Formation correspond to Banquereau and Laurentian Formations. The sequence corresponds to a Tertiary succession consisting in a series of downlapping or prograding sequences with a coarsening upward. In more detail, the Laurentian Formation corresponds to Plio-Quaternary progradational wedge forming, on average, 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.

Hydrocarbon occurrence (PL.4.3.1): Gas show are observed in the Bartonian sand in Emerillon.

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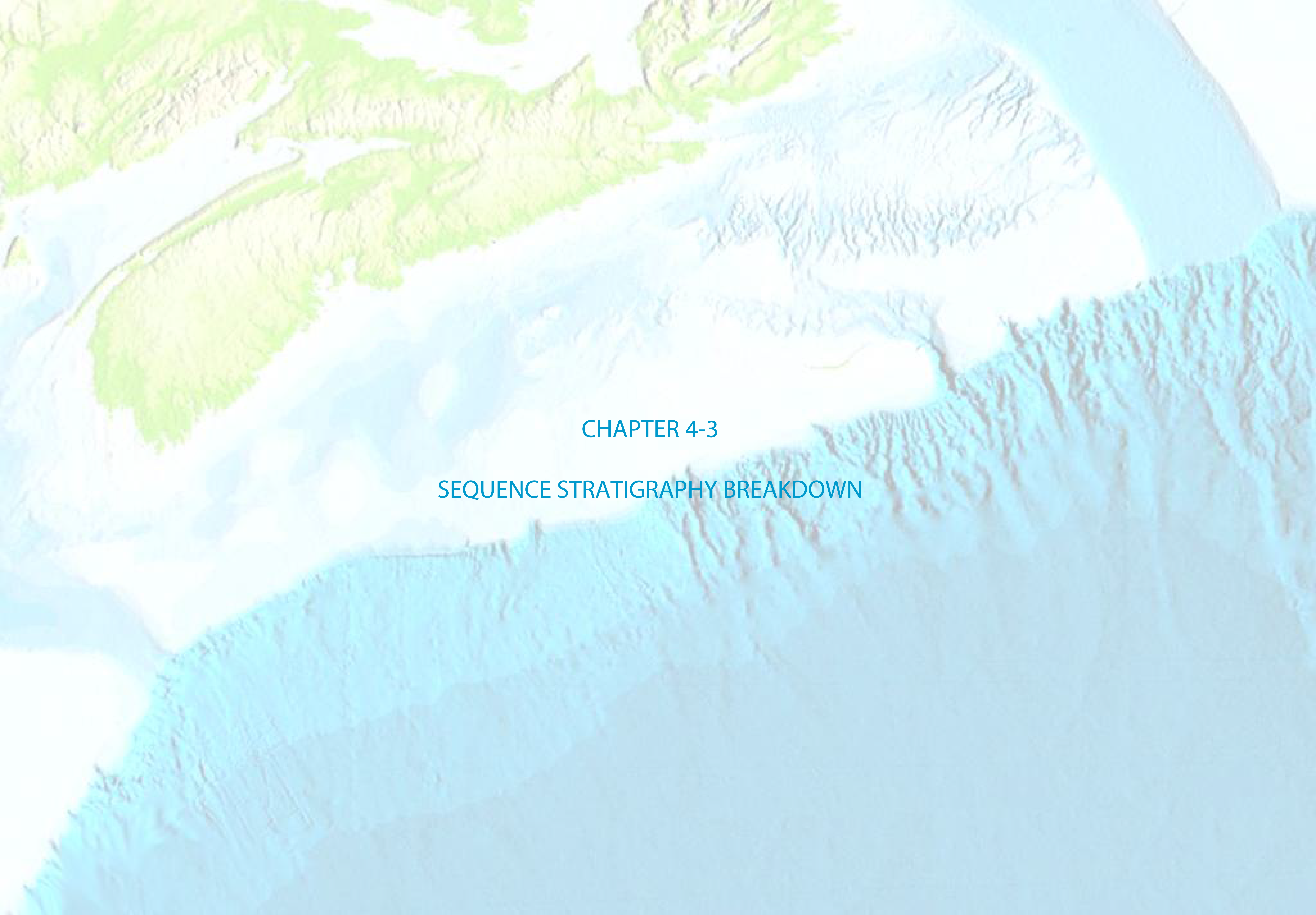
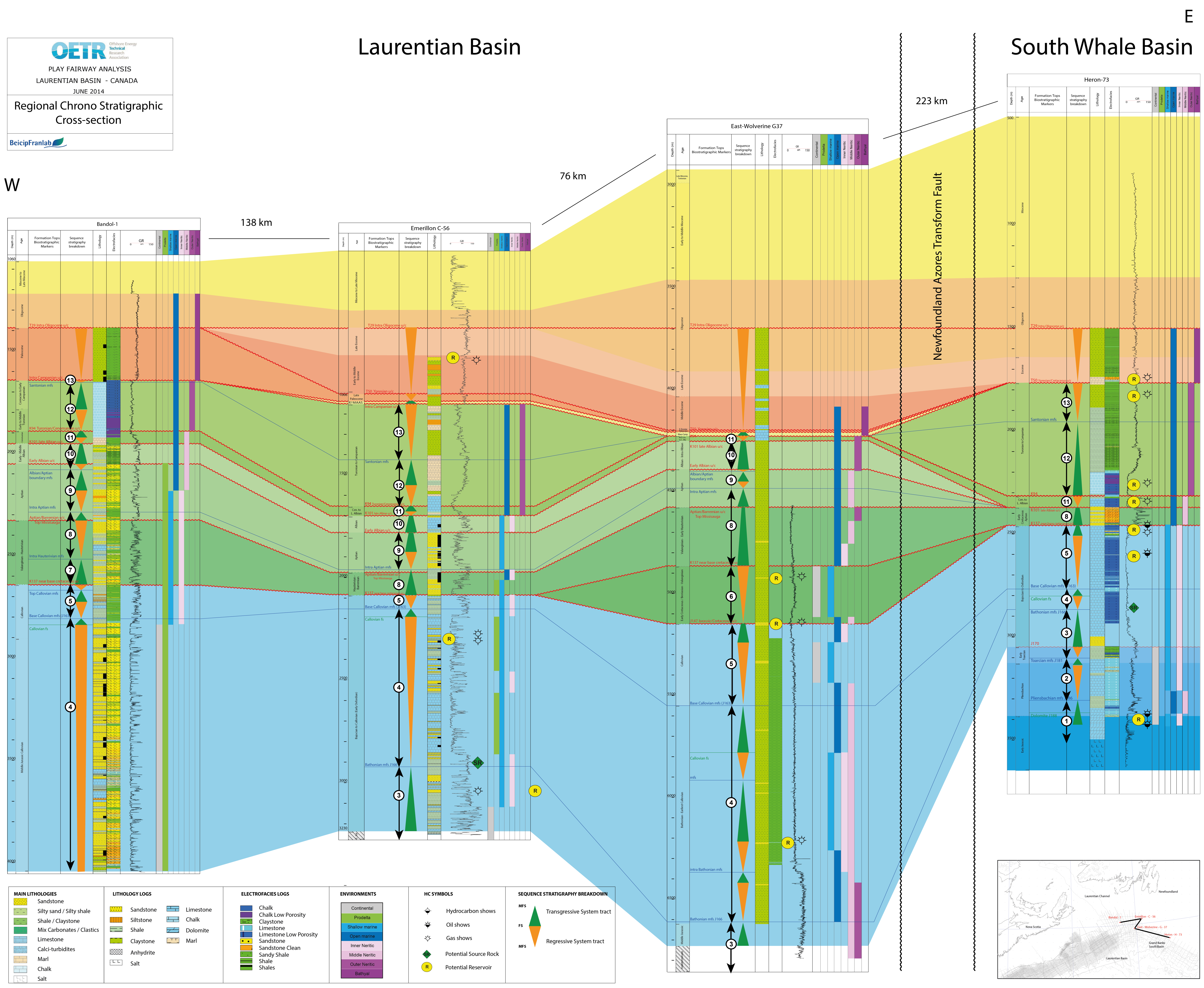


CHAPTER 4-3

SEQUENCE STRATIGRAPHY BREAKDOWN



Stratigraphic cross-section from Laurentian Basin to South Whale Basin

The stratigraphic cross-section illustrates a regional architecture of sedimentary deposits from Jurassic to Eocene interval.

Based on integration of biostratigraphy, lithological results and gama ray signature, between 9 and 12 sequences have been identified on the different wells. The sequences cover a timespan from early Jurassic to mid Oligocene, and the different sequences are associated with specific lithologies and environments.

Sequence 1 is **early Jurassic** and terminates with the **Pliensbachian MFS (J186)**. Depositional environment corresponds to the transition from continental to shallow marine under restricted condition.

Sequence 2 extends from **Pliensbachian to Toarcian MFS (J181)**. Space accommodation is driven by thermal subsidence subsequent to the North Atlantic Ocean opening. The environment corresponds to the transition from restricted shallow marine to open marine with a trend to deepening water.

Sequence 3 extends from **Toarcian to Bathonian MFS (J166)**. After the Toarcian MFS a transition from transgressive to regressive condition is observed with a paroxism at **J170** which also corresponds to the transition from Toarcian to Bajocian. No significant environmental change is observed from the previous sequence.

Sequence 4 is middle Jurassic in age and ends with the **Base Callovian MFS (J163)**. This sequence is observed in all the wells used in this study. This sequence marks the end of the regressive trend observed during the late early Jurassic. Sediment signature suggests a more continental influence with prodeltaic sediment. Depositional environment is inferred to be shallow water, which is also supported by the presence of thick carbonate units.

Sequence 5 extends from **Base Callovian MFS to Tithonian**. This time frame corresponds to a period of global transgression although classical Regression - Transgression cycles can be identify. A large part of the transgressive period is missing because of the impact of the **K147 and K137 unconformities**. On the shelf, sediments are mostly shale and carbonates associated with a shallow water environment. In deep water facies analysis suggests a shallowing trend.

Sequence 6 extends from **late Tithonian to early Valanginian**. This sequence is essentially preserved in deep water due to the impact of the **Valanginian unconformity (K137)**. This sequence marks the begining of a regressive trend. Depositional environment is inferred to be shallow water with a growing continental influence.

Sequence 7 corresponds to the **Vallanginian - Hauterivian** interval and ends with the **Intra-Hauterivian MFS (K130)**. This sequence is often missing due to the impact of successive unconformities occuring during the Cretaceous. Depositional environment corresponds to shallow water under continental influence.

Sequence 8 extends from **Hauterivian to intra Aptian** and terminates with the **intra Aptian MFS**.This sequence is found across the Laurentian Basin but largely eroded or missing in South Whale Basin. The sequence is associated to a deepening trend (inner to middle neritic) with open shallow water on the shelf.

Sequence 9 is **Aptian** of age and ends with the **Albian/Aptian boundary MFS**. This sequence is eroded in South Whale Basin and partly eroded in Laurentian Basin. This sequence corresponds to a more open marine condition with localized carbonate formations.

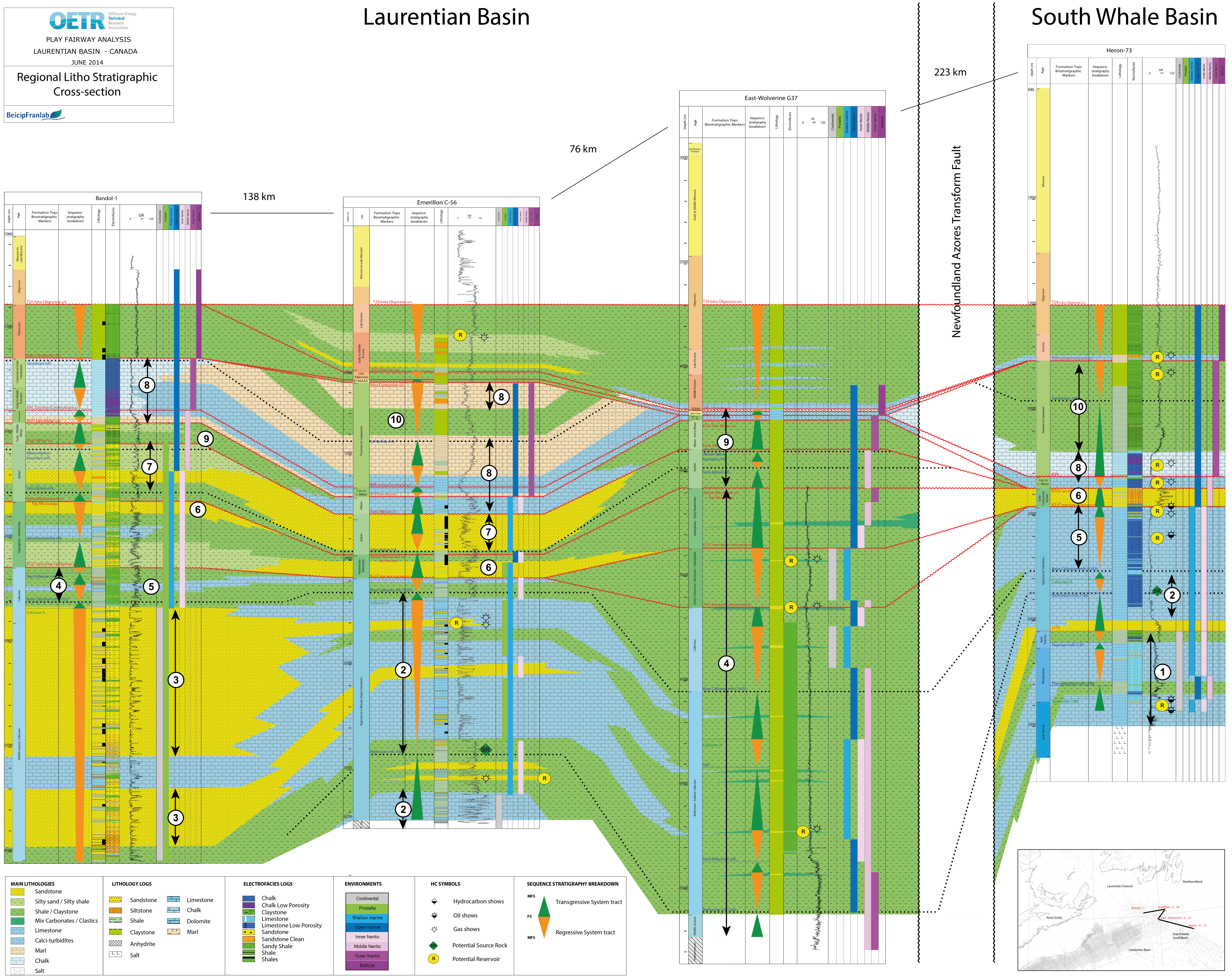
Sequence 10 is a transgressive phase occuring during the **Albian**. The sequence is partially preserved due to the late **Albian unconformity (K101)**. Resulting environment are infered to be shallow water alternating with estuary environment on the shelf.

Sequence 11 is **Cenomanian** of age. Most of the sequence is missing because of the **Turonian/Cenomanian unconformity (K94)**. Depositional environments are inner to middle neritic under open marine condition.

Sequence 12 extends from **Cenomanian to Santonian** and ends with the **Santonian MFS**. This sequence is characterized by a deepening trend in water depth which favor Chalk and Marl deposition.

Sequence 13 extends from **Santonian to Ypresian**. A significant part of the sequence is missing due to the **Ypresian unconformity (T50)**. Sedimentation occurs under deepwater condition as shown by the large distribution of Chalk and Marl.

SEQUENCE STRATIGRAPHY BREAKDOWN - Wells correlation



Stratigraphic cross-section from Laurentian Basin to South Whale Basin

The stratigraphic cross-section illustrates a regional architecture of sedimentary deposits from Jurassic to Eocene interval.

Early Jurassic starts with a thick **Dolomite** unit overlaying a salt formation. The **Dolomite** formation is topped by a thick **limestone** unit deposited from the **Pliensbachian to the Toarcian**. Its extension is restricted through time to the South Whale Basin and the E-NE part of the Laurentian Basin.

Jurassic period is mostly composed of a **mix of clastic and carbonate** sediment. To the western part of the Laurentian Basin thick laminated sandstone and mudstone successions are recorded with locally interbeded carbonate units. To the eastern part of the basin, sandstone beds are progressively replaced by interbedded oolitic limestone beds. South Whale Basin shows carbonate dominated beds with local sandstone beds.

Sedimentary formations are mostly characteristic of prodeltaic environment (where thick sandstone are observed) and shallow water environment (inner neritic) ; strong continental influence for early Jurassic sequences.

Deep water sedimentary formations (East-Wolverine) are shale dominated with punctual sandstone beds (few meters thick).

To the late Jurassic, environment evolves from outer to inner neritic environment with a trend to shallowing up and a growing continental influence when approaching the late Tithonian (K147).

Early Cretaceous starts with laminated sandstone and shale with few local carbonate units, with a trend to thick sandstone units toward Emerillon. Above the **Albian u/c** oolitic limestones are observed with a lateral change to chalk formation toward Heron.

This suggests a regressive trend followed by successive transgressions. Environments are inferred to be shallow water and coastal embayment evolving toward more open marine condition and middle neritic environment.

Late Cretaceous to Ypresian interval is characterized by chalk/marl/shale and mudstone suggesting more open marine condition and a deepening trend with neritic to bathyal condition reached at the Ypresian u/c. On the slope (East-Wolverine), mudstone dominates for most of the Cretaceous with few thin sand beds (few meters thick) replaced by detrital carbonates during the late Cretaceous (Cenomanian to Maastrichtian) times.

Ypresian to mid Oligocene interval corresponds to regressive trend with prodeltaic formation prograding over the shelf and feeding the basin with turbidites. At the Ypresian base, sedimentary sequences are largely composed of chalk and marl except near Bandol because of the impact of the intra Oligocene unconformity. The type of sedimentation quickly evolves into marine shale and prodeltaic mud in relation to the transgressive phase.

1- Ioquois equivalent Formation

2- Scatarie equivalent Formation

3- Mohican equivalent Formation

4- Verrill Canyon equivalent Formation

5- Abenaki equivalent Formation

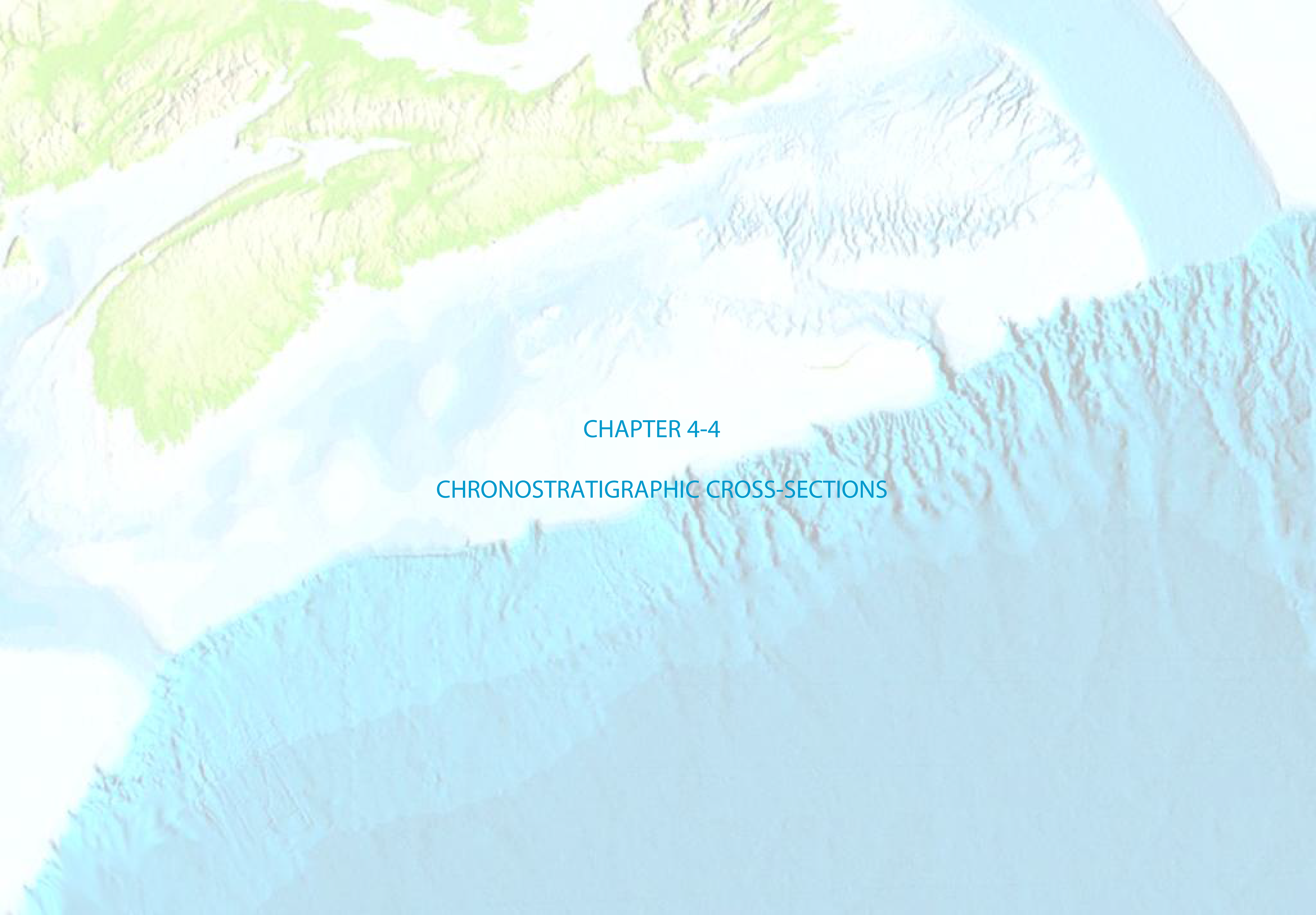
6- Missisauga equivalent Formation

7- Logan Canyon equivalent Formation

8- Wyandot / Petrel equivalent Formation

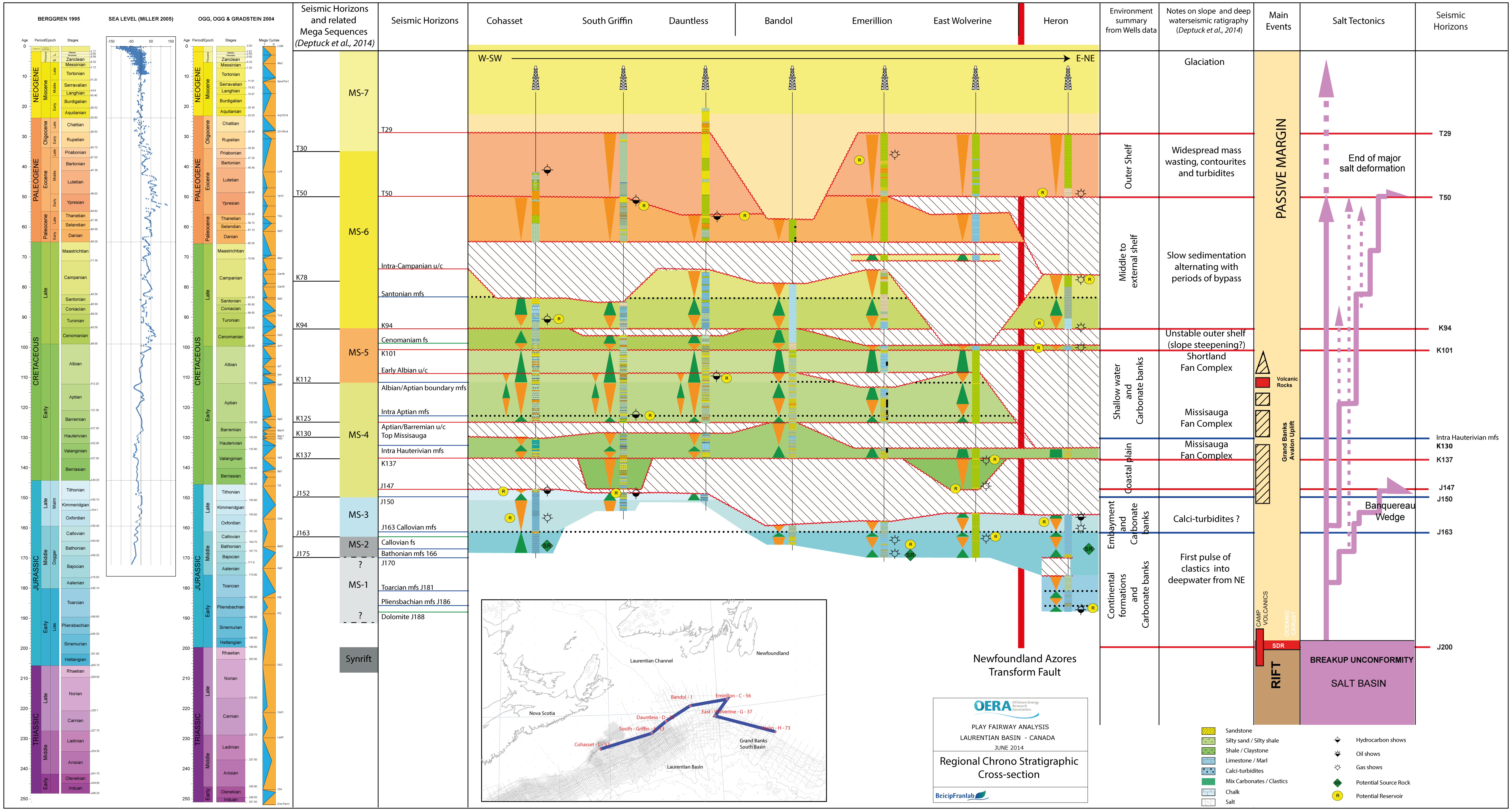
9- Shortland Shale equivalent

10- Dawson equivalent Formation



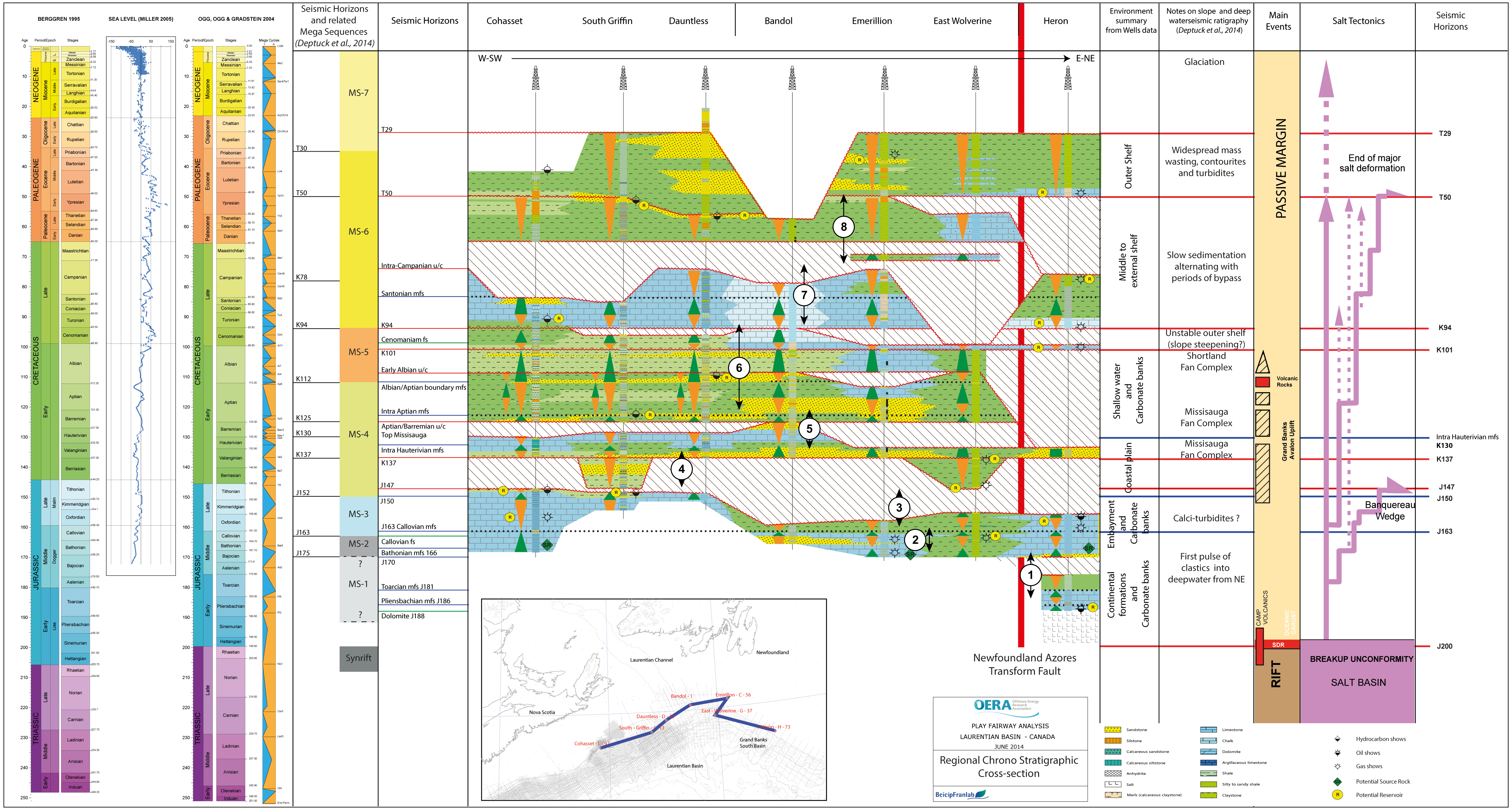
CHAPTER 4-4

CHRONOSTRATIGRAPHIC CROSS-SECTIONS



BERGGREN 1995
SEA LEVEL (MILLER 2005)
OGG, OGG & GRADSTEIN 2004
Seismic Horizons and related Mega Sequences (Deptuck et al., 2014)
Seismic Horizons
Cohasset
South Griffin
Dauntless
Bandol
Emerillion
East Wolverine
Heron
Environment summary from Wells data
Notes on slope and deep waterseismic ratigraphy (Deptuck et al., 2014)
Main Events
Salt Tectonics
Seismic Horizons
W-SW
E-NE
NEOGENE
PALEOGENE
CRETACEOUS
JURASSIC
TRIASSIC
MS-7
MS-6
MS-5
MS-4
MS-3
MS-2
MS-1
Synrift
T30
T50
K78
K94
K112
K125
K130
K137
J152
J163
J175
T29
Intra-Campanian u/c
Santonian mfs
Cenomaniam fs
K101
Early Albian u/c
Albian/Aptian boundary mfs
Intra Aptian mfs
Aptian/Barremian u/c
Top Missisauga
Intra Hauterivian mfs
K137
J147
J150
J163 Callovian mfs
Callovian fs
Bathonian mfs 166
J170
Toarcian mfs J181
Pliensbachian mfs J186
Dolomite J188
Outer Shelf
Middle to external shelf
Shallow water and Carbonate banks
Coastal plain
Embayment and Carbonate banks
Continental formations and Carbonate banks
Glaciation
Widespread mass wasting, contourites and turbidites
Slow sedimentation alternating with periods of bypass
Unstable outer shelf (slope steepening?)
Shortland Fan Complex
Missisauga Fan Complex
Missisauga Fan Complex
Calci-turbidites ?
First pulse of clastics into deepwater from NE
PASSIVE MARGIN
Volcanic Rocks
Grand Banks Avalon Uplift
CAMP VOLCANICS
SDR
RIFT
End of major salt deformation
Banquereau Wedge
BREAKUP UNCONFORMITY
SALT BASIN
T29
T50
K94
K101
Intra Hauterivian mfs
K130
K137
J147
J150
J163
J200
Newfoundland Azores Transform Fault
Laurentian Channel
Newfoundland
Nova Scotia
Bandol - 1
Emerillon - C - 56
East Wolverine - G - 37
Dauntless - D - 35
South - Griffin - J - 13
Heron - H - 73
Cohasset - L - 97
Grand Banks South Basin
Laurentian Basin
OERA
PLAY FAIRWAY ANALYSIS
LAURENTIAN BASIN - CANADA
JUNE 2014
Regional Chrono Stratigraphic Cross-section
BeicipFranlab
Sandstone
Silty sand / Silty shale
Shale / Claystone
Limestone / Marl
Calci-turbidites
Mix Carbonates / Clastics
Chalk
Salt
Hydrocarbon shows
Oil shows
Gas shows
Potential Source Rock
Potential Reservoir

STRATIGRAPHY



Lithologic cross-section in time showing the sedimentary facies and sequences across the margin.

Sequences have been regrouped into 8 sequences to harmonize with the 2011 PFA.

1- Pliensbachian to Bajocian: Overall it is a transgressive formation consisting primarily of dolomite deposited under slightly restricted marine conditions topped by Limestone

2- Bajocian to Callovian: Transgressive sequence with non-marine siliciclastics grading into Callovian shallow-marine oolitic carbonates. Marine shale deposited in late Callovian realted to the Callovian MFS which drowned carbonate plateforms.

3- Callovian to Tithonian: Carbonate sedimentation restarts at the Callovian-Oxfordian boundary with reef platforms development during the Oxfordian. Offshore, marine shale accumulates (East-Wolverine). Reef development slows down with the Tithonian transgression and is finally drown with the Tithonian MFS.

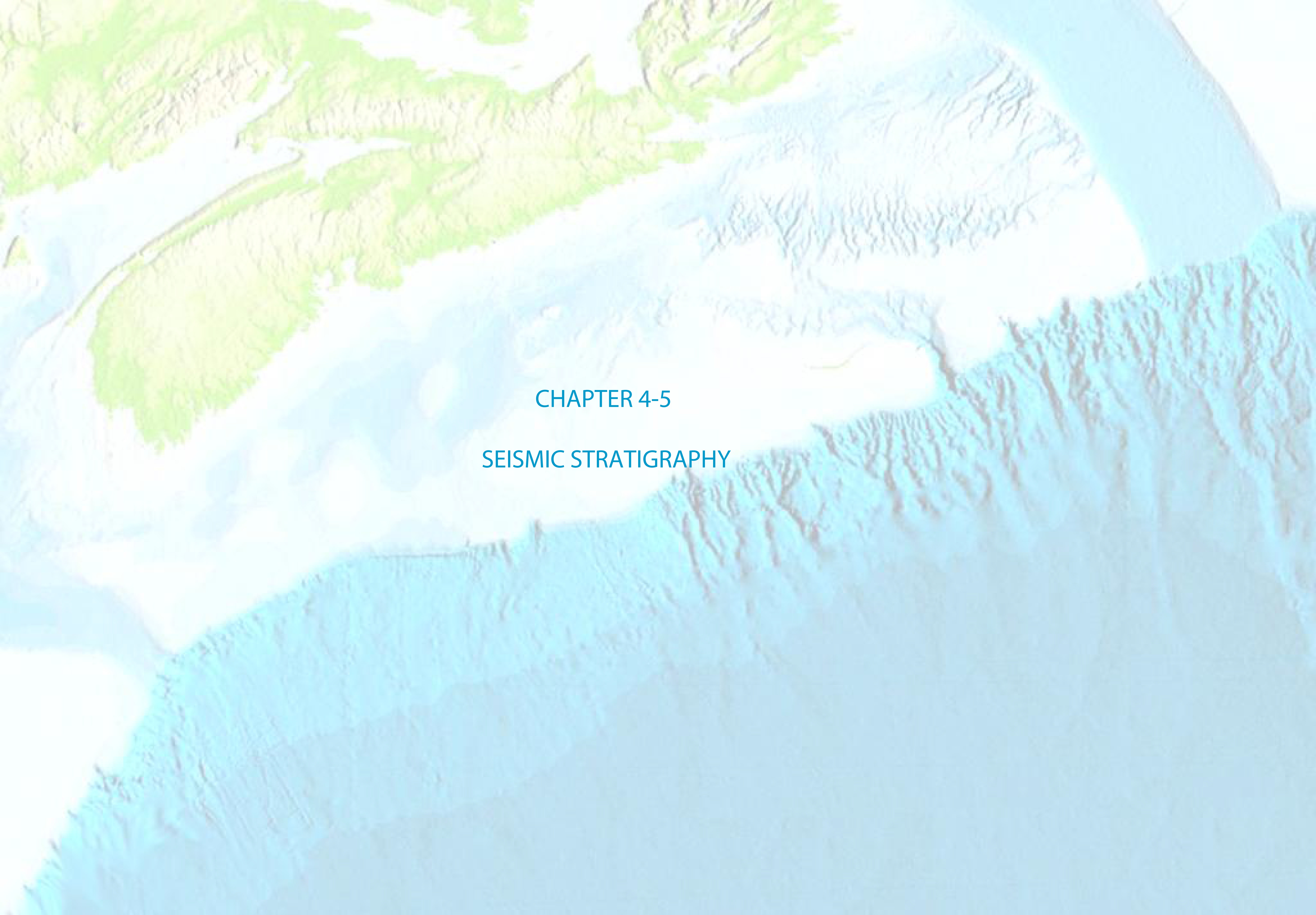
4- Tithonian to Valanginian: This interval contains moslty prodeltaic and open-marine shales. During the Valanginian, shale grades locally into sandstones related to deltaic progradations. Most of this interval is missing on the shelf and upper slopes due to the impact of the Berriasian-Valanginian unconformity (K137).

5- Valanginian – Aptian sequence: Following the drowning, reef platforms stop developing until the intra Hauterivian MFS. During the begining of the regression patchy carbonate plateforms develop away from siliciclastic inputs. Most of the sedimentation is dominated by shallow-marine siliciclastics input. The Aptian-Barremian unconformity is Recognized across the Laurentian Basin.

6- Aptian – Cenomanian: Overall shallow water sedimentation predominantly shaly with locally sand progradation during the early Aptian regression. This section is absent from the well in South Whale Basin . The Cenomanian lies unconformably on the Hauterivian.

7- Turonian – Campanian: Drastic reduction of siliciclastic influx coincident with detrital carbonate in shallower water and a sharp increase in chalk/marl sedimentation under deep open-marine conditions. The top chalk is diachronous on the shelf. Carbonate and chalk formations are significantly eroded by the intra Campanian u/c. The Maastrichtian is preserved in the E-NE part of the basin.

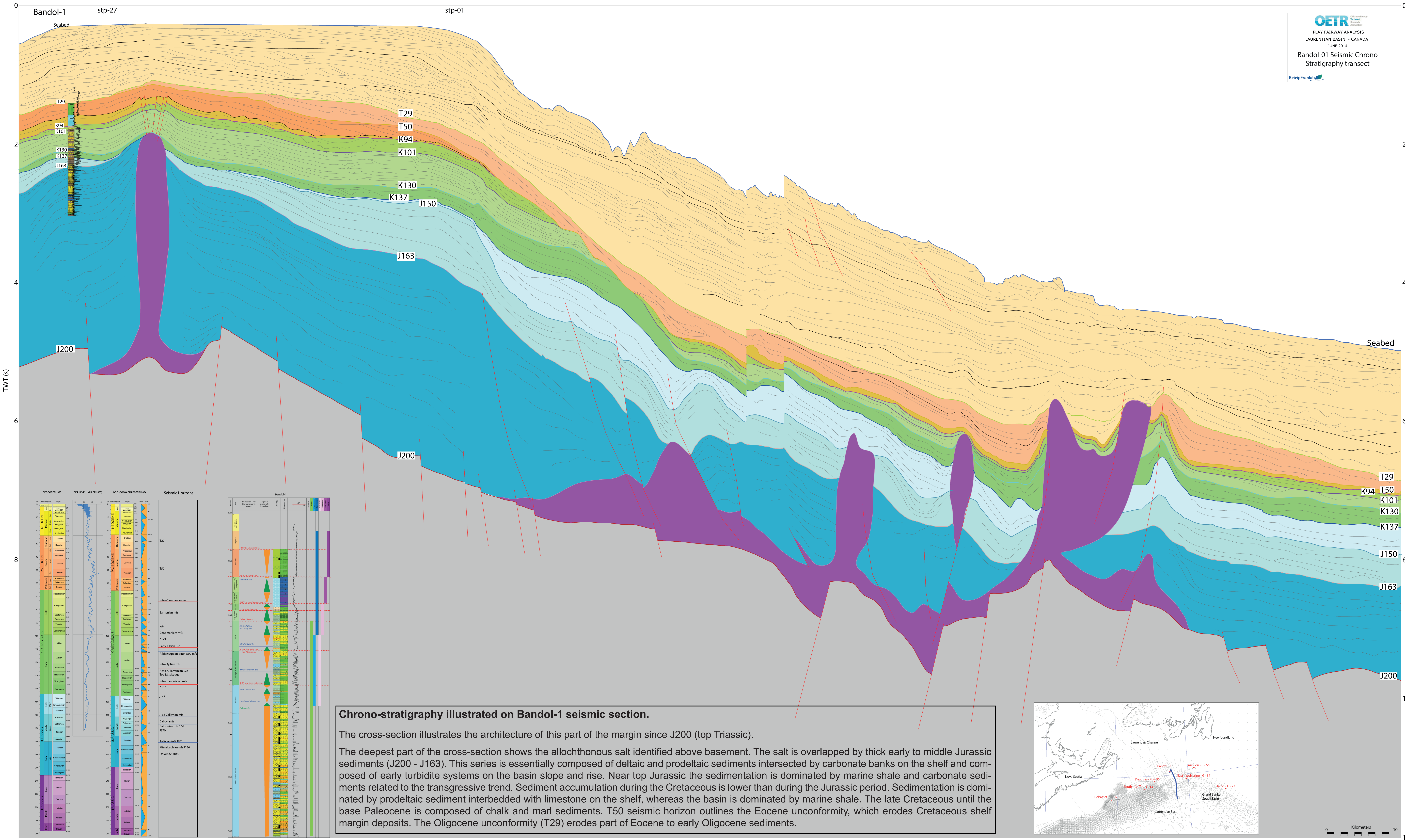
8- Campanian – Ypresian: Gradual transition from chalk to marine shale related to a regressive phase. Mix siliciclastic and carbonate turbidites are found offshore. Near the top Ypresian, sandstones are boserved related to prograding clinoforms. The sequence is cut by the Ypresian u/c (T50). Above the unconformity the sequence is draped by laterally persistent Ypresian chalk.



CHAPTER 4-5

SEISMIC STRATIGRAPHY

STRATIGRAPHY - SEISMIC STRATIGRAPHY



Chrono-stratigraphy illustrated on Bandol-1 seismic section.

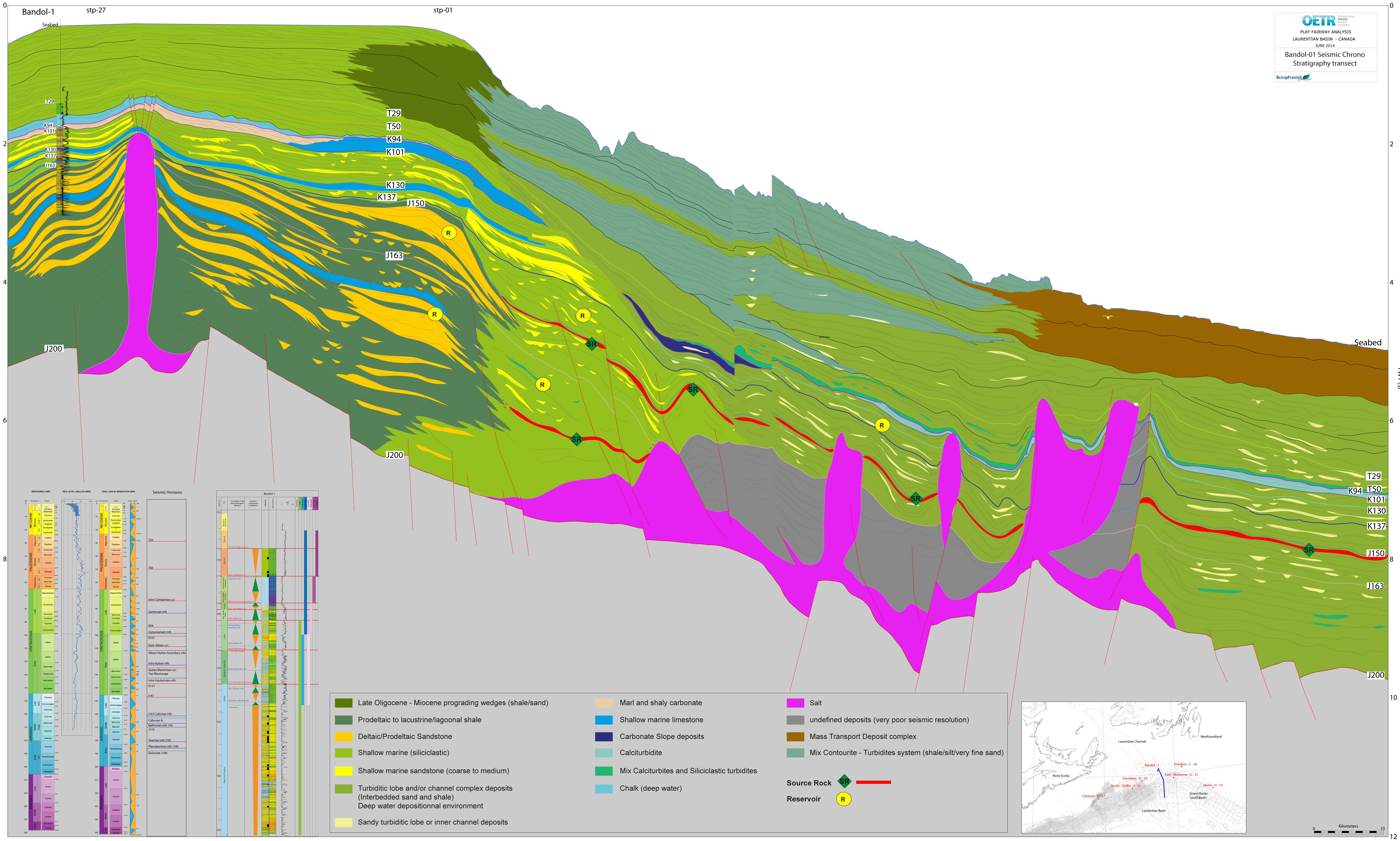
The cross-section illustrates the architecture of this part of the margin since J200 (top Triassic).

The deepest part of the cross-section shows the allochthonous salt identified above basement. The salt is overlapped by thick early to middle Jurassic sediments (J200 - J163). This series is essentially composed of deltaic and prodeltaic sediments intersected by carbonate banks on the shelf and composed of early turbidite systems on the basin slope and rise. Near top Jurassic the sedimentation is dominated by marine shale and carbonate sediments related to the transgressive trend. Sediment accumulation during the Cretaceous is lower than during the Jurassic period. Sedimentation is dominated by prodeltaic sediment interbedded with limestone on the shelf, whereas the basin is dominated by marine shale. The late Cretaceous until the base Paleocene is composed of chalk and marl sediments. T50 seismic horizon outlines the Eocene unconformity, which erodes Cretaceous shelf margin deposits. The Oligocene unconformity (T29) erodes part of Eocene to early Oligocene sediments.

PL. 4-5-1 **Architectural cross-section 1: Bandol-1 Seismic chronostratigraphy (lines stp-27 and stp-01)**

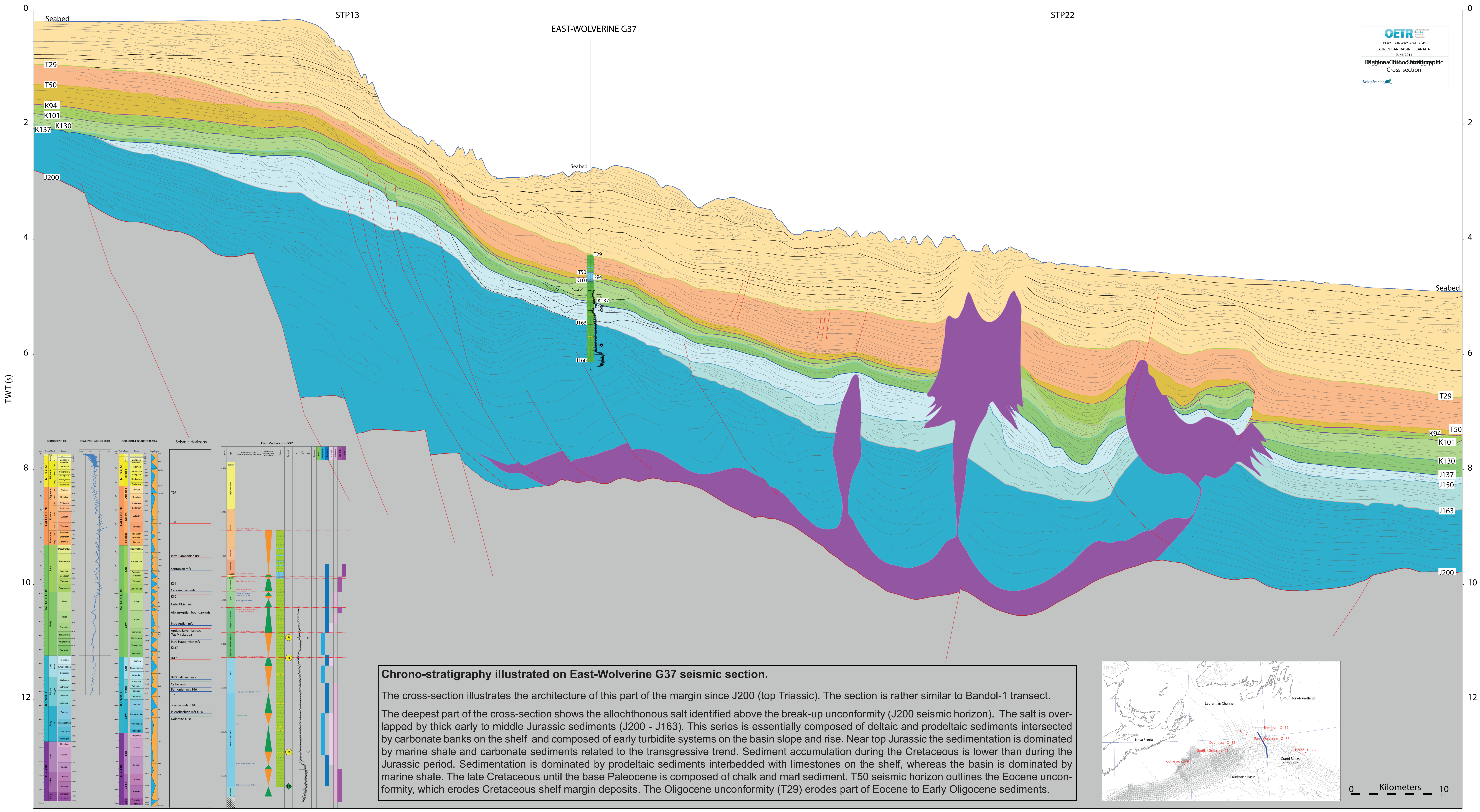
STRATIGRAPHY - SEISMIC STRATIGRAPHY

Laurentian sub-basin study - CANADA - June 2014



Architectural cross-section 1: Bandol-1 Seismic lithostratigraphy (lines stp-27 and stp-01) **PL. 4-5-2**

STRATIGRAPHY - SEISMIC STRATIGRAPHY



Chrono-stratigraphy illustrated on East-Wolverine G37 seismic section.

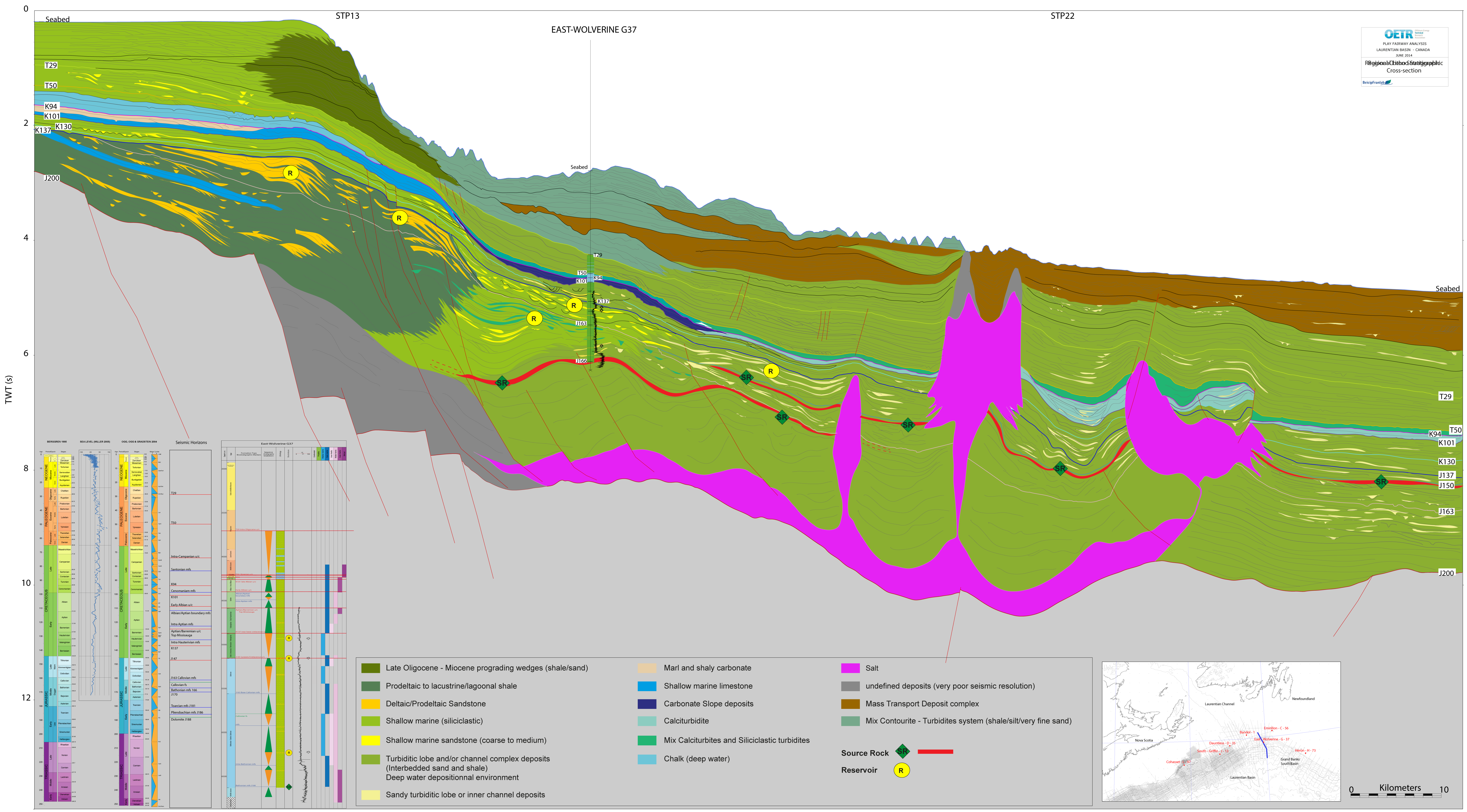
The cross-section illustrates the architecture of this part of the margin since J200 (top Triassic). The section is rather similar to Bandol-1 transect.

The deepest part of the cross-section shows the allochthonous salt identified above the break-up unconformity (J200 seismic horizon). The salt is overlapped by thick early to middle Jurassic sediments (J200 - J163). This series is essentially composed of deltaic and prodeltaic sediments intersected by carbonate banks on the shelf and composed of early turbidite systems on the basin slope and rise. Near top Jurassic the sedimentation is dominated by marine shale and carbonate sediments related to the transgressive trend. Sediment accumulation during the Cretaceous is lower than during the Jurassic period. Sedimentation is dominated by prodeltaic sediments interbedded with limestones on the shelf, whereas the basin is dominated by marine shale. The late Cretaceous until the base Paleocene is composed of chalk and marl sediment. T50 seismic horizon outlines the Eocene unconformity, which erodes Cretaceous shelf margin deposits. The Oligocene unconformity (T29) erodes part of Eocene to Early Oligocene sediments.

PL. 4-5-3 **Architectural cross-section 2: East-Wolverine G37 - Seismic chronostratigraphy (lines stp-13 and stp-22)**

STRATIGRAPHY - SEISMIC STRATIGRAPHY

Laurentian sub-basin study - CANADA - June 2014



Architectural cross-section 2: East-Wolverine G37 - Seismic lithostratigraphy (lines stp-13 and stp-22)

PL. 4-5-4