CHAPTER 3

STRATIGRAPHY

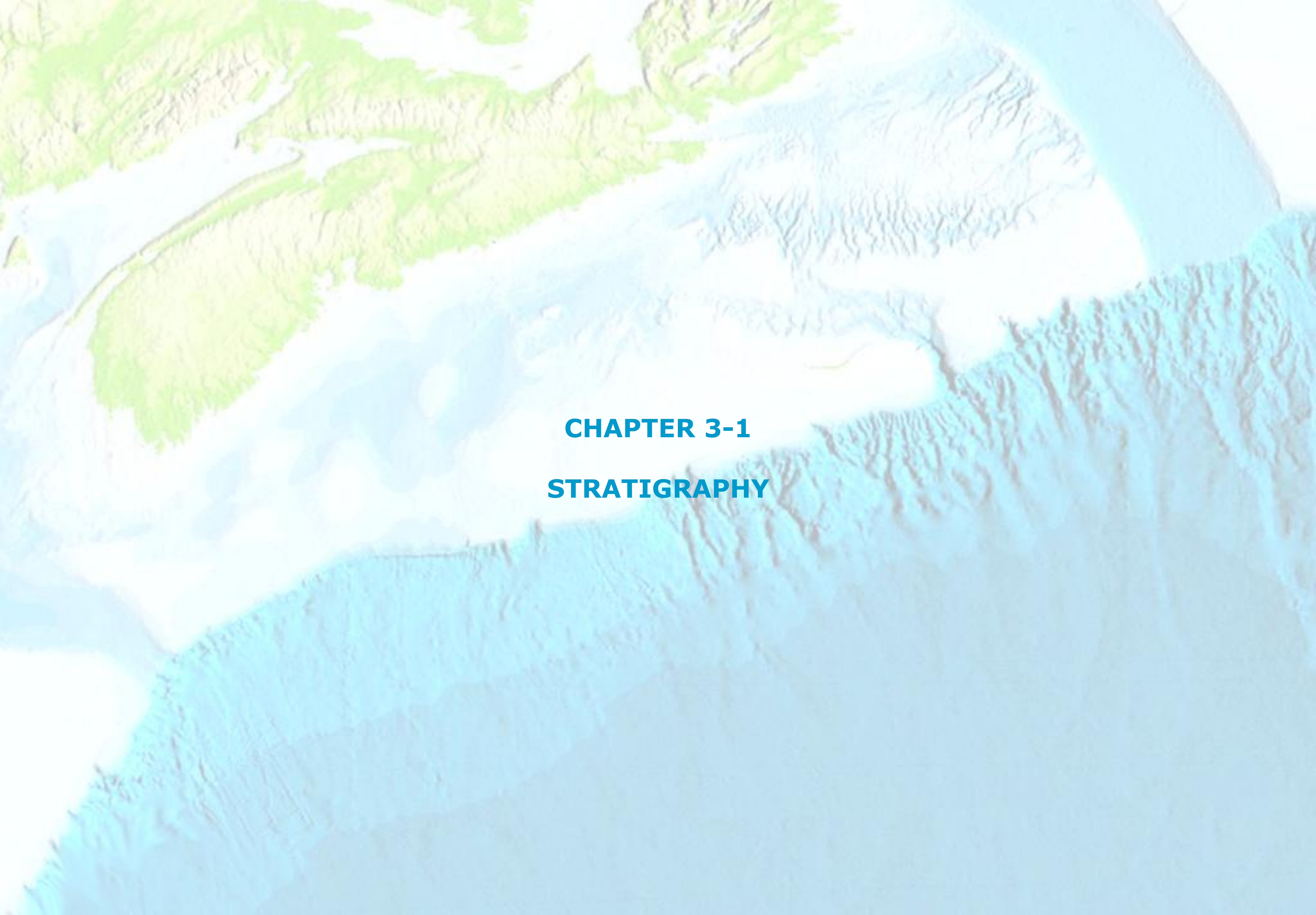
Objectives

The objective of Chapter 3 is to integrate new results from biostratigaphy, sequence stratigraphy, sedimentary environment of the Scotian Basin. Based on 20 key wells, the geological formations from early Triassic to Pliocene in age were described into the frame of the main tectono-sedimentological sequences. This succession encompasses the Pre-salt –Pre-rift series till the Break Up at 200Ma, the late Triassic to Mid Jurassic sequence (200-163 Ma), the Mid to Late Jurassic sequence (163–150Ma), the Lower Cretaceous sequence of the Missisauga delta (150 to 125 Ma); the Mid-Upper Cretaceous of the Logan Canyon (125 to 94 Ma) sequence and the Upper Cretaceous – Tertiary system. Therefore the age dating of the geological formations through the basin architecture were also defined by biostratigraphic markers, some of them being regional seismic horizons.

Finally an updated Stratigraphic Chart, Geological Composite Well Log, several lithostratigraphic and chronostratigaphic cross sections were produced meanwhile the architectural aspect of these main deposit sequences were designed along structural seismic cross-sections at regional scale.

Generalized stratigraphy framework

The Scotian Basin contains Mesozoic-Cenozoic sedimentary rocks, up to 15km thick that were deposited during the rifting of Pangea and the opening of the North Atlantic ocean. The earliest fill in the basin, deposited during Triassic rifting, consists of red continental clastics and evaporites. With the transition to seafloor spreading in the Early Jurassic, the rift basins were gradually filled by clastics and carbonates. Fully marine conditions developed by Mid to Late Jurassic, leading to an array of alluvial plain, deltaic, and carbonate facies development. Following the Avalon uplift, the Early Cretaceous was dominated on the shelf by deltaic progradation and shelf clastic deposits. Late Cretaceous/ Early Tertiary sedimentary deposits were 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). These are overlain by unconsolidated glacial till, glaciomarine silts, and marine sediments that were deposited during the Quaternary..



CHAPTER 3-1

STRATIGRAPHY

INTRODUCTION – STRATIGRAPHY

Objectives

In Chapter 3, the objective is to build a stratigraphic framework of the Mesozoic-Cenozoic sedimentary record of the Scotian margin in order to establish the chronology and age of major geological events, which controlled the sedimentary infill of the basin. This resulted in the following:

- An updated version of the stratigraphic chart of the Scotian Basin presented in Figure 1, this Plate and in Plate PL. 3-3-1b;
- A sequence stratigraphic breakdown at studied wells illustrating major long-term stratigraphic sequences;
- A timeframe for 10 seismic horizons representing the relevant sequence stratigraphic surfaces, out of the 13 horizons interpreted.
- A facies and lithological interpretation at wells for calibration of stratigraphic modeling (Dionisos® software) and petroleum system modeling (Temis Suite 2008® software).

Well database and methodology

Among the Official Directory from GSC/CNSOPB of 205 wells listed in Table 1-2 of Annex 1, the core well database consists of a selection of 20 key wells distributed over the Scotian shelf and slope. These 20 wells were primarily selected for the quality of their biostratigraphic content (for further detail, see Plate PL. 3-3-1a). They were also used as a basis for defining the lithostratigraphic and sequence stratigraphic study of the Scotian Basin.
The Geological Composite Well logs are presented in Enclosures 3-1 to 3-20. They display a (1) logs suite (Cali, SP, GR, Res, Neutron, Density, DT); (2) a lithological column; (3) biostratigraphic surfaces; (4) formation tops; (5) calculated VSH and PHIE curves, (6) TOC, (7) Phi/K core, (8) core and test intervals; (9) HC occurrence; (10) sequence stratigraphy breakdown and (11) depositional environments.

Lithological and PHIE computation in the key wells

The lithological interpretation was carried out on the 20 key wells (see Table 1, this Plate) and presented in the respective geological composite logs. On each composite log, lithologies derive from available data provided in well final reports. Such information includes qualitative log interpretations, mud reports, geological mud logs, existing composite well logs, and master logs.

The qualitative lithological interpretation presented in composite logs is determined by the Vsh log calculated on the 20 key wells. For each single run, the Vsh derives from Gamma Ray log min-max (see Table 4-2 of Annex 4). 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 and mixtures of siliciclastics and carbonates described in final well reports.
PHIE calculation (Annex 4: Well log results) derives from Neutron/Density logs (PHIT) and Vsh (shale effect).

Biostratigraphy in the key wells

Multi-disciplinary analysis of 24 wells is provided to support sequence stratigraphic interpretation at wells and seismic correlations at the scale of the Scotian Basin. New quantitative biostratigraphic analyses of 8 wells drilled on the shelf were carried out and 12 wells with pre-existing data were re-interpreted. In addition 4 wells were analyzed for their biostratigraphic content focusing on the Late Jurassic interval (see Chapter 3-3).

The biostratigraphic interpretation provides the timeframe and stratigraphic age references (datum) for constructing the sequence stratigraphic breakdown.

Sequence stratigraphic breakdown in the key wells

The sequence stratigraphic breakdown is performed on the 20 key wells based on biostratigraphic and lithological information. In each single well, major stratigraphic surfaces derive from biostratigraphic dating. Between those major stratigraphic surfaces, depositional environments are obtained through the combination of lithologies, log responses and biofacies. The resulting vertical stacking of depositional environments is interpreted in terms of the 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.

Eight long-term stratigraphic sequences, with average duration of 5-15 Ma, are defined from Middle Jurassic to Oligocene. These 2nd order sequences are propagated at the scale of the Scotian Basin through seismic mapping and well correlations. They highlight major stages of the sedimentary infill of the margin.

Well correlations on extended well database

The geological complexity of the margin cannot be addressed through the interpretation of the 20 key wells only. For such a reason, the stratigraphic analysis of the Scotian Basin was extended to 136 wells listed in Table 4-1 of Annex 4. These wells are used to ascertain stratigraphic correlations between distant key wells and support seismic horizons interpretations over the whole basin.

Content

Chapter 3 includes the following:

- ***Lithostratigraphic overview*** (Plates 3-2-1a to 3-2-3b) describes the geological setting of the Scotian Basin based on the published lithostratigraphic framework;
- ***Biostratigraphy*** (Plates 3-3-1a and 3-3-1b) gives a summary of biostratigraphic-calibrated surfaces and their integration into the updated stratigraphic chart (Figure 1, this Plate; and Plate 3-3-1a);
- ***Chronostratigraphic sections*** (Plates 3-4-1 to 3-4-3) display the long-term sequences in time (Wheeler diagrams) along 4 cross-sections highlighting time and spatial distribution of depositional sequences and time-gaps;
- ***Geological cross-sections*** (Plates 3-5-1a and 3-5-1b) illustrate, along 2 transects, the lateral variation of lithofacies (reservoirs and seals) between key wells and their relationships with biostratigraphically calibrated surfaces;
- ***Architectural cross-sections*** *on Bible lines* (Plates 3-5-2a to 3-5-3b) show the geometry of the seismically interpreted depositional sequences in their relationships to salt tectonics, along 4 depth-converted Bibles lines.

Table 1: List of the 20 key wells selected for the stratigraphic study

	Well	KB (m)	Water Depth (m)	TD (m)	Formation at TD	Stratigraphy
1	ALBATROS B13	24.0	1 341	4 046	Misaine	Callovian
2	ALMA F67	24	68	5 054	Abenaki	Tithonian
3	ANNAPOLIS G24	35.5	1 711.00	6 182	Verrill Canyon /M. Missisauga	Hauterivian
4	BALVENIE B79	25.0	1803.0	4 750	Logan Canyon /Shortland Shale	Mid Albian
5	BONNET P23	25.0	133.5	4 336	Iroquois	Break Up Unc.
6	CHEBUCTO K90	22.8	86.2	5 235	Verrill Canyon /M. Missisauga	Hauterivian
7	COHASSET L97	32.9	21.6	4 872	Iroquois	Bajocian
8	CRIMSON F81	21.4	2091.5	6 676	Verrill Canyon /M. Missisauga	Valanginian
9	DAUNTLESS D35	31.4	69.2	4 741	Baccaro	Oxfordian
10	EVANGELINE H98	20.9	175.0	5 044	U. Missisauga	Aptian/Barremian
11	GLENELG J48	24.0	83.7	5 148	Verrill Canyon /L. Missisauga	Top Jurassic
12	GLOOSCAP C63	22.9	99.0	4 542	Argo Salt	Late Triassic
13	HESPER P52	40.5	44.5	5 679	Baccaro	Oxfordian
14	NEWBURN H23	24.0	977.0	6 070	Verrill Canyon /M. Missisauga	Hauterivian
15	SHELBURNE G29	25.0	1153.5	4 005	Baccaro	Base Berriasian
16	SHUBENACADIE H100	24.1	1476.5	4 200	Logan Canyon /Shortland Shale	Cenomanian
17	SOUTH GRIFFIN J13	39.6	63.4	5 911	Mic-Mac	Oxfordian
18	TANTALLON M41	24.0	1516.0	5 602	Verrill Canyon /M. Missisauga	Valanginian
19	WEST ESPERANTO B78	23.3	91.1	5 703	Scatarie	Late Bathonian
20	WEYMOUTH A 45	25.0	1689.7	6 520	Verrill Canyon /M. Missisauga	Hauterivian

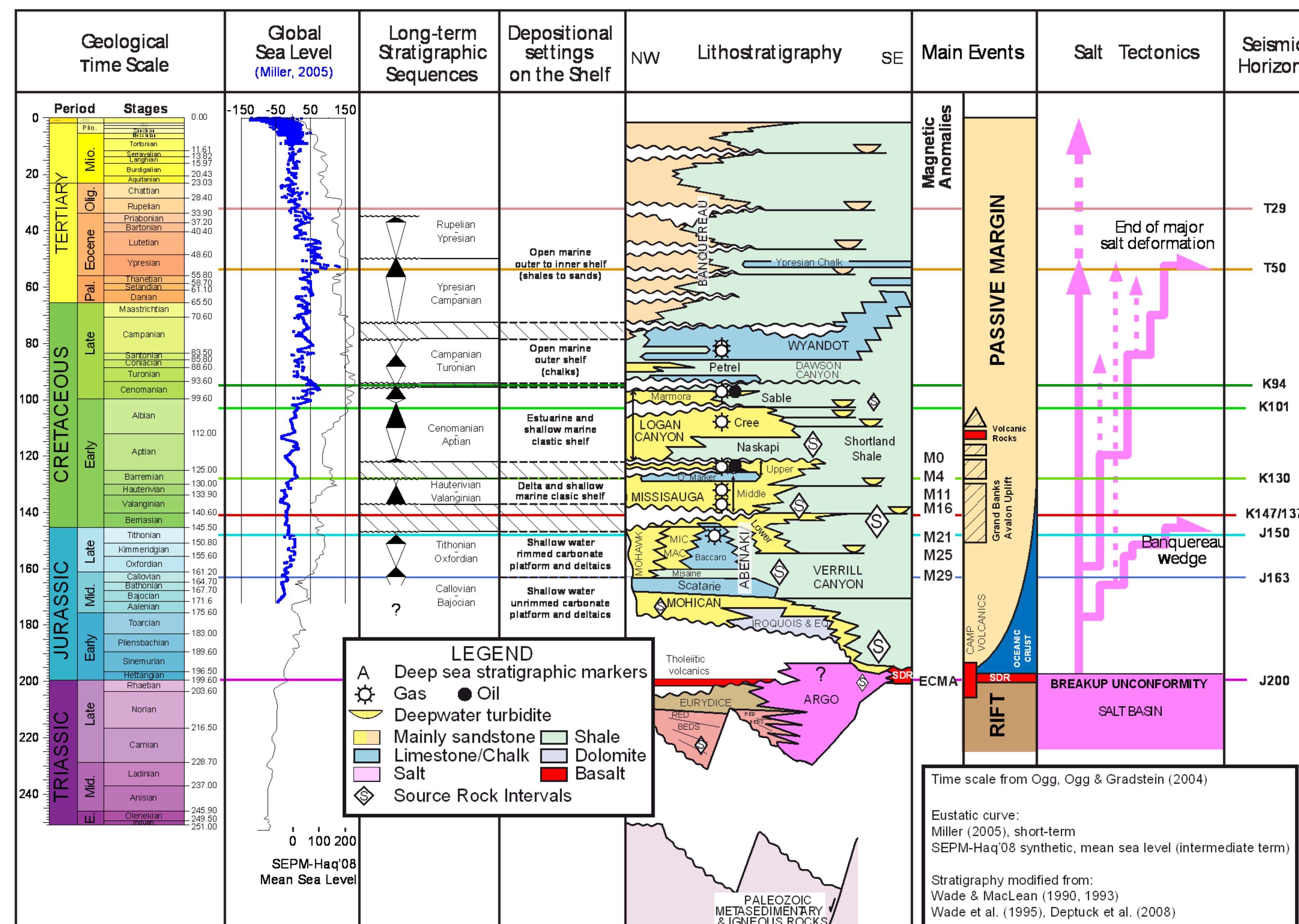
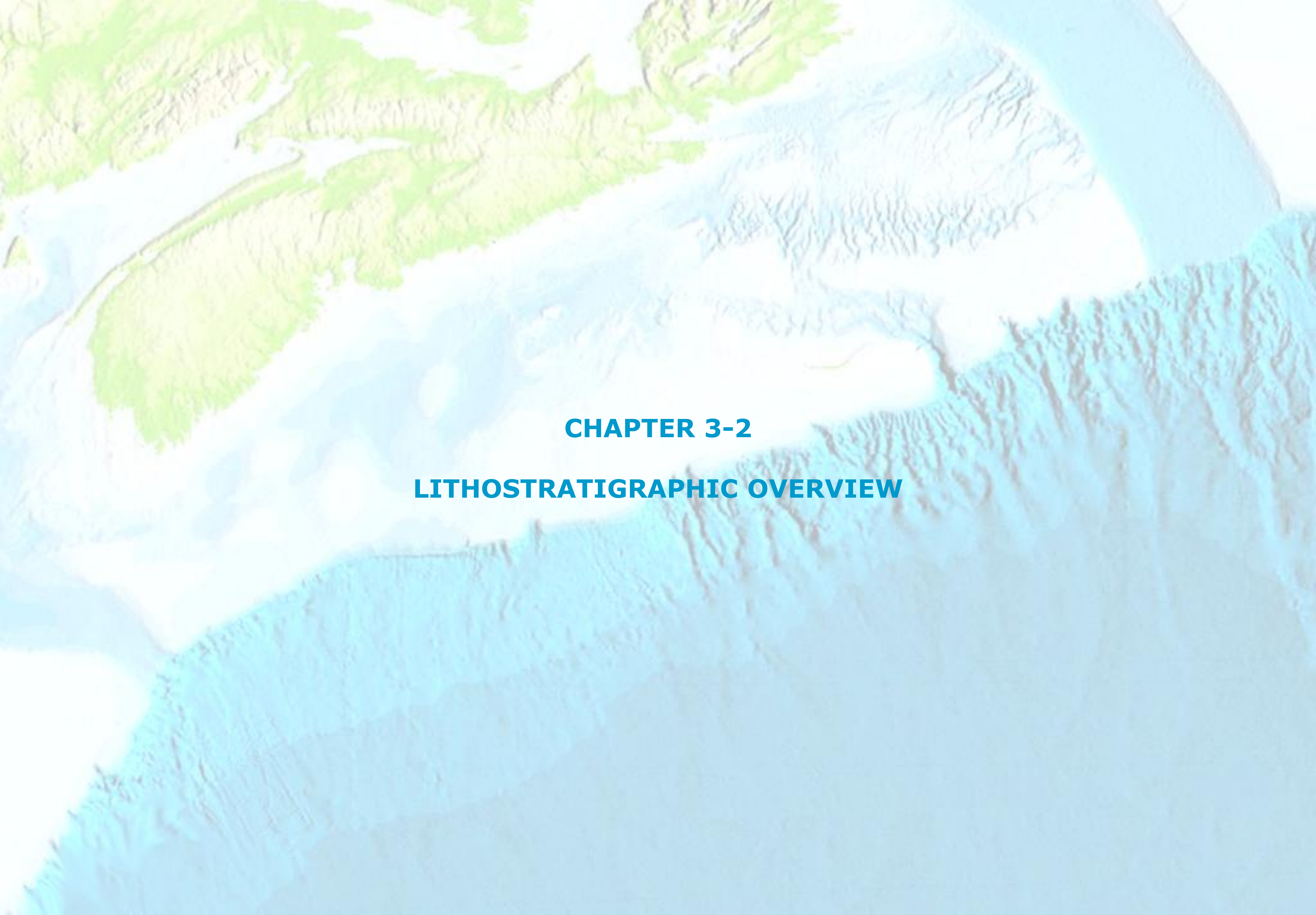


Figure 1: New stratigraphic Chart of the Scotian Basin.



CHAPTER 3-2

LITHOSTRATIGRAPHIC OVERVIEW

Stratigraphic Overview

Generalized stratigraphy of the Central Scotian Shelf

The Scotian Basin contains Mesozoic-Cenozoic sedimentary rocks, up to 15km thick in place that were deposited during the rifting of Pangea and the opening of the North Atlantic. The earliest fill in the basin, deposited during Triassic rifting, consists of red continental clastics and evaporites. With the transition to seafloor spreading in the Early Jurassic, the rift basins were gradually filled by clastics and carbonates. Fully marine conditions developed by Mid to Late Jurassic, leading to an array of alluvial plain, deltaic, and carbonate facies development. Early Cretaceous consecutive to the Avalon uplift was dominated on the shelf 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 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). These are overlain by unconsolidated glacial till, glaciomarine silts, and marine sediments that were deposited during the Quaternary.

Basement and preserved Carboniferous - Early Triassic deposits

Very few wells (10 wells, PL. 6-2-9b) reached basement horst made of granite complex and metamorphosed sediments (gneiss and schist). Seismic recognized tilted blocks and associated troughs infilled with unknown sedimentary deposits of Early Triassic or Carboniferous age. These sediments are exposed and preserved onshore on the western rim of the Scotian shield mainly along the Fundy bay. Eastward from Halifax, the geological map indicates limited outcrops of Carboniferous age. Offshore, eastward these series could be present in the deepest troughs observed in seismic sections.

Triassic

Formations: Eurydice and Argo Salt

Number of exploration wells reaching the Triassic: 17 (PL. 6-2-9b and Annex 4, Table 4-1: Formation Tops and Biostratigraphic Surface)

Eurydice Formation

Identification

- Type section: Eurydice P-36 well
- Age: Late Triassic
- Well type on the study area: Moheida P-15

Description

The oldest of the synrift sequences related to the opening of the Atlantic is a thick series of Late Triassic/ red sandstones, siltstones and shales named **Eurydice Formation**. Wells have encountered the Eurydice Formation both beneath the Grand Bank and the Scotian Shelf. In the Orpheus Graben, where the type section of the Eurydice Formation is defined, almost 600m of the formation were drilled (Eurydice P-36) and seismic data indicates a total formation thickness of over 3000m. More than 1500m of Eurydice Formation were drilled in the Naskapi Graben complex and seismic data indicate a thickness of over 3000m (Wade and MacLean; 1990).

On the Scotian Shelf, the Moheida P15 well shows the Eurydice formation with a well developed clastic section (Figures 1 and 2). Eurydice sands and shales are said to be locally contemporaneous to the salt deposits of the Argo Formation. The salt basin fills the Triassic basin preceding the break up of the North Atlantic opening.

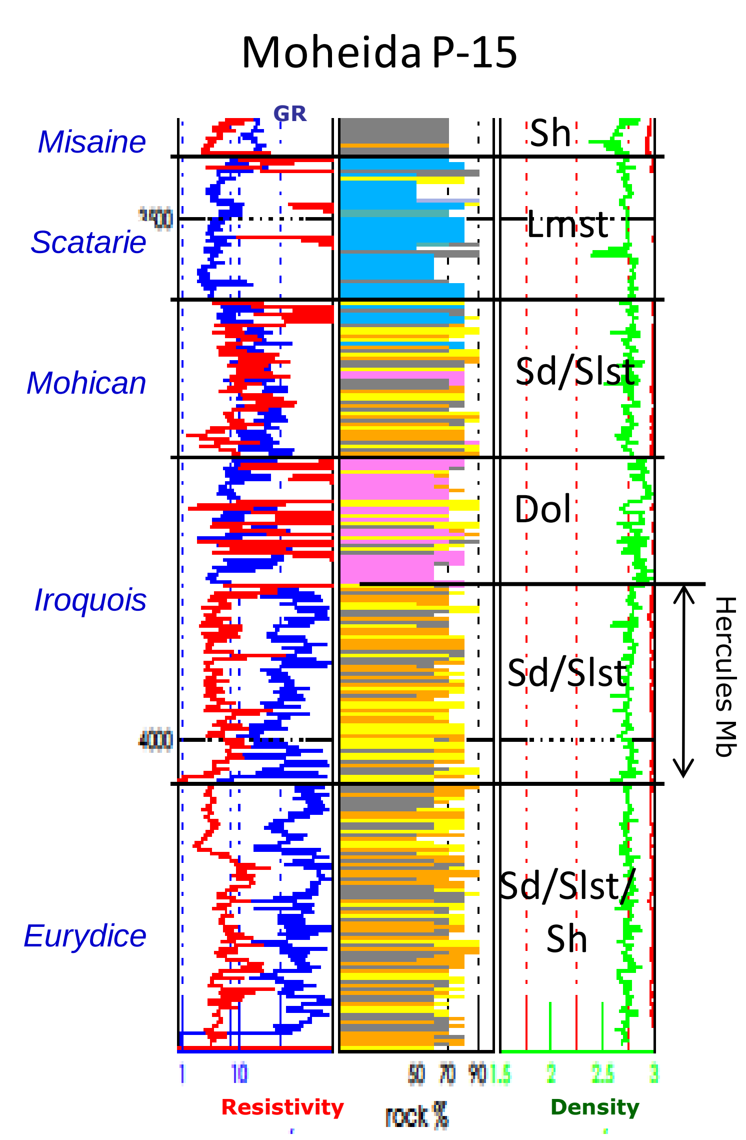


Figure 1. Litholog interpretation of Moheida P15 well, (after Fensome, modified)

Argo Formation

Identification

- Type section: Argo F-38 well
- Argo Salt age: Early-Late Triassic to Early Jurassic
- Type wells on the study area: Glooscap C-63 (Argo Salt)
- Lithostratigraphic Cross-Section 1 (PL. 3-5-1a and Enclosure 3-21)
- Architectural Cross-Sections on Bible Lines (PL. 3-5-2 & 3)

Description

The **Argo Formation** Overlies the Eurydice Formation, interfingering with it on the basin margins. The Argo Formation consists primarily of a series of massive beds of pale orange salt separated by zone of red shales. The distribution of salt along the Scotia margin suggests that the major basin is shaped by the structural network inherited from the basement trends and the boundary between continental and oceanic crust during the synrift phase. The original thickness of salt is estimated to 2000m at least.

The salt has flowed extensively due to subsequent sediment loading and, possibly, to periodic reactivation of the rift fault system during the later stages of continental breakup. Salt pillows, diapirs and canopies are common along the margin, beneath the continental slope from eastern Georges Bank to western Grand Banks.

Hydrocarbon occurrence: No hydrocarbon shows are reported in the Argo Formation, wherever penetrated on the Scotia margin. Hydrocarbon fluid inclusions were observed in the “autochthonous “salt penetrated at Glooscap C-63 and in the Weymouth A-45 salt canopy,

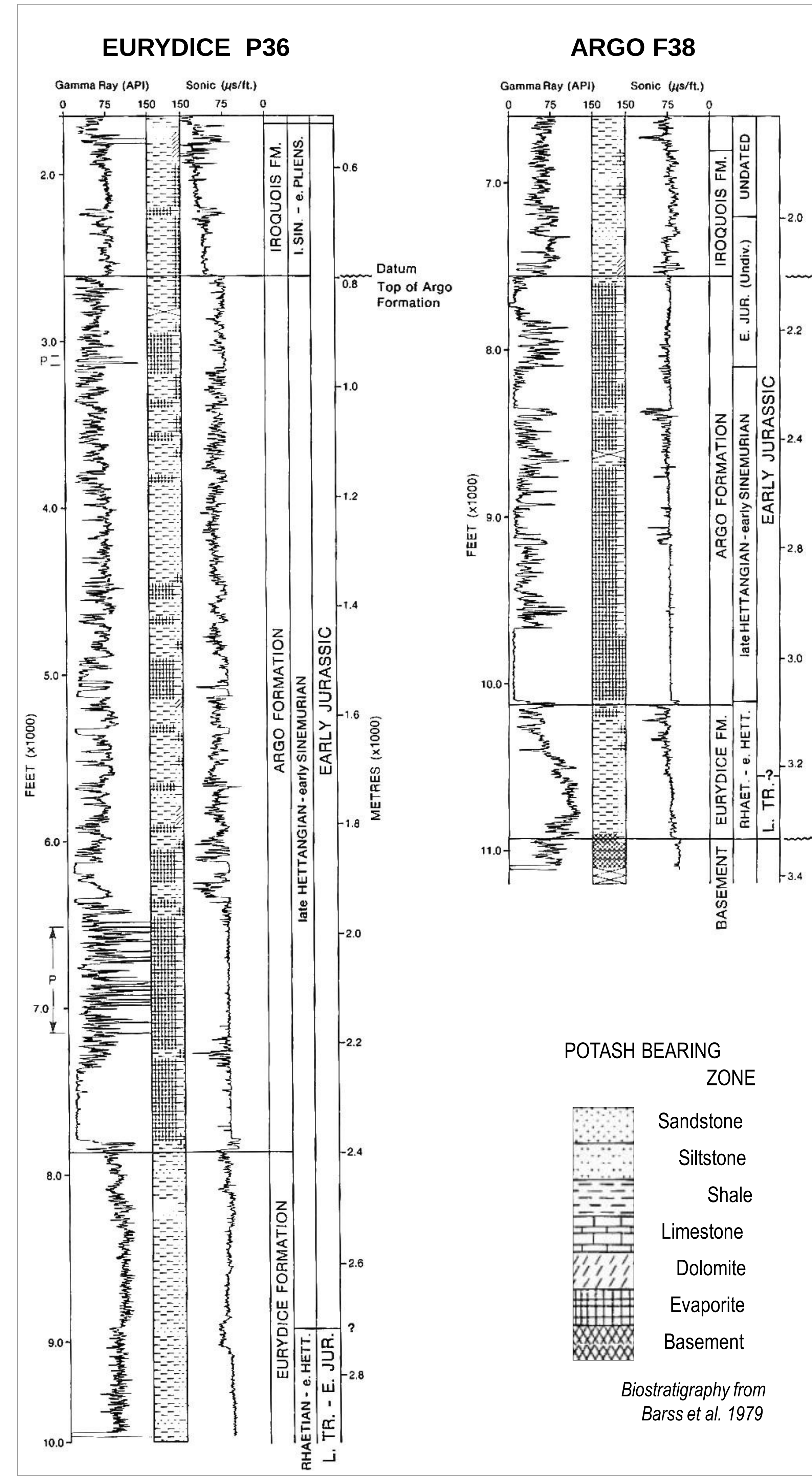


Figure 2. Example of Salt Occurrence at Argo F38 and Eurydice P36, (after Wade and MacLean, 1990).

The Breakup Unconformity - J200

The J200 **Breakup Unconformity** separates synrift and post rift sequences in the Scotian Basin and corresponds to a major geologic event when North American and African continents split apart and North Atlantic Ocean began to open. It is dated earliest Jurassic J200Ma. The unconformity can be traced across the LaHave Platform and the Canso Ridge and is readily identifiable across the shallow grabens and distally beyond the zones of salt diapirism beneath the lower slope. It is marked by a strong, regionally mappable seismic event separating fairly deformed Upper Triassic to Lower Jurassic sediments to undeformed Lower Jurassic and younger sediments. In the Mohican and Orpheus Grabens very thick sections of Eurydice and Argo formations lie beneath the Breakup Unconformity. The post breakup surface on the shelf was then a complex of elongated fault blocks. The Mohican Formation completed the filling of the rift grabens and overlapped the basement highs.

Early to Middle Jurassic - J200–J163

Offshore Nova Scotia continent, sands and shales brought to the coast by river systems began filling the young Nova Scotia Basin, with thickest accumulations at large deltas formed at the mouths of major drainage systems. Elsewhere, reefs developed parallel to the shoreline in the warm shallow seas.

Identification

- Formations/Members: Iroquois (carbonate platform, locally basal clastic sequence), Mohican (fluvial-strand plain), Scatarie (carbonate platform)
- Number of exploration wells reaching the Early to Middle Jurassic: (PL. 6-2-9b and Annex 4, Table 4-1: Formation Tops and Biostratigraphic surface): Iroquois (14 wells), Mohican (17 wells) and Scatarie (19 wells)
- Type section on the study area: Glooscap C-63.
- Regional top sequence/seismic horizon: Top Scatarie (J163)
- Lithostratigraphic Cross-Section 1 (Plate 3-5-1) and Geological Composite Well Log Glooscap C63 (Enclosure 3-12)
- Architectural Cross-Sections on Bible Lines (PL. 3-5-2/3)
- Age: - Iroquois: Toarcian-Aalenian
  - Mohican: Toarcian-Bajocian

Description

Iroquois and Mohican Formations (Toarcian-Bajocian)

Beneath the Scotian Shelf, the Iroquois and Mohican Formations overlie the breakup unconformity. The transgressive **Iroquois Formation**, which consists primarily of dolostone, deposited under slightly restricted marine conditions, is coeval with the lower part of the Mohican Formation on the LaHave Platform where it reaches a maximum thickness of about 800m. It may be represented by a series of thin dolomitic beds in the lower part of wells drilled on the western Grand Banks. A basal sequence of prograding clastics - the **Hercules Member** of the Iroquois Formation - developing in the Mohican Sub-basin ends northward over the Naskapi Ridge with the deposition of shallow marine carbonate (Figures 1 and 3).

Sandstones and shales of the **Mohican Formation** form a very thick Early to Middle Jurassic clastic sequence deposited into sub-basins adjacent to the hinge zone. The formation is widespread on the Scotian Shelf and has been encountered in a number of wells. The thickest Mohican section drilled is just over 400m on LaHave Platform and 300m at Glooscap C-63 (Figure 4) but seismic data indicate that the formation is more than 4000m thick south of the hinge zone in the Abenaki Sub-basin. The Mohican Formation thins dramatically at the hinge zone and either pinch out against it or is truncated by the post-Jurassic Avalon Unconformity.

Along the Lithostratigraphic Cross-Section 1 (PL. 3-5-1, Enclosure 3-21) and in Key Wells (Enclosures 3-5 and 3-7) from Bonnet P-23 to Cohasset L-97, these Formations are well depicted on litholog with increasing thickness of the Iroquois dolomitic facies toward Bonnet, whereas the Mohican fluvio-deltaic clastics developing at Glooscap C-63 well, pinch out both west ,and east toward the Cohasset area.

Hydrocarbon occurrence: No HC show are reported nor observed and wells are dry holes on Nova Scotia Shelf.(Chapt. 6, PL. 6-2-9b).

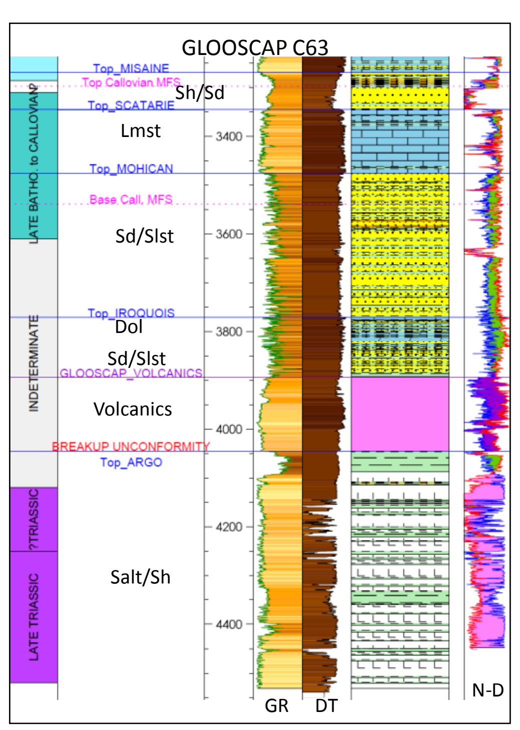
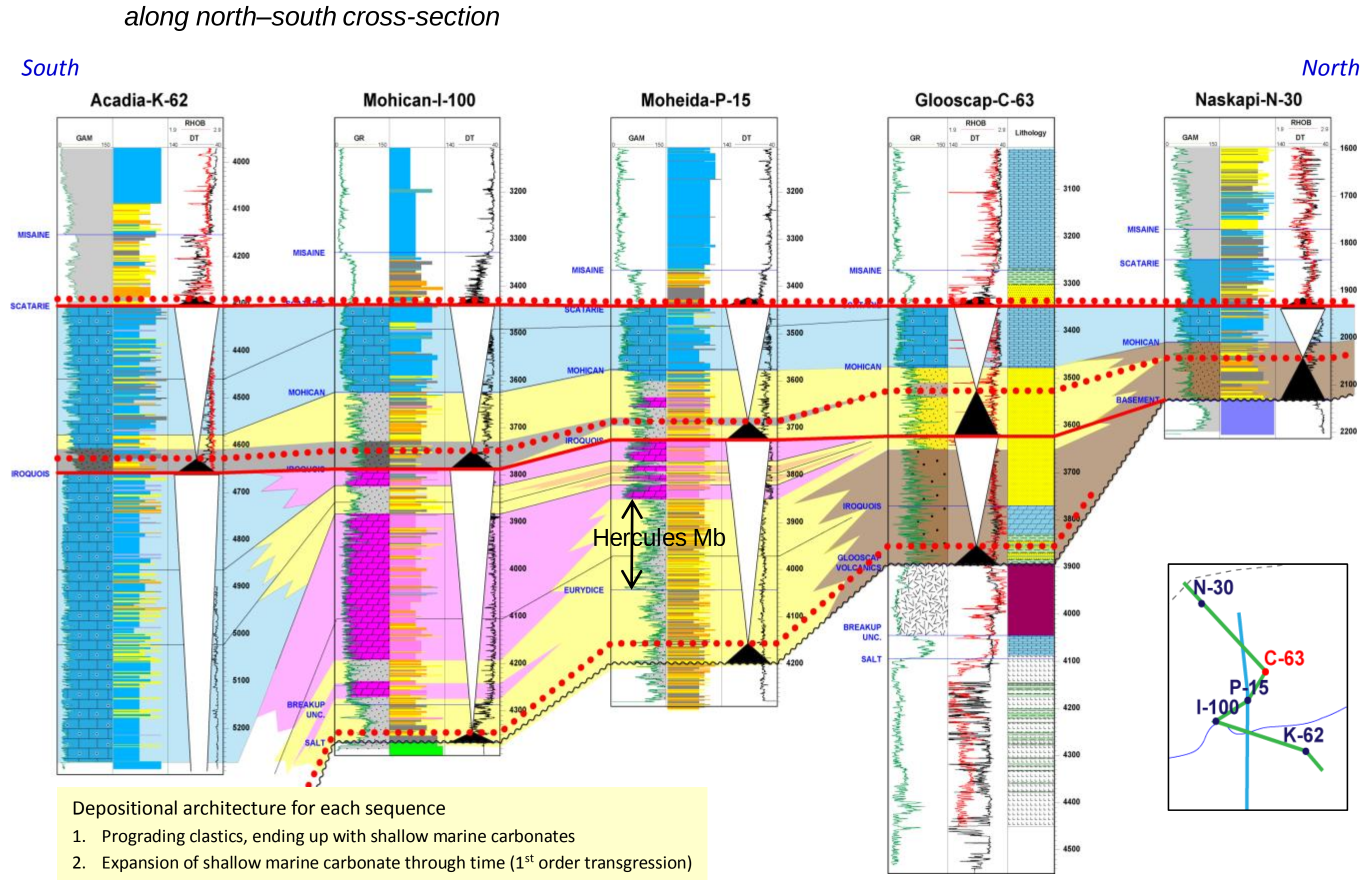


Figure 4: Litholog interpretation on the Glooscap C63 well along the Late Triassic - Early Jurassic section

Figure 3: Stratigraphy of the Early-Middle Jurassic along north–south cross-section



Mid to Late Jurassic Sequence (Callovian to Kimmeridgian–Tithonian) - J163 – J150

By the Late Jurassic there were a variety of depositional environments south of Nova Scotia. Southwestern, a delta was developing at the mouth of a river system draining the Bay of Fundy-Gulf of Maine and adjacent regions. East of this feature, a narrow (10 to 20 km wide) carbonate shoal extended almost to Sable Island before being cut off by a second deltaic complex from a distributary of the ancestral St Laurence River. Basinal shales, siltstones and fine grained sandstones were deposited seaward over the deep water areas.

Identification

- Formations: Mic Mac (fluvial deltaic), Mohawk (continental clastics), Abenaki (carbonate platform and reef margin split in four members), Verrill Canyon (prodelta and open marine, deep water shales)
- Number of exploration wells reaching the Mid to Late Jurassic Sequence: 76 wells (PL. 6-3-8b and An.4, Table 4-1: Formation Tops and Biostratigraphic Surface) Scatarie: 19 wells, Misaine-Callovian MFS: 25 wells, Mic Mac/Abenaki:76 wells
- Type sections: Cohasset L-97 (Baccaro Mb); West Esperanto B-78 (Mic Mac Fm)
- Type sections in the study area: Baccaro Mb: Bonnet P-23, Glooscap C-63, Cohasset L-97, Dauntless D-35; Mic Mac Fm: West Esperanto B-78
- Regional top sequence/seismic horizon: Top Baccaro close to Tithonian MFS (J150)
- Chronostratigraphic Cross-Sections (PL. 3-4a,b)
- Lithostratigraphic Cross-Sections 1 and 2, (PL. 3-5-1a,b) and Geological Composite Well Logs for Bonnet P-23, Glooscap C-63, Cohasset L-97, West Esperanto B-78, and Dauntless D-35 (Enclosure 3).
- Architectural Cross-Sections on Bible Lines (PL. 3-5-2/3)

Description

Mic Mac Formation

The Mohican Formation is overlain by a second very thick, predominantly siliciclastic, post-rift sequence, the **Mic Mac Formation**. In Scotian Basin, the Mic Mac Formation and its lateral equivalents the Abenaki, Mohawk, and Verrill Canyon formations span the late-Middle and Late Jurassic. Mic Mac Formation belongs to the clastic fluvio–marine deltaic prograding system developed over Sable and Huron Sub-basins (West Esperanto B-78).
The Mic Mac Formation ranges in thickness from 5500m in the Huron and Laurentian Sub-basins to an erosional (Berriasian/Valanginian Unc.) or depositional edge along the LaHave Platform till Canso Ridge and Avalon Uplift. Over Sable Sub-basin, East and Southeast of Sable Island (Bluenose, Venture, South Venture, SW Banquereau areas) it consists of 4000 to 5000m of interbedded sandstones, shales and limestones. To the north and west of Sable Island, along the hinge zone, there is a prominent carbonate bank facies, the **Abenaki Formation** (Figure 5). The more continental facies, landward of the bank is designated **Mohawk Formation** (Mohawk B-93 well); it is comprised of texturally mature felspathic sandstone and siltstone with interbedded shale and limestone. Distally, all these units, the carbonate and clastic facies grade into fine grained basinal facies, the **Verrill Canyon Formation**.
On the eastern part of the Abenaki Sub-basin, the Mic Mac Formation consists of shales with thin to thick interbeds of sandstone and siltstone. (Mic Mac H-86, J-77). Further south, where only the upper part of the formation has been drilled, there is thick intervals of limestone, which cap the prograding sequences of the Mic Mac clastics (Sauk A-57). Further seaward, over the outer shelf and distal areas, no well reaches the Jurassic but the seismic expression of sandstones and limestones of the Mic Mac Formation are replaced by the seismic facies of marine shales of the Jurassic Verrill Canyon Formation (SW Banquereau, Tantallon, etc..)

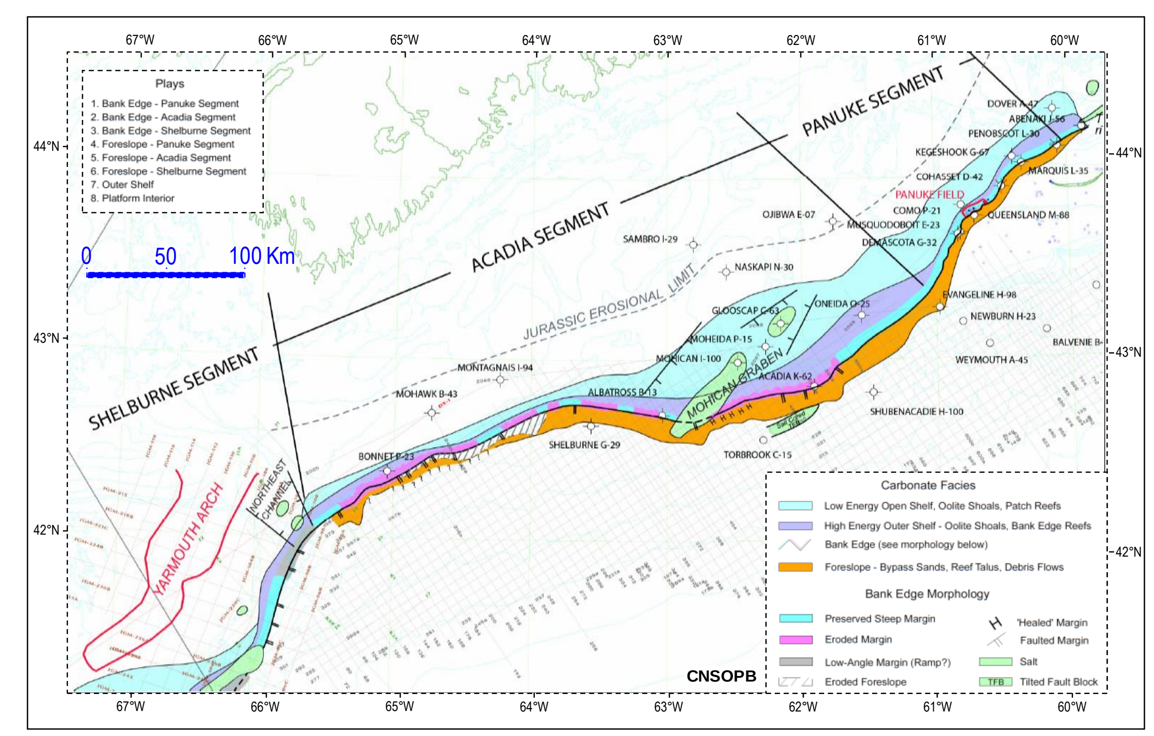
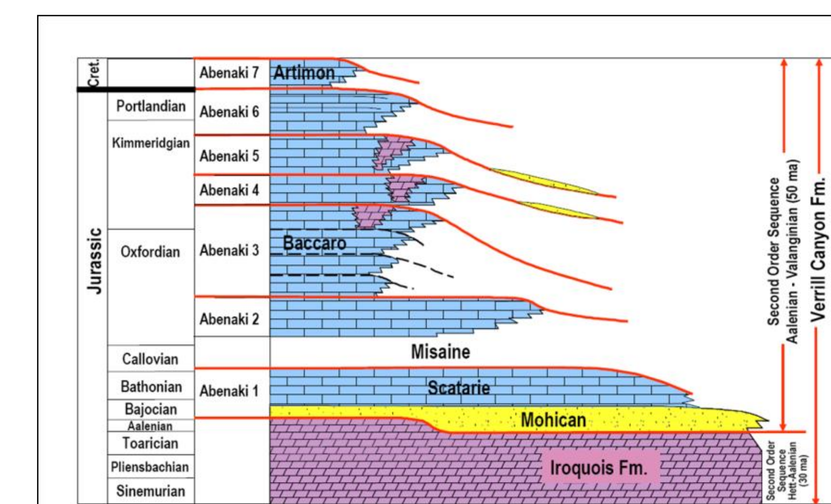


Figure.5: Abenaki Formation Morphology, carbonate facies complex after A. Kidston et al, (2005).



Detailed sequence stratigraphic chart for the Abenaki Formation (Encana)

Figure 6: Detailed sequence stratigraphic chart for the Abenaki Formation (Encana)

Abenaki Formation

The Abenaki Formation and particularly the Baccaro Member is the scope of an exhaustive study in the present PFA Project with the ***Carbonate Project (Chapter 9).***
The Abenaki Formation, a predominantly limestone unit; extends from the Middle Jurassic (Mid Bajocian) to the lowermost Early Cretaceous (basal Valanginian) a period of virtually continuous deposition of approximately 30 Ma. The Abenaki Formation is divided into four members, namely the **Scatarie, Misaine, Baccaro** and **Artimon Members** (Figure 6). It forms a distinctive thick outer shelf carbonate bank complex and a prominent seismic sequence. It is best developed at the hinge zone between LaHave Platform, Shelburne and Sable Sub-basins. At Bonnet P-23, it reaches 1600m close to the maximum drilled thickness of this formation (PL. 3-5-1, Encl. 3-5).

The Scatarie Member (Abenaki 1) is predominantly an oolithic limestone. It is the most extensive member of the Abenaki Formation from Erie D-26 and Wyandot E-53 to the north-east to Bonnet P-23 in the south-west and recognized in 19 exploratory wells over the studied area of the Scotian margin (PL. 6-2-9b). It represents a seaward thickening wedge with at least four deepening-upward transgressive sequences from the northern depositional edge to a southward maximum thickness reaching 600m in Acadia K-62 type section (Figure 3). Lithological variations occur in the proximal and distal areas. Top Scatarie is a strong seismic horizon in both the shelf and basinal areas due to its position below the Misaine shales and above the Mohican clastics. Thanks to its good regional picking, this seismic horizon was selected as a key seismic marker in the present study (J163). According to the revised biostratigraphy (Chapter 3-3), the Scatarie Member is intra Callovian in age and includes the Base Callovian MFS (Bonnet P-23, Cohasset L-97, West Esperanto B-78) but lies within the top of the Mohican Formation at Glooscap C-63 (PL. 3-5-1a Cross-Section1).

The Misaine Member (Abenaki 2) is a transgressive facies that overlies the Scatarie Mb. limestone. It is the only clastic interval composed of dark grey calcareous shales with minor laminated limestone (up to 250m thick) pinching out landward over the platform with interbedded proximal sandstone. It is representative of the Callovian regional transgressive flooding event well developed along the Jurassic shelf margin (A. Kidston, 2005) and well observed along profile (PL. 3-5-1a) in Bonnet P-23, Glooscap C-63, Cohasset L-97. A total thickness map of the Misaine Member based on the well correlations is presented on PL. 6-2-9a.

The Baccaro Member (Abenaki 2,3,4,5,6, Figures 6 and 8) is the thickest and best developed carbonate unit in the Abenaki Formation (see Regional Cross-Sections on Plates 3-5-1 and the Geological Composite Well Log on Enclosures 3). It is composed of numerous stacked, shoaling upwards, aggrading and prograding parasequences where the dominant lithology is limestones with minor shales and sands intervals. Dolomite facies of secondary origin is present in the Abenaki 2 to 5 sequences. Its areal extend is narrow and variable, a 15-20km wide belt that follows the Jurassic hinge line and defines the seaward limit of the Abenaki platform margin (Figure 5). The age of Baccaro Member extends from early Oxfordian to Tithonian.

The Artimon Member (Abenaki 7) is the youngest and the thinnest sequence (30-115m) of the Abenaki Formation that extend into the Cretaceous Berriasian (Wierzbicki et al, 2002). It is composed of argillaceous limestones with sponge mounds suggesting a reef depositional environment and interbedded occasionally with calcareous shales. Of limited areal extent, it is recognized in the eastern part of the Abenaki Platform edge and in the Cohasset-Panuke area. It is coeval or overlapped by the fluvial-deltaic clastics of the Missisauga Formation.

WEST ESPERANTO B78

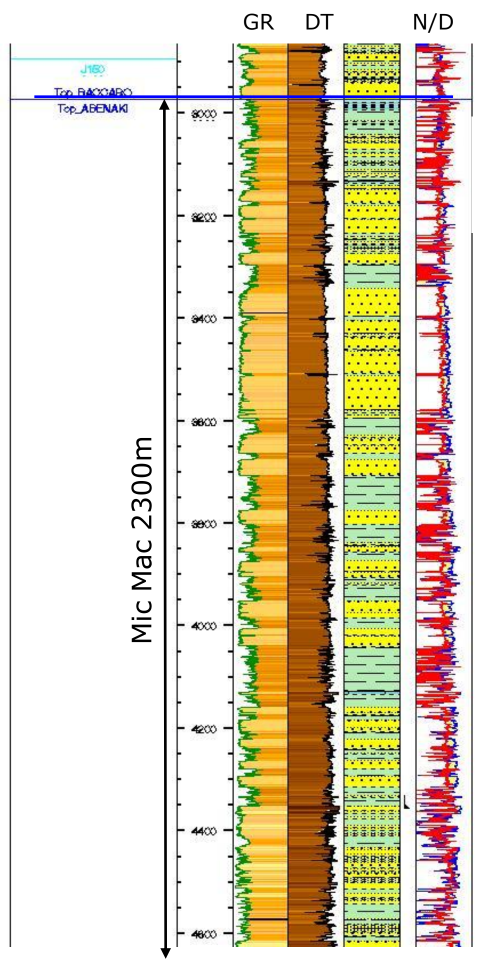
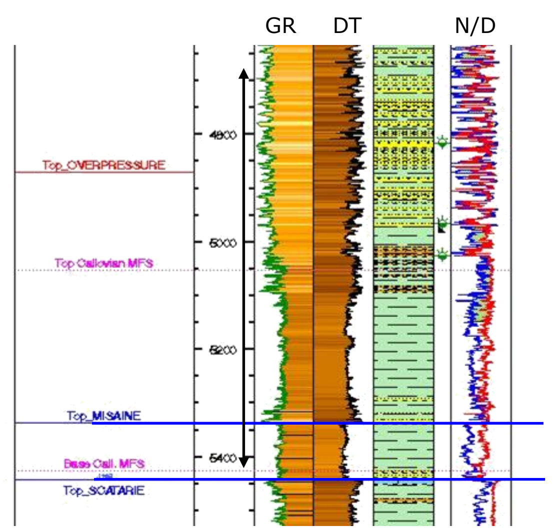


Figure 7: Litholog interpretation of West Esperanto key well along the Mic Mac section



COHASSET L97

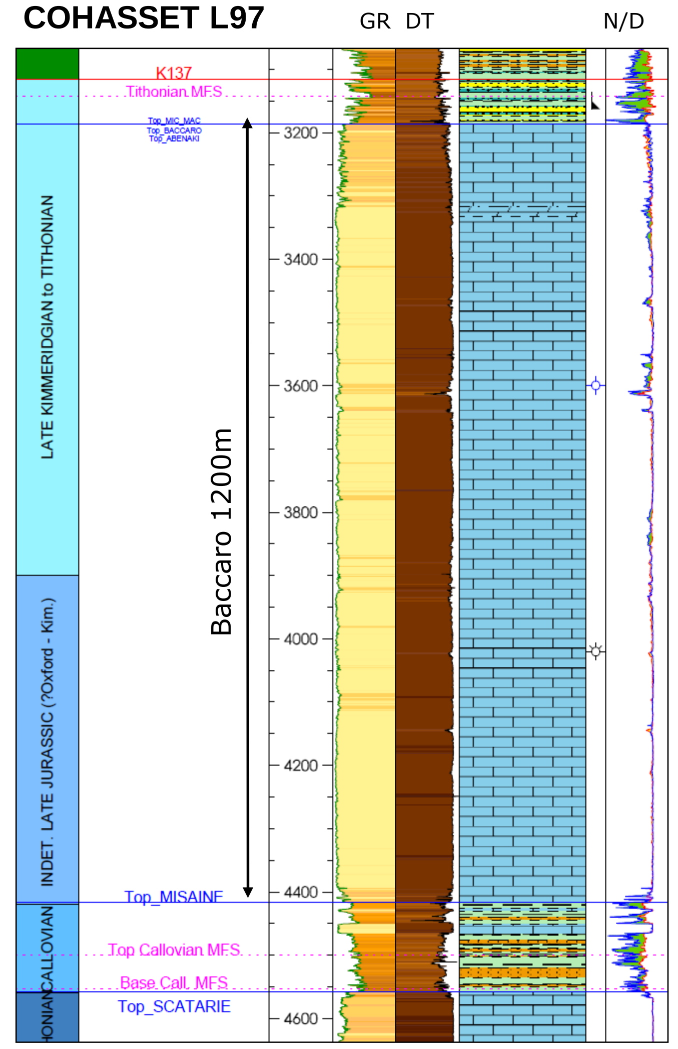


Figure 8: Litholog interpretation of Cohasset L97 key well along the Abenaki section

Along the Lithostratigraphic Cross sections 1 (Plate 3-5-1a) and Key wells:

The huge carbonate sequence from Callovian to Kimmeridgian is observed regionally from Bonnet P-23 to Cohasset L-97 and further east to in South Griffin, Hesper, Dauntless. Over West Esperanto and surrounding areas, prominent clastic deposits of the Upper Jurassic delta prevail precluding the development of the carbonate bank.

The Chronostratigraphic Cross-Sections (Plates 3-4-1 to 3-4-3) over the Scotian Basin show the distribution in time of each main sequence and associated deposit types, evidencing the isochronous and diachronous tectono-sedimentary events.

Hydrocarbon occurrence: (see Chapter 6, PL. 6-3-8b) HC accumulations (oil and gas) are known in the Mic Mac sands and in the Abenaki limestone-dolostone of the carbonate bank in the Cohasset-Panucke areas and developed as gas field.

Verrill Canyon Formation (Middle – Late Jurassic up to Early Cretaceous)

Identification

- Type wells: - Upper Jurassic Verrill Canyon: Alma F-67, Shelburne G-29
  - Early Cretaceous Verrill Canyon/Missisauga equ: Annapolis G-24 Chebucto K-90, Newburn H-23, Tantallon M-41
- Type sections: Alma F-67 (Late Jurassic Mic Mac eq); Annapolis G-24 (Missisauga eq.)
- Chronostratigraphic Cross-Sections (PL 3-3)
- Lithostratigraphic Cross-Sections 1 and 2 (PL. 3-5-1) and Geological Composite Well Logs (Enclosures 3)
- Architectural Cross-Sections on Bible Lines (PL. 3-4-2/3)

Description

The Verrill Canyon Formation is the deep water facies equivalent to the Mohawk, Abenaki, Mic Mac, and Missisauga formations. It consists primarily of grey to brown calcareous shale with thin beds of limestone, siltstone, and sandstone. The Verrill Canyon Formation was deposited in the prodelta, outer shelf, and continental slope settings. Very few wells have reached the Late Jurassic Verrill Canyon and based on seismic isopach map it ranges in thickness from 350m in the southwestern Scotia margin (Shelburne G-29 about 200m to TD) to more than 900m in the northeast (Tantallon M-41).

Along the Lithostratigraphic Cross-Section 2 (PL. 3-5-1b) and Key wells:

The basinward shales of the Verrill Canyon (shales, mudstone), Late Jurassic in age, was encountered only in few deep wells and only described in Alma F-67, where 150m down lo TD have been penetrated. Upward, this shaly deposit continues along the Early Cretaceous as a distal equivalent of Missisauga sands.

Avalon Uplift

During the latest Jurassic the eastern margin of Canada was affected by the breakup of Iberia from North America. Most strongly impacted was the margin south of Newfoundland where there was significant uplift, deformation and extensive erosion of Jurassic and older strata. This break up unconformity, the **Avalon Unconformity**, is observed from the Avalon Uplift westward into the eastern Scotian Basin. During this event there was a corresponding shift in the depocentres westward from the Laurentian to the Sable Sub-basins.

The Early Cretaceous Sequence (Berriasian/Valanginian - Barremian) J147-K125

Deposition of the Early Cretaceous sands is roughly coeval with the breakup of Newfoundland from Europe, which uplifted offshore Newfoundland and proximal parts of Laurentian Sub-basin, generating the Grand Banks Avalon uplift (Avalon Unconformity, Jansa and Wade, 1975, MacLean and Wade, 1992). From seismic data, the angular unconformity smoothen toward the southwest and is not visible in the lowermost Cretaceous strata in the Sable Subbasin (Wade and MacLean, 1990, PFA, 2011).

Identification

- Number of exploration wells reaching Early Cretaceous Sequence Missisauga Formation: 126 wells (PL. 6-4-11 and Annex 4, Table 4-1: Formation Tops and Biostratigraphic Surface)
- Formation/Members: It is classically divided into Lower, Middle and Upper Missisauga Members and its deep basinward shaly facies is equivalent to the Verrill Canyon Formation.
- Age: - Lower Missisauga: Berriasian (K147/K137)
  - Middle Missisauga: Valanginian-Hauterivian MFS (K137-K130)
  - Upper Missisauga: Intra Hauterivian MFS) - Barremian (K130-K125)
- Type sections: Missisauga H-54, Venture H-22, (Figure 12; Wade and MacLean, 1990)
- Type sections in the study area: - Whole section: Alma F-67, Cohasset L-97, South Griffin J-13;
  - Mid and Upper Missisauga : Chebucto K-90, Glooscap C-63; Hesper P-52, West Esperanto B-78, Dauntless D-35
  - Early Cretaceous Verrill Canyon: Annapolis G-24
- Regional top sequence seismic horizon: Intra Hauterivian MFS (K130).
- Chronostratigraphic Cross-Sections (PL. 3-3).
- Lithostratigraphic Cross-Sections 1 and 2 (PL. 3-5-1a and 3-5-1b) and Geological Composite Well Logs C-63, L-97, P-52, F-67, B-78, G-24 (Enclosures 3).
- Architectural Cross-Sections on Bible Lines (PL. 3-5-2/3).

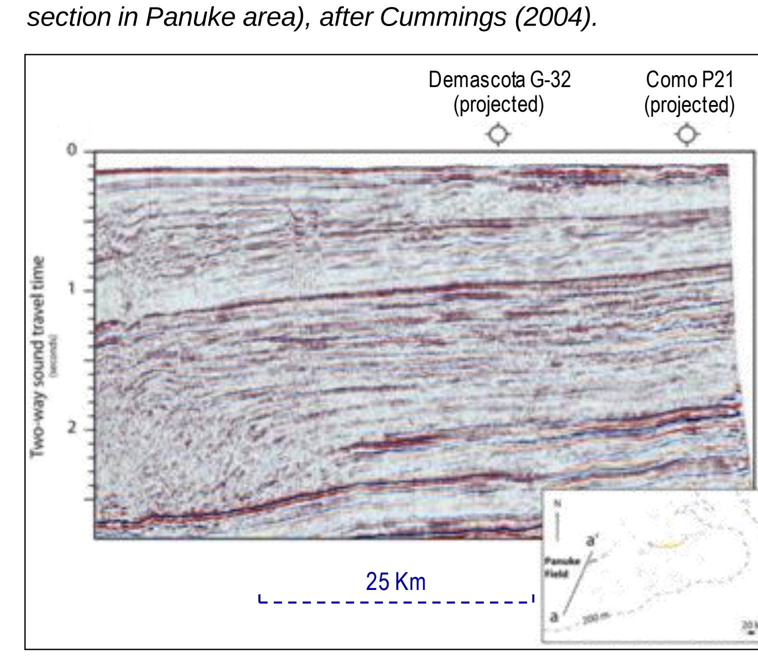
Description

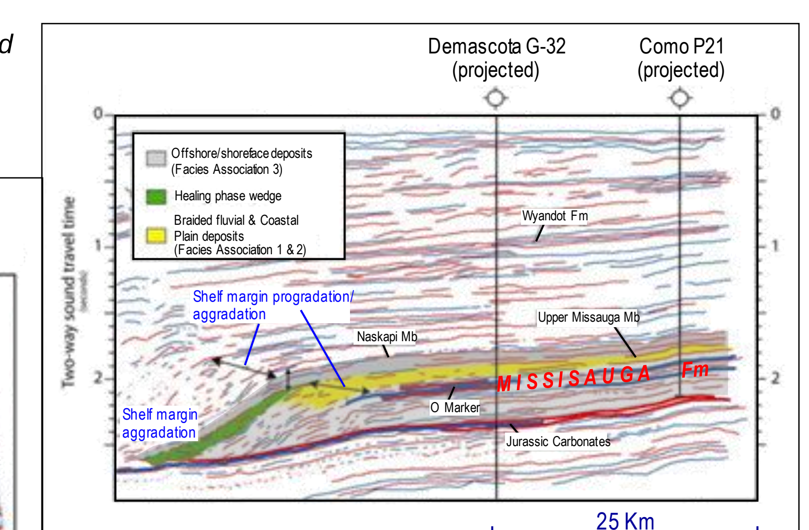
Missisauga Formation

The Missisauga Formation is widespread on the Scotia margin, where it varies considerably in both facies and thickness (PL: 3-5-1: Regional Lithostratigraphic Cross-Sections) correlated to reactivation of crystalline basement uplift providing coarse-grained fluvio-detaic sediments (Pe-Piper & MacKay, 2006). The resulting Early Cretaceous Missisauga Formation comprise fluvial, deltaic and shelf sediments, mainly deltaic sands up to the shelf edge over Sable Sub-basin (Sable Delta), Shelburne Sub-basin to the West and Huron, Tantallon Sub-basins to the East. Basinwards, deepwater sands distribution were governed by canyons incisions, basin floor turbidite systems (Steel et al, 2003) and salt tectonics (Balvenie, Annapolis, Crimson wells). The "O" Marker a well observed seismic marker on the shelf separates the Lower – Mid Missisauga prograding cycles from the Upper Missisauga one and represents a transgressive period (Hauterivian) marked by carbonate deposits (MFS dated K130). Toward the southeast, the "O" Marker dips and becomes increasingly hard to identify. Along the western rim of the Sable Sub-basin (SW Panuke carbonate hinge line) the Missisauga progradations downlap and pinch out onto the underlying Abenaki Formation (Figure 9), (Cummings, 2004). The Missisauga Formation is divided in three members (Wade and MacLean, 1990): the Lower, Middle and Upper Members. The areal extent of the Upper Member is limited to the north by an erosional edge on the LaHave Platform and it shales out basinward.
Across the LaHave Platform and Canso Ridge it is less than 1000m thick and consists of 60-80% sandstone with some significant local limestone facies in the southwest (Bonnet P-23, Albatross B-13). In the Sable Sub-basin, more than 2700m have been drilled (Venture) and its total thickness is estimated up to 3500m with 30-50% sandstone/siltstone content. Basinward, the Missisauga Formation grades into turbidites and shales in the Cretaceous portion of the Verrill Canyon Formation (Figures 10, PL. 3-5-1 and deepwater wells on PL. 3-5-2/3: Architectural Cross-Sections).

Small outcrops of the equivalent fluvial rocks on land are known as the Chasewood Formation (Stea &Pullan, 2001).

Figure 9: Progradational nature of the Missisauga Fm Upward and Basinward downlapping on the Abenaki carbonate bank (uninterpreted and interpreted dip oriented seismic cross section in Panuke area), after Cummings (2004).





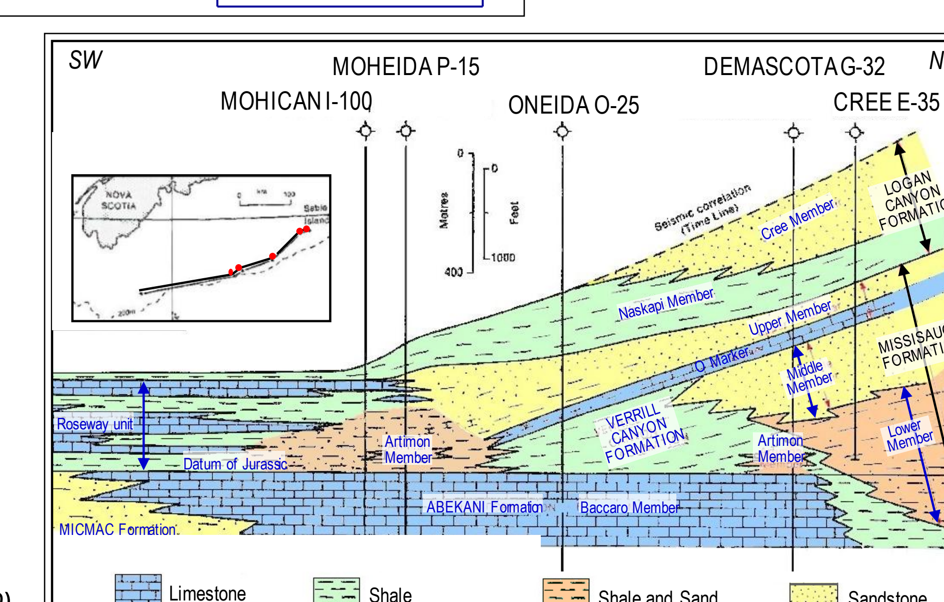


Figure 10: Relationships within the Missisauga Formation on the LaHave Platform, after Wade and MacLean (1990)

The Lower Missisauga:

The type section consists of fine grained coarsening upward sandstone and minor thin limestones within a section of grey marine shales (Venture H-22, Figure 12) limited at its base by a limestone unit of the Kimmeridgian or at the top Abenaki carbonates. The base of the Missisauga, dated Berriasian (K147-K137), is difficult to pick correctly in wells when Missisauga sands overly lithologically similar deposits of the Mic Mac Formation. This Member of limited extent constitutes the lower unit of the Sable Island delta that developing in areas, where rapid subsidence and high rate of clastic deposits prevail. Sandstone deposits thicken rapidly along growth faults trending SW-NE from Cree, Thebaud, Venture and Citnalta areas eastward to Bluenose. Thickness increases from zero edge west of Sable Island, where it overlies the Abenaki carbonate bank, to 300m at Citnalta, then 1000m in the Venture field and at least 2000m at the shelf edge (Wade and MacLean, 1990). The Berriasian Lower Missisauga is incomplete (Cohasset L-97) or absent as a consequence of the Berriasian-Valanginian unconformity.

South of a line Alma – Chebucto - South Griffin, the deltaic sandstones of the Lower Missisauga Formation turn progressively to the dominantly shale facies of the Verrill Canyon Formation (see cross sections Plates 3-5-1a and 3-5-1b).

The Middle Missisauga:

The Middle Missisauga is a thick section of sandstone dated Valanginian-Mid Hauterivian (K137-K130) comprised between the last shaly continuous sequence of the underlying unit when deposited or preserved or over the last Jurassic rocks and at the top of the carbonates beds of the Hauterivian flooding event ("O" Marker; Figure 12). This prograding sequence extends over a large area of the Scotian Basin.

The Upper Missisauga

A series of mixed mudstone-sandstone-oolithic limestone beds of Hauterivian age – "O" Marker - constitutes the base of the Upper Missisauga Member. The "O" Marker represents a transgressive episode (intra Hauterivian MFS) in a regional regressive period. It covers a broad and flat delta plain over much of the Scotian Shelf. Basinward, the marker disappears as the facies grades laterally into deep water shales (Plate 3-5-1b, Cross-Section 2) making difficult the correlation between inner and outer shelf. The "O" Marker was selected on seismic picking as the key horizon K137 to follow the intra-Hauterivian MFS that in turn represents the top of the lower Early Cretaceous cycle. Above, a Late Hauterivian-Barremian prograding deltaic system made of thick and massive sandstone interbedded with shale is developing all over the Scotian shelf. Its northward limit is erosional meanwhile it shales out in the deep marine environment. The top of this upper sequence could be incomplete due to the Barremian unconformity (128-125 Ma) that prevails on the shelf.

The "O" Marker is eroded on the platform, not deposited on the eastern margin; shaling out to the south and southeast and downlaping to the southwest.

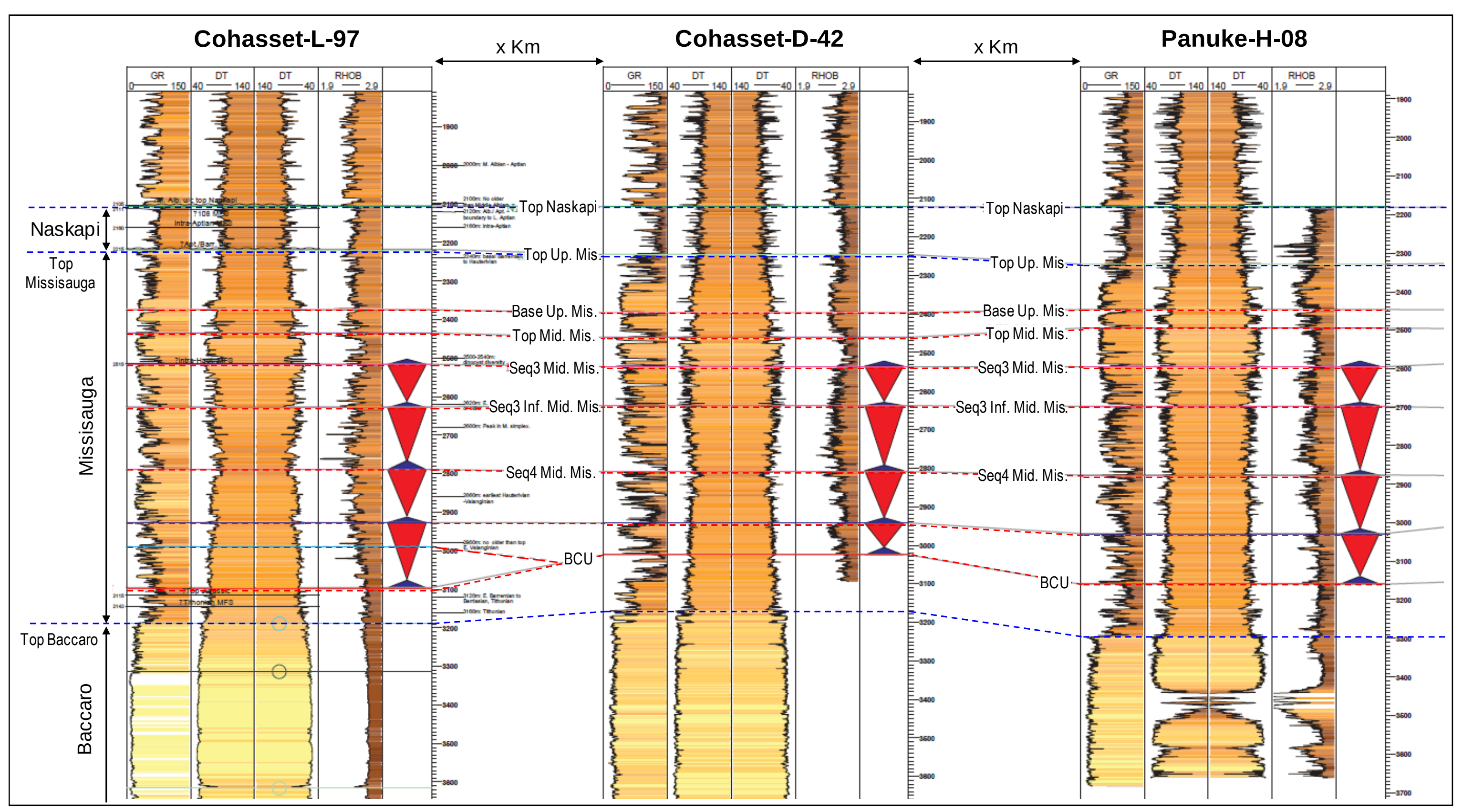


Figure 11: Missisauga stacking parasequences in Cohasset-Panuke area

Along the Lithostratigraphic Cross sections 1 and 2 (Plates 3-5-1a and 3-5-1b) and Key wells:

These two regional transects document the Missisauga Formation over the Scotian Shelf from west (Glooscap C63) to east (Dauntless D35) and partly over the outer shelf (Annapolis G24, Crimson F81). Major features are observed and described above as the great thickness variation, the main unconformities (Berriasian, Barremian), the lithological aspects also detailed on the lithocolumn.

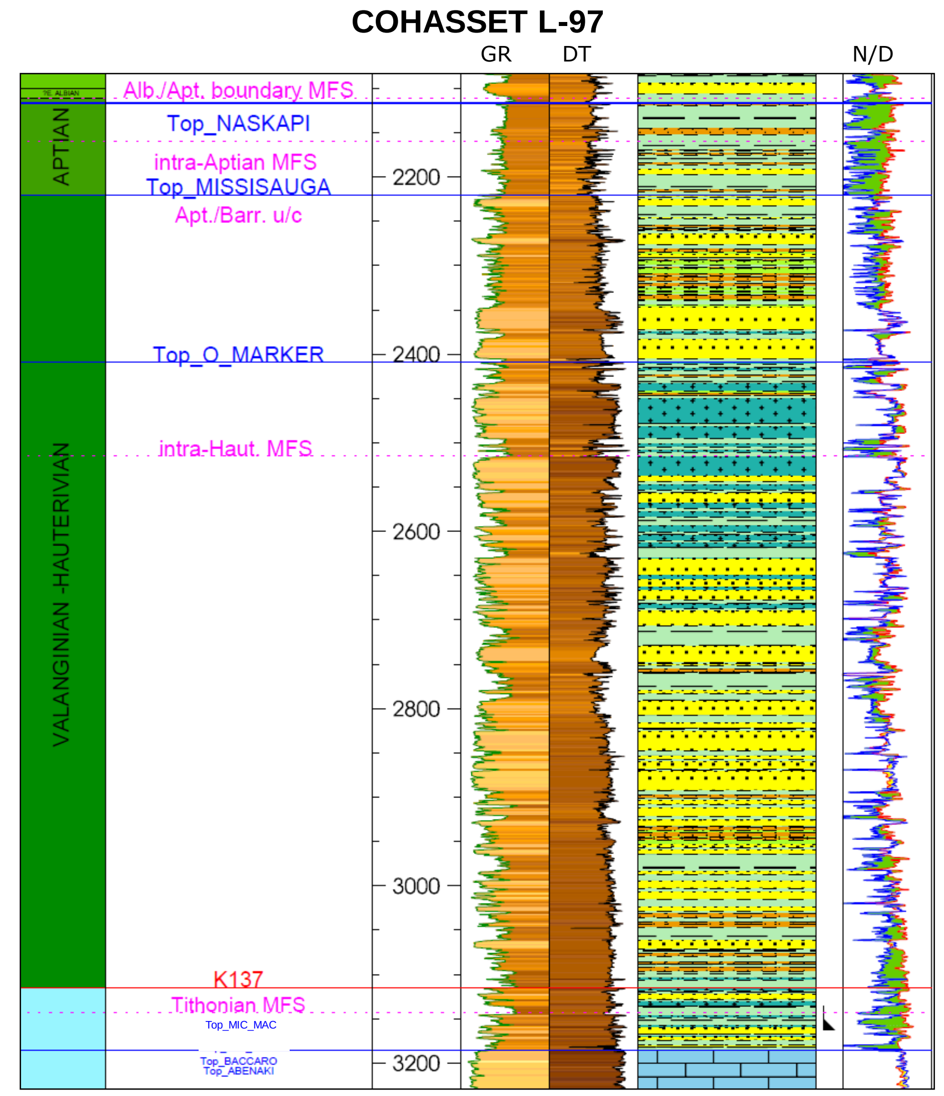


Figure 13: Missisauga in Cohasset L97

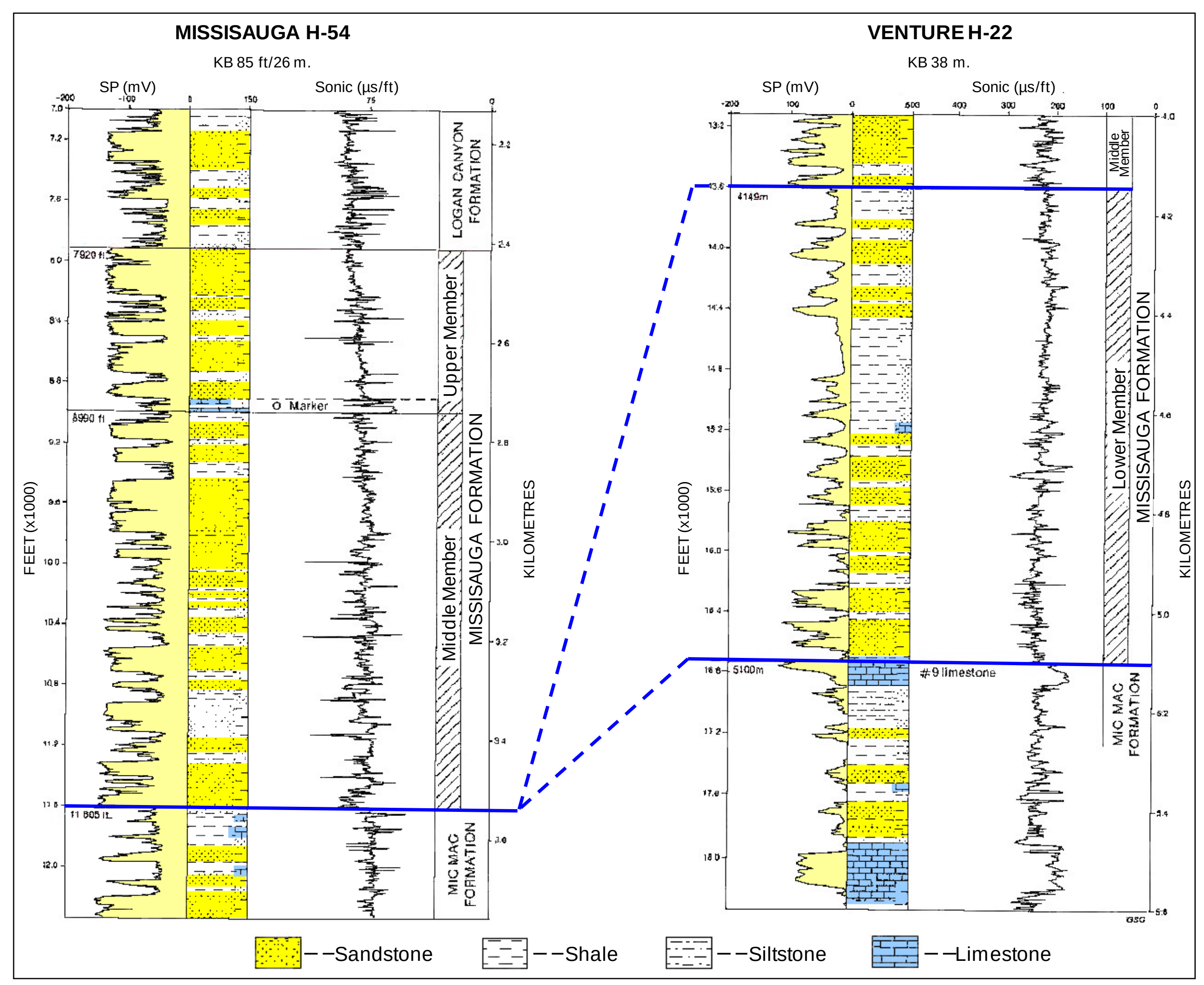


Figure 12: Type section of the Missisauga Formation and its members, (after Wade and MacLean, 1990)

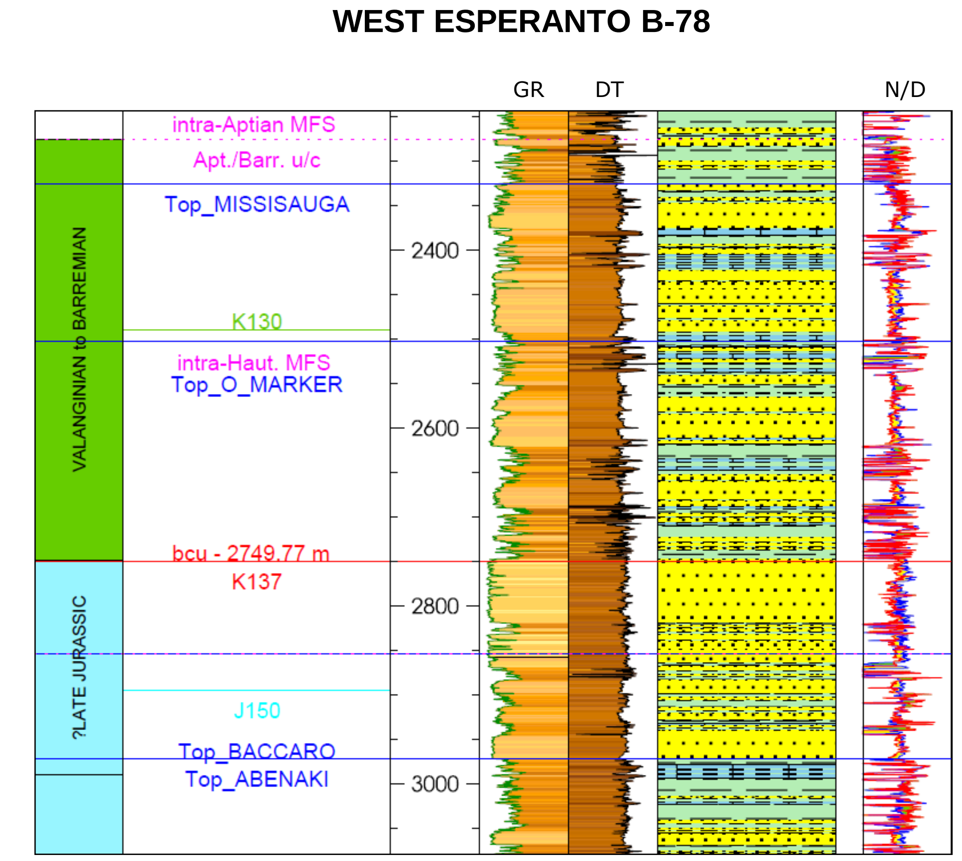


Figure 14: Missisauga in West Esperanto B78

The Chronostratigraphic Cross-Sections over the Scotian Basin show the distribution in time of each main sequence and associated deposit types, evidencing the isochronous and diachronous tectono-sedimentary events (PL. 3-4-1 to 3-4-3)

Hydrocarbon occurrence (see Chapter 6, PL. 6-4-11) : So far, the Missisauga delta of the Sable Sub-basin is the most prolific hydrocarbon province explored in the Scotian Basin. The areal distribution of the HC accumulations between Lower, Middle and Upper Members reflects the southward prograding system.

The Aptian - Cenomanian Sequence - K125-K94

Identification

- Number of exploration wells reaching the Aptian - Cenomanian Sequence Logan Canyon Formation: 132 wells (PL. 6-5-11 and Annex 4, Table 4.1: Formation Tops and Biostratigraphic Surface)
- Formations: Logan Canyon Fm distributed in four subsequences and outershelf equivalent Shortland Shale
- Type sections: Cree E-35, Dauntless D-35 (Figures 15,16)
- Type wells on the study area: Alma F-67, Glenelg J-48, Dauntless D-35, Balvenie B-79 (Shortland Shale), Figures: 16, 17, 18
- Regional top sequence seismic horizons: Top Cenomanian Unconformity (K94), Late Albian Unc. (K101)
- Chronostratigraphic Cross-Sections (PL. 3-4)
- Lithostratigraphic Cross-Sections 2 (PL. 3-5-1) and Geological Composite Well Logs F-67, J-48, D-35, B-79 (Enclosures 3)
- Architectural Cross-Sections on Bible Lines (PL. 3-5-2 & 3-5-3)

Description

Logan Canyon Formation and Shortland Shale

The Logan Canyon Formation is an upward fining trend similar to the Missisauga but with a maximum thickness of about 2500m. 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**) (Wade,1991b; 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 sea level (Grant et al., 1986). Sandstones of the Logan Canyon Formation grade distally to the deep water shale facies of the **Shortland Shale**, a distal turbidites/shale equivalent deposited in prodelta, outer shelf, and continental slope settings.

Facies distribution and sequence stratigraphic breakdown of the Aptian - Cenomanian sequence were interpreted along the Regional Lithostratigraphic Cross Sections and detailed on the Geological Composite Well Logs. The Chronostratigraphic Cross-Sections over the Scotian Basin show the distribution in time of each main sequence and associated deposit types, highlighting the isochronous and diachronous tectono-sedimentary events.

Naskapi Member

Contact between the Barremian Missisauga sandstone and the above Aptian monotonous succession of offshore mudstone is generally abrupt and fairly easy to pick on log profile (GR) in basinward areas. Over more proximal areas (Sable Sub-basin) some gradational transition makes the contact more variable. The Naskapi Member up to 350m thick although sand bodies were observed in it, is considered a regional seal for the main Missisauga reservoir. The Intra Aptian MFS, which coincide with the Naskapi Member, is well depicted all over the basin.

Cree Member

Overlying the Naskapi shale, the sandy Cree Member consists of interbedded sandstones and dark grey shales with minor siltstone (Figures 15 and 16: Cree E-35 well; Dauntless D-35). Coarse to medium at the base the sandstone fine upward. The Cree Member is dated late Aptian to late Albian. Its upper limit generally coincide with the Late Albian unconformity (K101), a fair to good regional seismic horizon that was selected to map the top of the Early Cretaceous.

Sable Member

Predominantly shaly resulting from a more rapid transgression (Dauntless D-35), the Sable Member contains number of thin sandstone and siltstone beds. When the Sable member is dominated by sandstones in Alma, Cohasset, Chebucto, it becomes difficult to separate it from the fining upward sequence of the Cree Member.

Marmora Member

Lying above the Sable Shale, the Marmora Member represents the upper sandstone sequence of the Logan Canyon which continues the general trend of upward thinning and fining sand beds. It is dated Late Albian to Late Cenomanian. and the upper limit generally coincide with the Late Cenomanian unconformity (K94), a fair to good regional seismic horizon selected to map the Late Cretaceous.

Shortland Shale

This shaly and monotonous facies represents the basinward lateral equivalent of the Logan Canyon sandstone. The type section is well developed in Balvenie B-79 (Figure 18) and Weymouth A-45.

Hydrocarbon occurrence (see Chapter 6, PL. 6-5-11): The Logan Canyon sandstones are the second most important hydrocarbon reservoirs in the Scotian Basin, mainly developed in the Cree Member.

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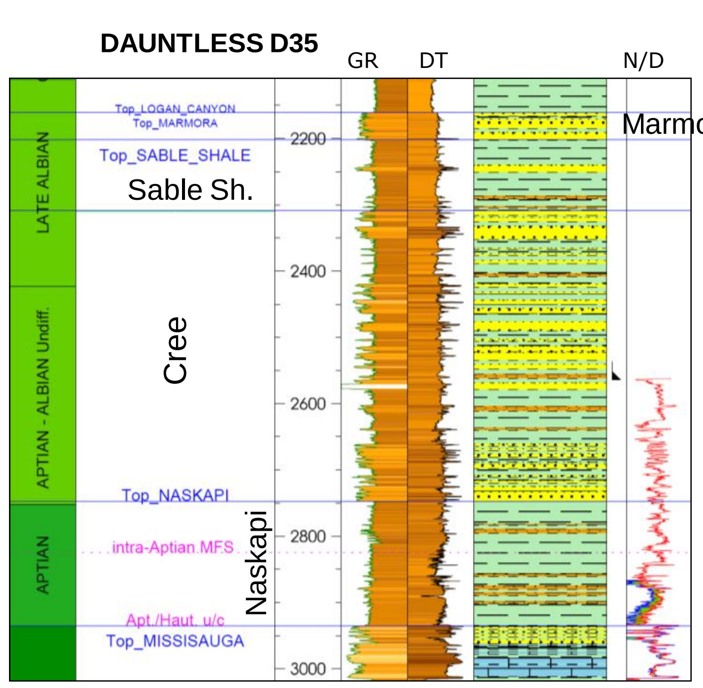

Figure 16.: Type section of Logan Canyon Formation, Dauntless D-35 (Key well PFA, 2011)

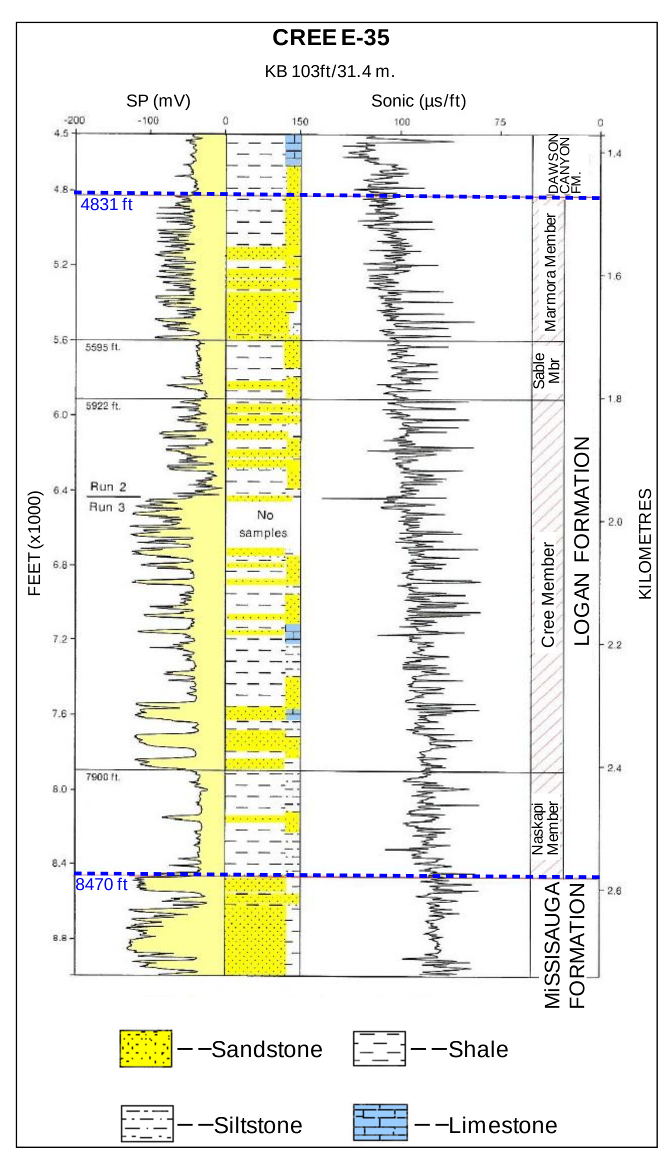

Figure 15. Type section of Logan Canyon Formation, Cree E-35 (modified from Wade and MacLean, 1990)

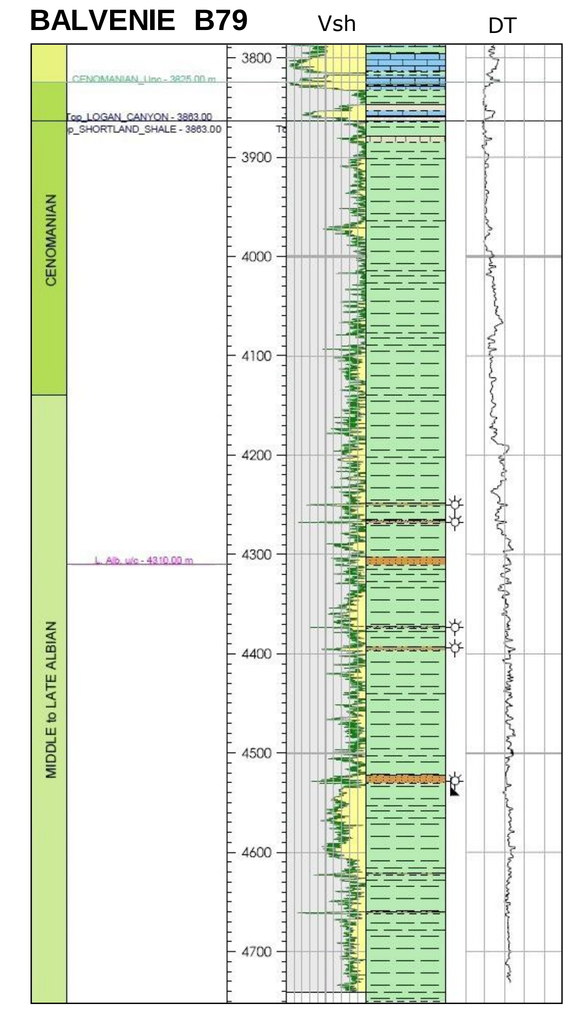

Figure 18: Type section of Logan Canyon Formation, Balvenie B-79 (Key well PFA, 2011)

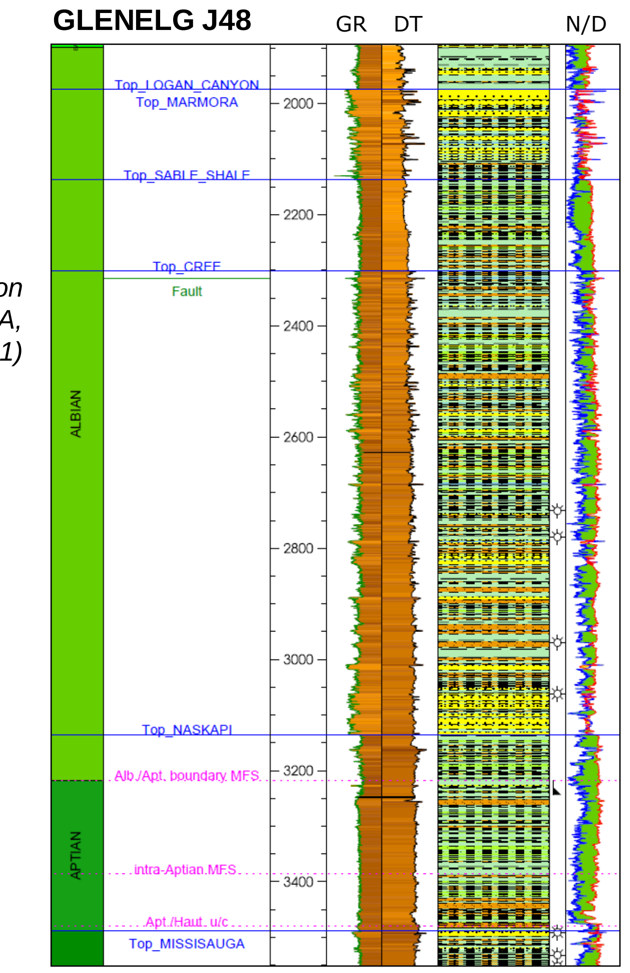

Figure17: Type section of Logan Canyon Formation, Glenelg J-48 (Key well PFA, 2011)

The Late Cretaceous to Eocene Sequence – K94-T50

Identification

- Number of exploration wells reaching the Late Cretaceous to Eocene Sequence:148 wells (PL. 6-5-5 and Annex 4, Table 4-1: Formation Tops and Biostratigraphic Surface)
- Formations: Dawson Canyon, Wyandot, Ypresian Chalk
- Age: Dawson Canyon (Turonian), Wyandot (Santonian-Maastrichtian), Ypresian Chalk (Base Eocene)
- Type wells on the study area: West Esperanto B-78, Chebucto K-90, South Griffin J-13, Balvenie B-79
- Regional top sequence seismic horizon: Base Eocene (T50)
- Chronostratigraphic cross-sections (PL. 3-4)
- Lithostratigraphic Cross sections 1 and 2 (PL. 3-5-1) and Geological Composite Well Logs B-78, K-90, J-13, B-79 (Enclosures 3)
- Architectural Cross-Sections on Bible Lines (PL. 3-5-2 & 3-5-3)

Description

Dawson Canyon Formation

The transgressive Dawson Canyon formation consists of marine shales, chalks and minor limestones deposited throughout the entire shelf of the Scotian Basin during Late Cretaceous time (Figures 19 and 20). The Dawson Canyon Formation varies in thickness from more than 500m on the LaHave platform to about 200m on the Canso Ridge and represents the most widely spread Cretaceous formation. Distally, it is often missing due to Tertiary erosion. The Petrel Member is a persistent series of limestones (Jansa and Wade, 1975) that form a regional seismic marker within the Dawson Canyon.

Wyandot Formation

The Wyandot formation is composed of chalk, chalky mudstone, marl and minor limestone (Figures 19 and 20). Its thickness ranges from less than 50m in some wells in the Sable Sub-basin area to about 400m in the southeastern corner of the Scotian Shelf, but it is missing over extensive portions of the basin due to Tertiary erosion. Beneath the outer shelf and slope, the top of the Wyandot Formation is often marked by an unconformity which is overlain by Tertiary sediments. The Dawson Canyon Formation is diachronous unit extending in age from Turonian, west-southwest of the Sable Sub-basin, to base Tertiary east-southeast of the Scotian Shelf.

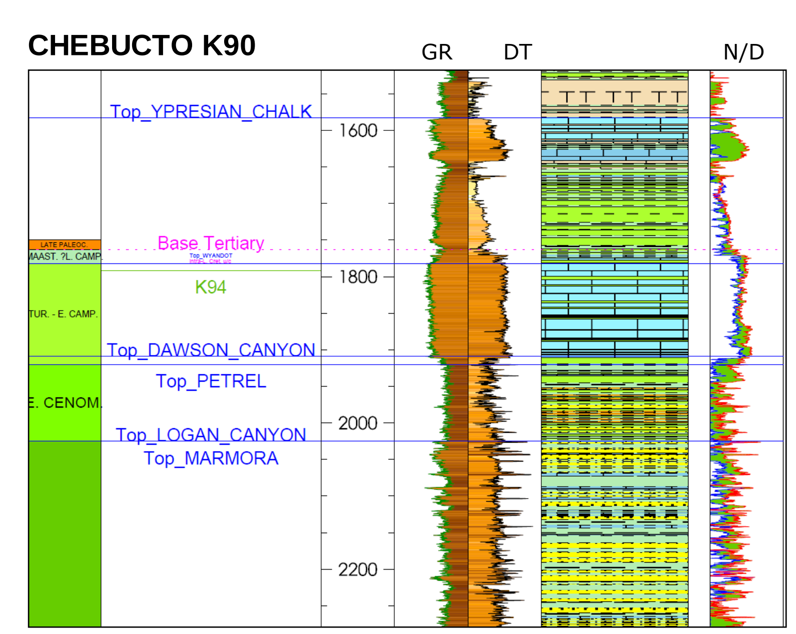

Figure 19: Type section of Dawson Wyandot Formations, Chebucto K-90 (Key well PFA, 2011)

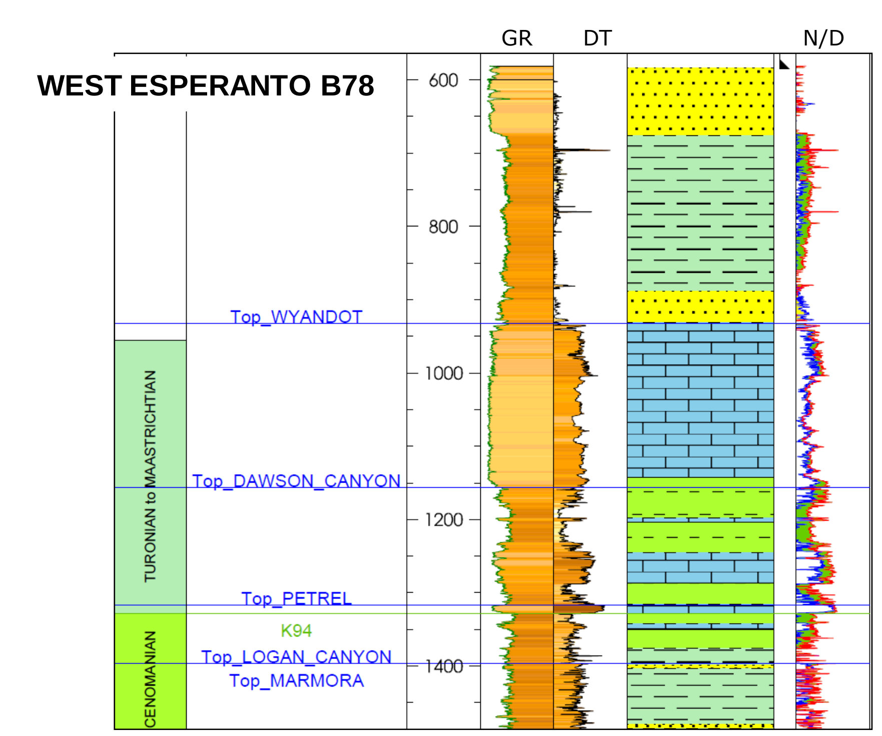

Figure 20: Type section of the Dawson Wyandot Formations, Chebucto K-90 (Key well PFA, 2011)

Ypresian Chalk

Early Eocene in age, this chalky formation represents a fair to good seismic marker corresponding to a regional transgressive episode. To the north of the Scotian Basin, it is frequently absent or disrupted by the numerous Tertiary unconformities prevailing in these areas.

The Chronostratigraphic Cross-Sections over the Scotian Basin show the distribution in time of each main sequence and associated deposit types, highlighting the isochronous and diachronous tectono-sedimentary events.

Hydrocarbon occurrence (see Chapt. 6- PL. 6-6-4b): The Chalk objective has low confidence respecting the exploration history and hydrocarbon shows and discoveries are very limited over the Scotian Basin along Late Cretaceous to Eocene sequence (Eagle D21, Sable E48 and Primrose F41 wells).

Late Eocene to Present Sequences

Banquereau Formation

The sedimentary succession between the top Ypresian and the top Cenozoic is included in the **Banquereau Formation**. It is coarsening upward, predominantly Tertiary in age and consists of a series of downlapping or prograding sequences with the results that in the northern (proximal) areas of the basin Paleocene or Eocene sediments overlie Cretaceous rocks whereas distally, Miocene or younger sediments do. Thickness ranges from a zero edge along the basin to more than 4km associated with areas of salt withdrawl beneath the continental slope.

Laurentian Formation

The Laurentian Formation is a progradational wedge of Quaternary and uppermost Pliocene sediments. Where it is thickest, along the outer shelf and upper slope, there is over 1500m of glaciomarine and marine sands, silts, and clays.

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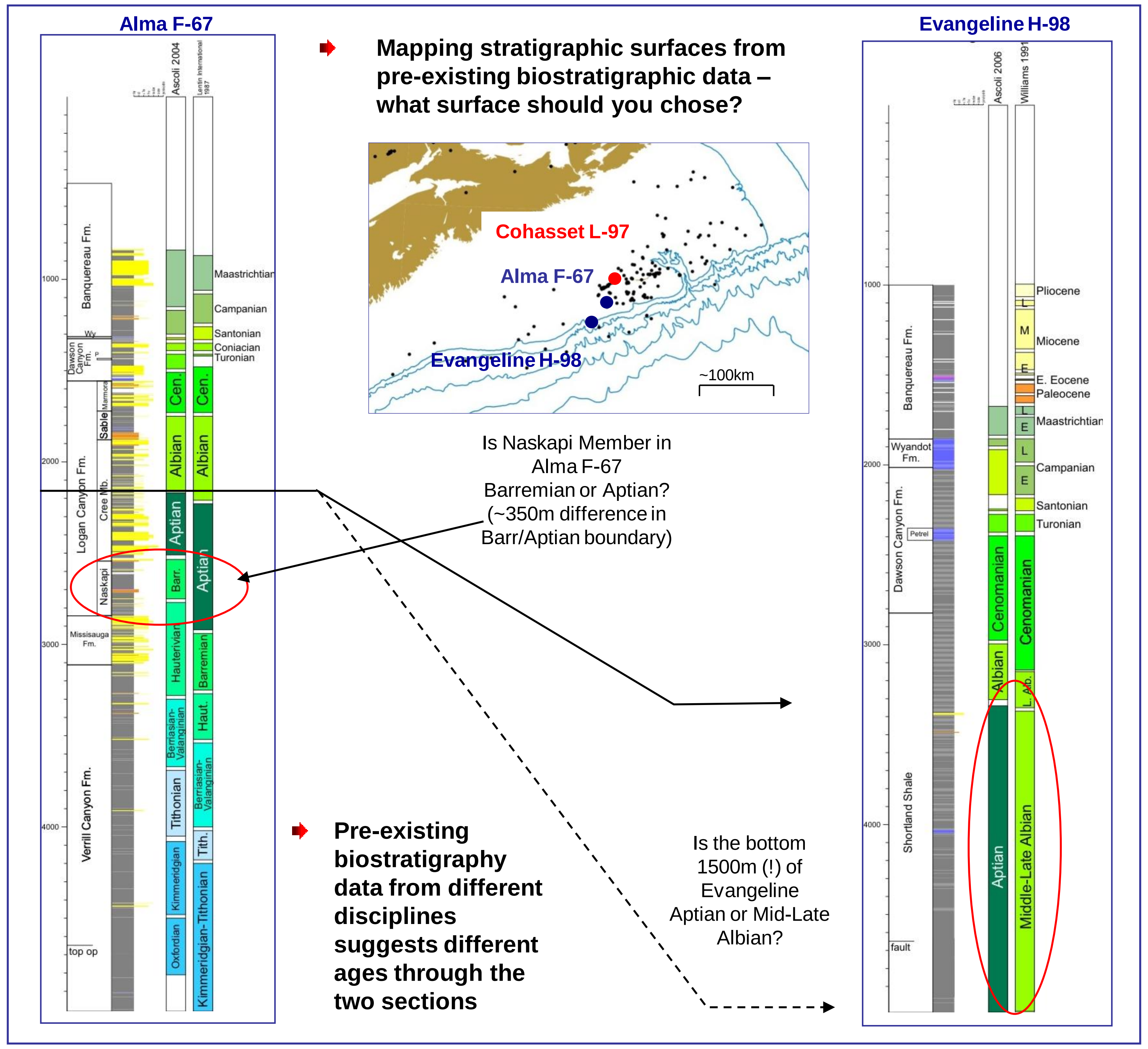
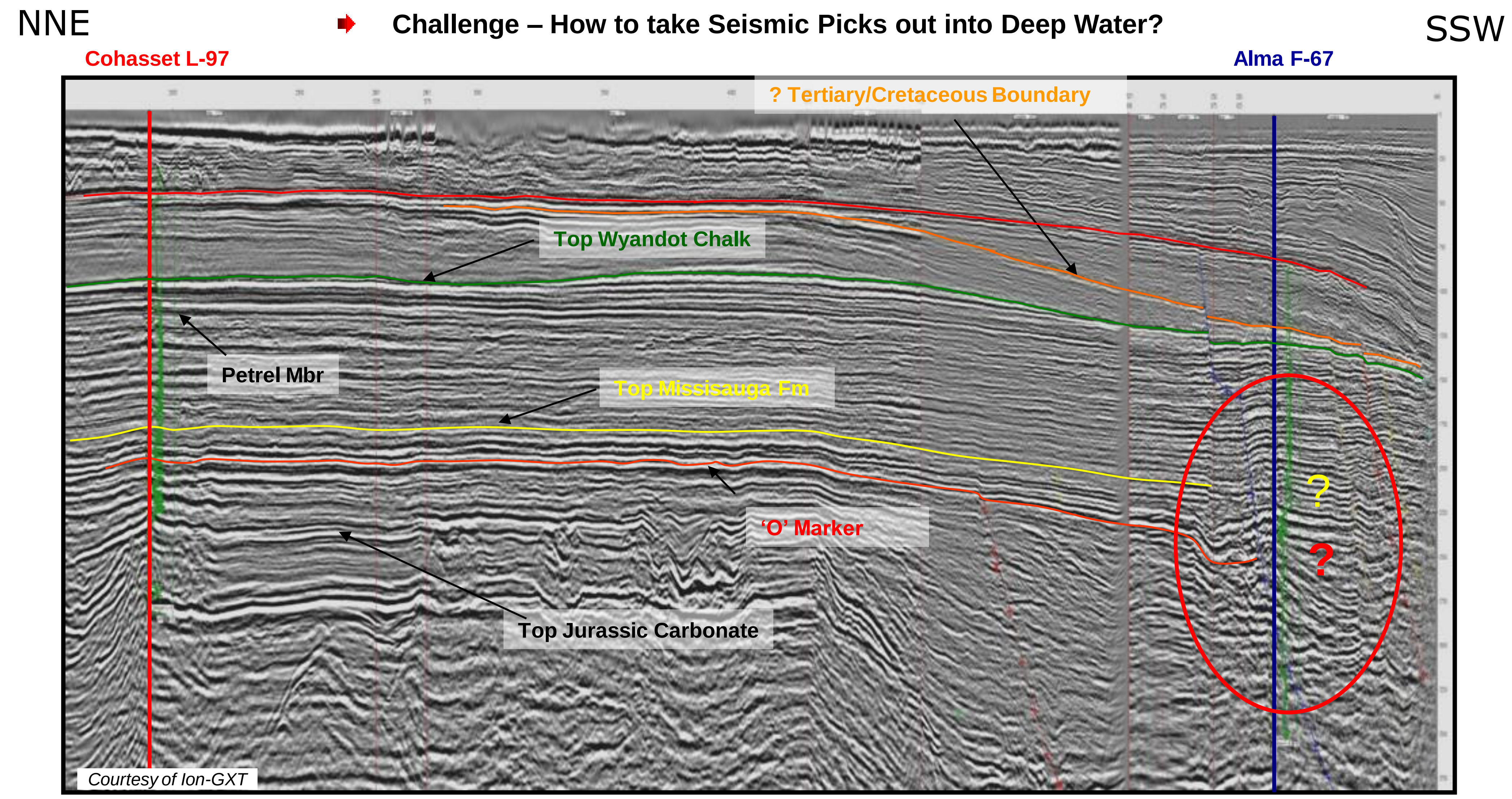
CHAPTER 3-3

BIOSTRATIGRAPHY

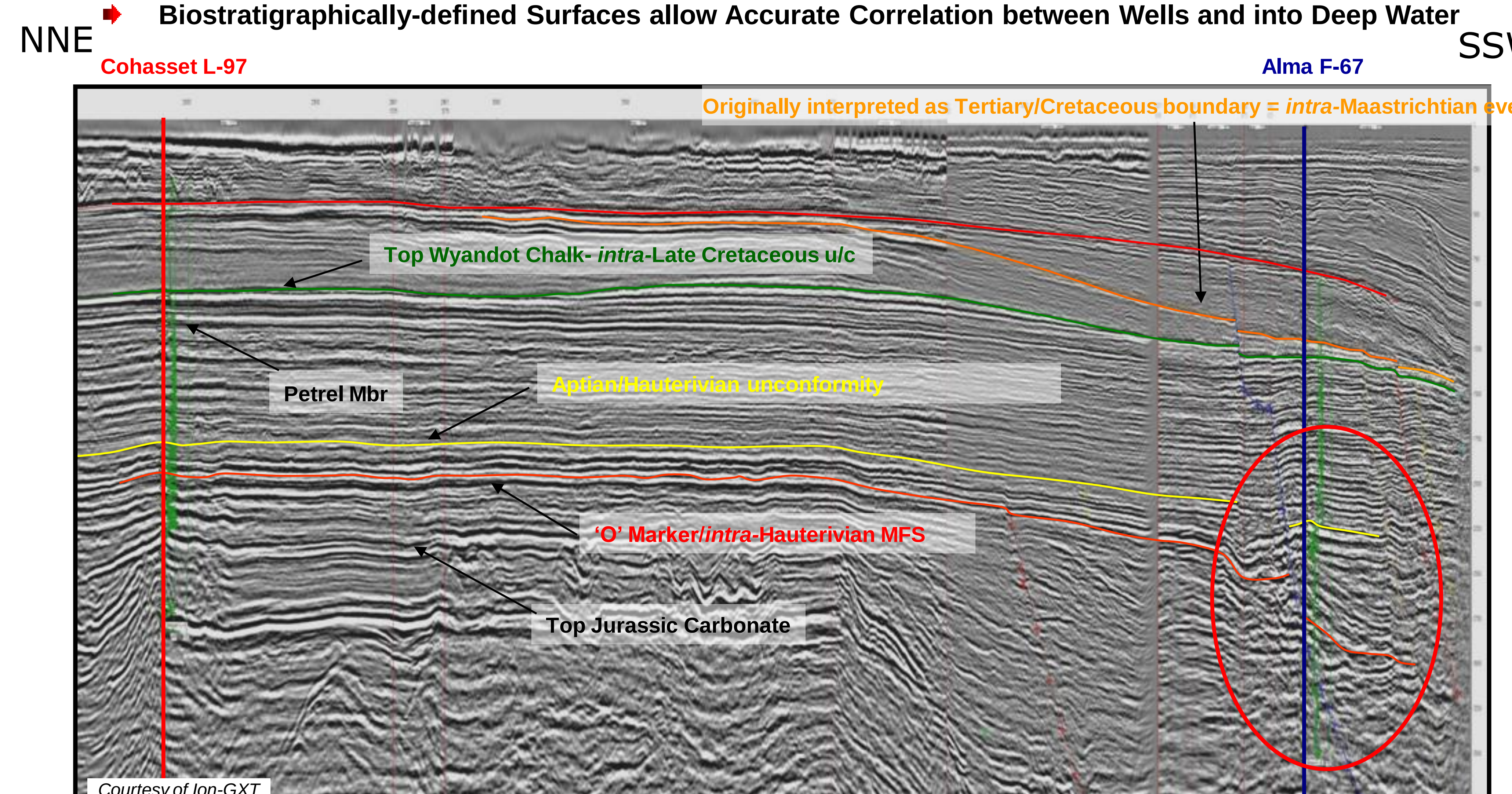


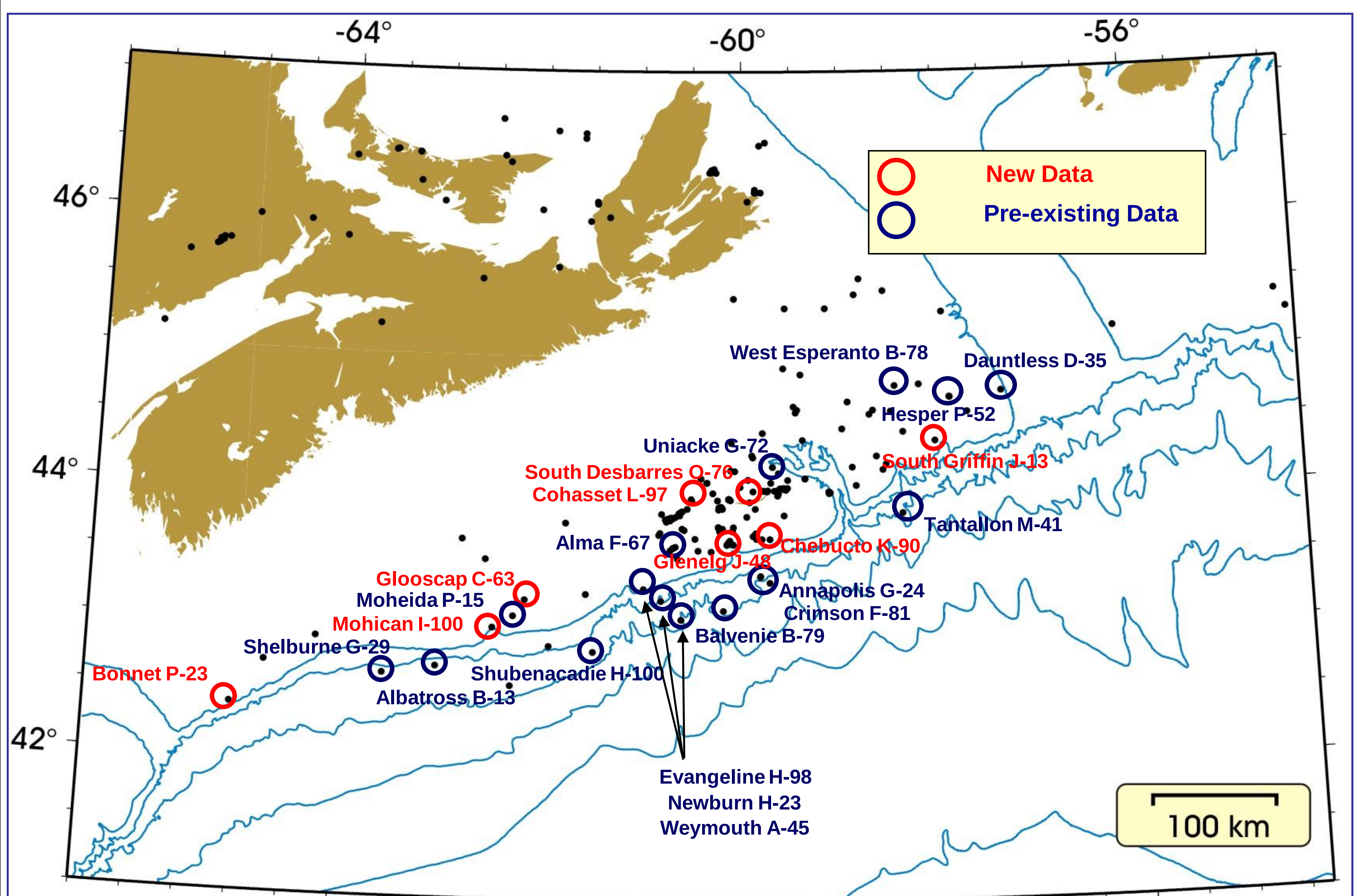
- Previous seismic mapping was heavily based on lithostratigraphic surfaces;
- Previous biostratigraphic data tended to be from single disciplines with little integration between disciplines or with wireline or seismic data;
- New multi-disciplinary quantitative biostratigraphic analyses of 8 key wells were undertaken, and the abundance and diversity trends used to define and calibrate major well-log sequence stratigraphic surfaces (maximum flooding surfaces/sequence boundaries);
- Pre-existing biostratigraphic data from a further 16 key wells were used to extend the well-log sequence stratigraphic surfaces across the area.

Challenge – How to take Seismic Picks out into Deep Water?



Biostratigraphically-defined Surfaces allow Accurate Correlation between Wells and into Deep Water





- **Biostratigraphically-calibrated seismic surfaces recognised between wells:**

Unconformities (8):

Intra-Oligocene (T29)
Intra-Ypresian (T50)
Late Campanian
Turonian/Cenomanian boundary (base Petrel Mbr) (K94)
Late Albian (K101)
Middle Albian
Aptian (base Naskapi Mbr)
Intra-Base Cretaceous (K147/137)

Maximum Flooding Surfaces (7):

Santonian/Coniacian Chalk
Albian/Aptian boundary
Intra-Aptian (Naskapi)
Intra-Hauterivian (related in part to the 'O' Marker) (K130)
Tithonian (J150)
Base Tithonian
Top Callovian (J161)

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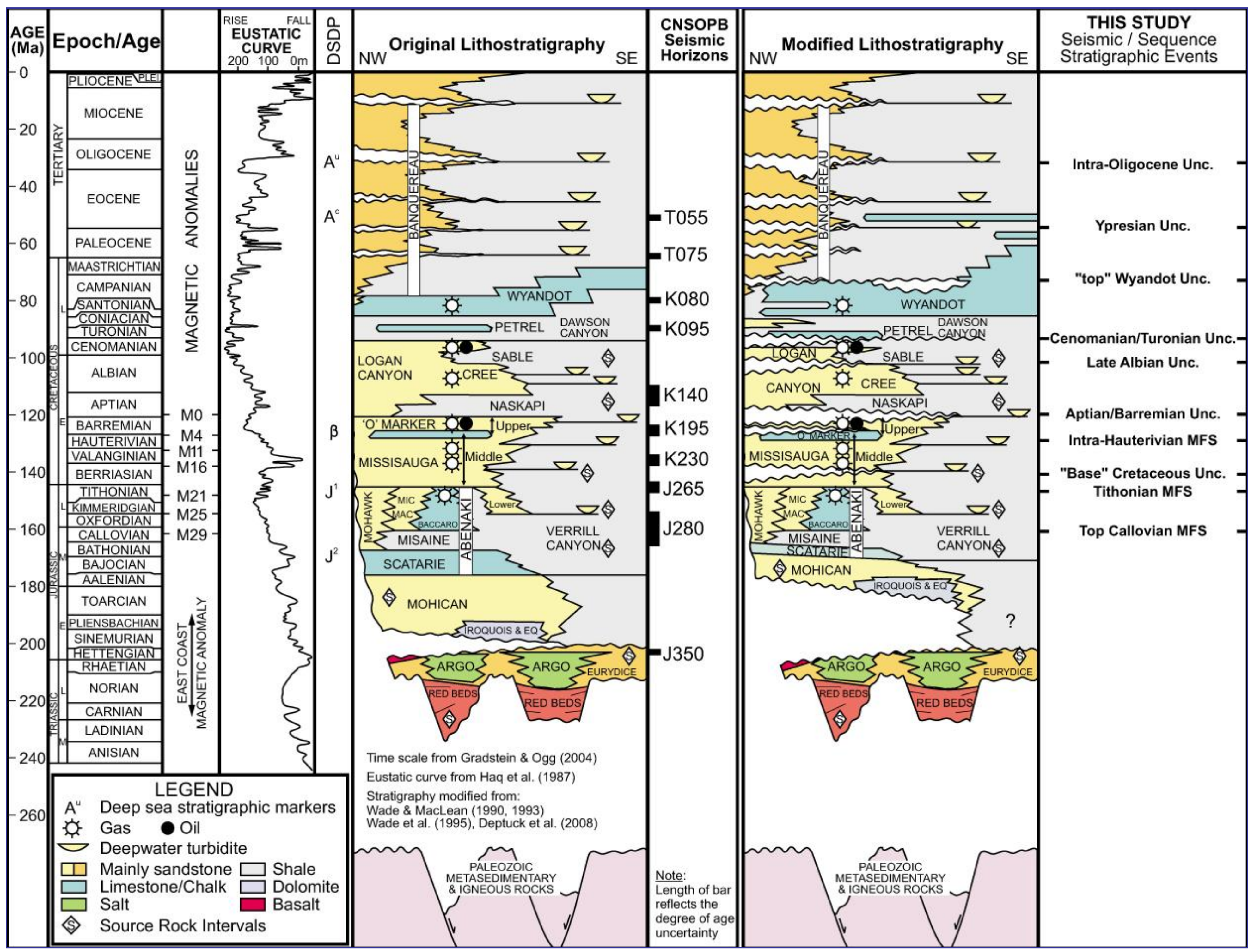
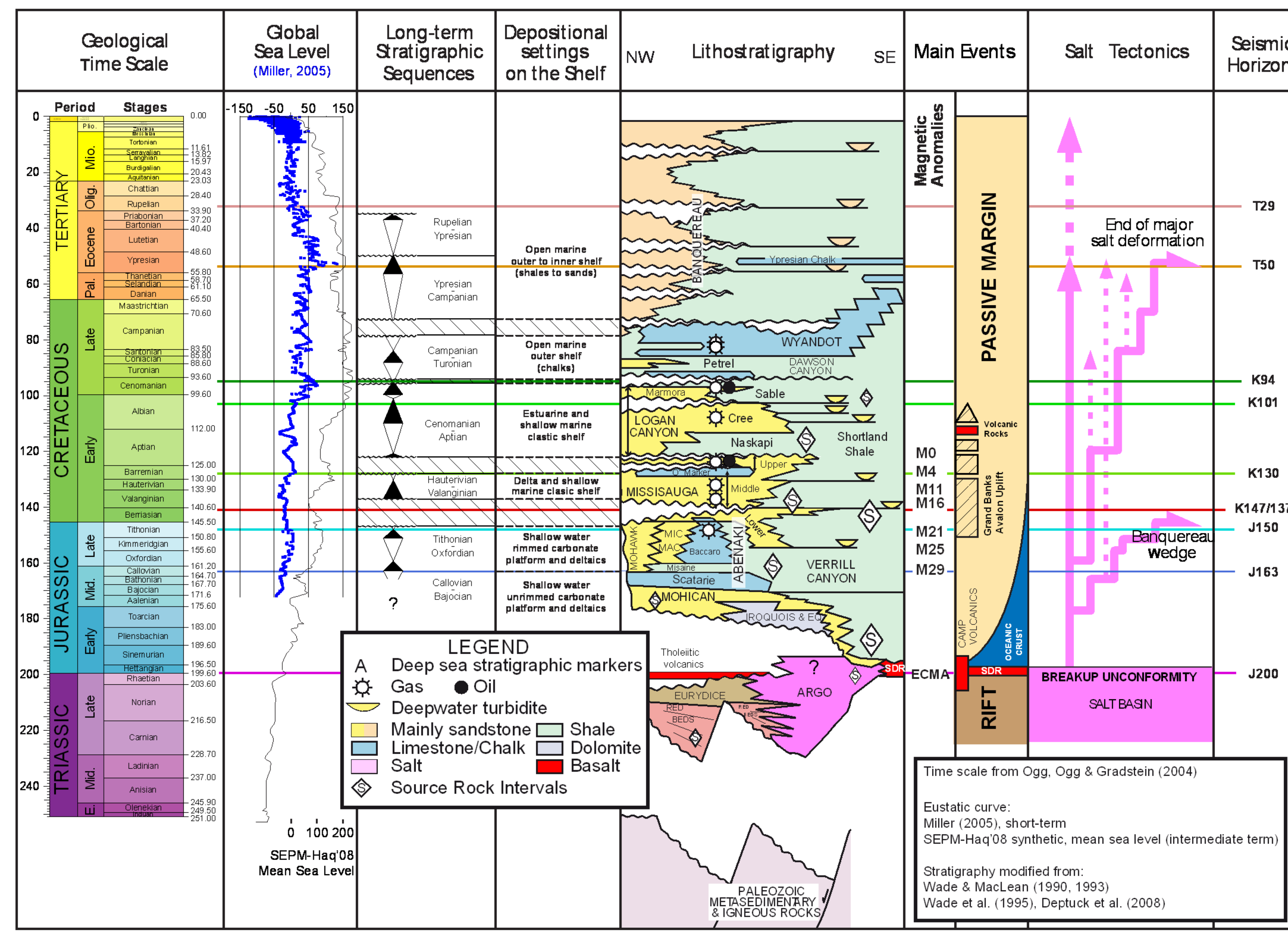
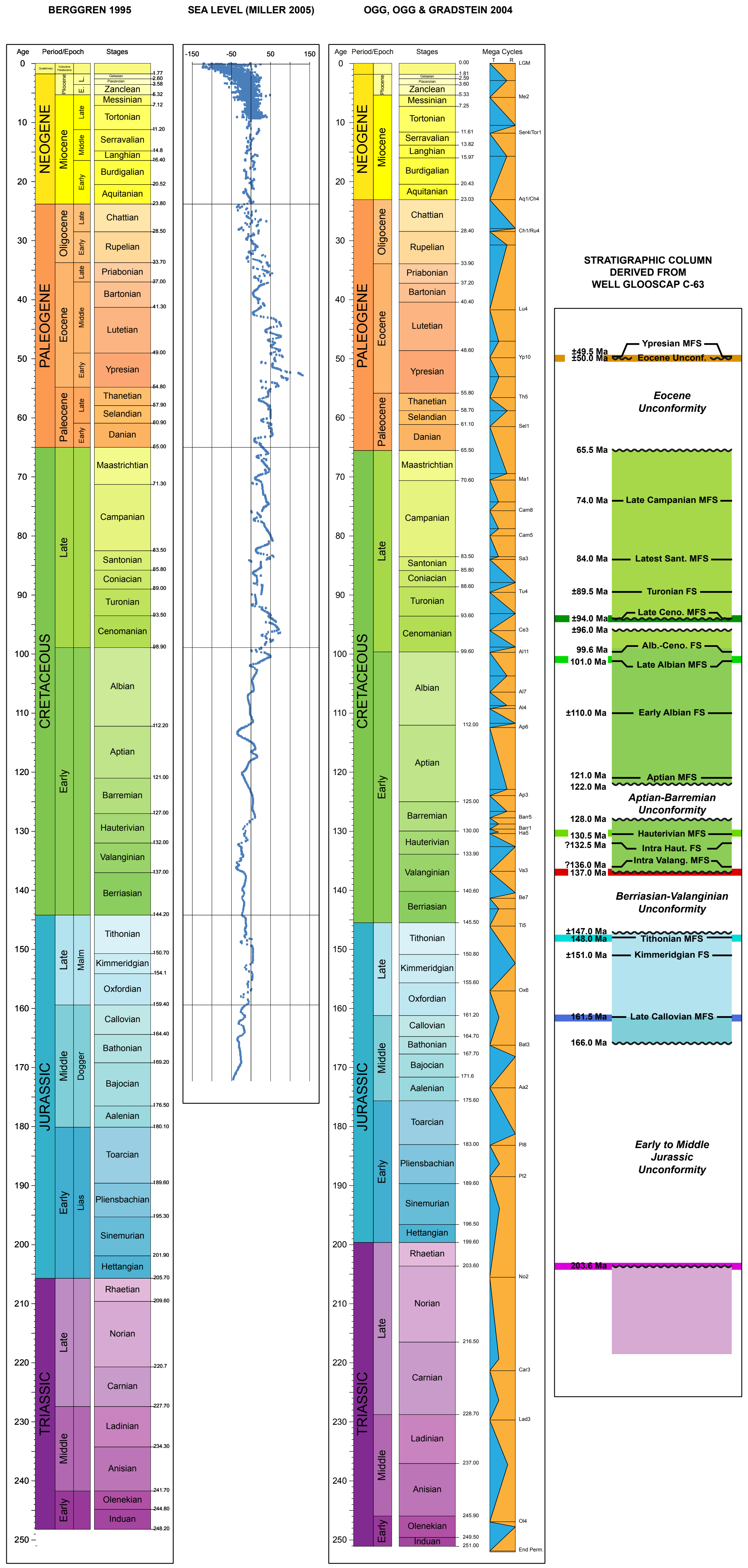
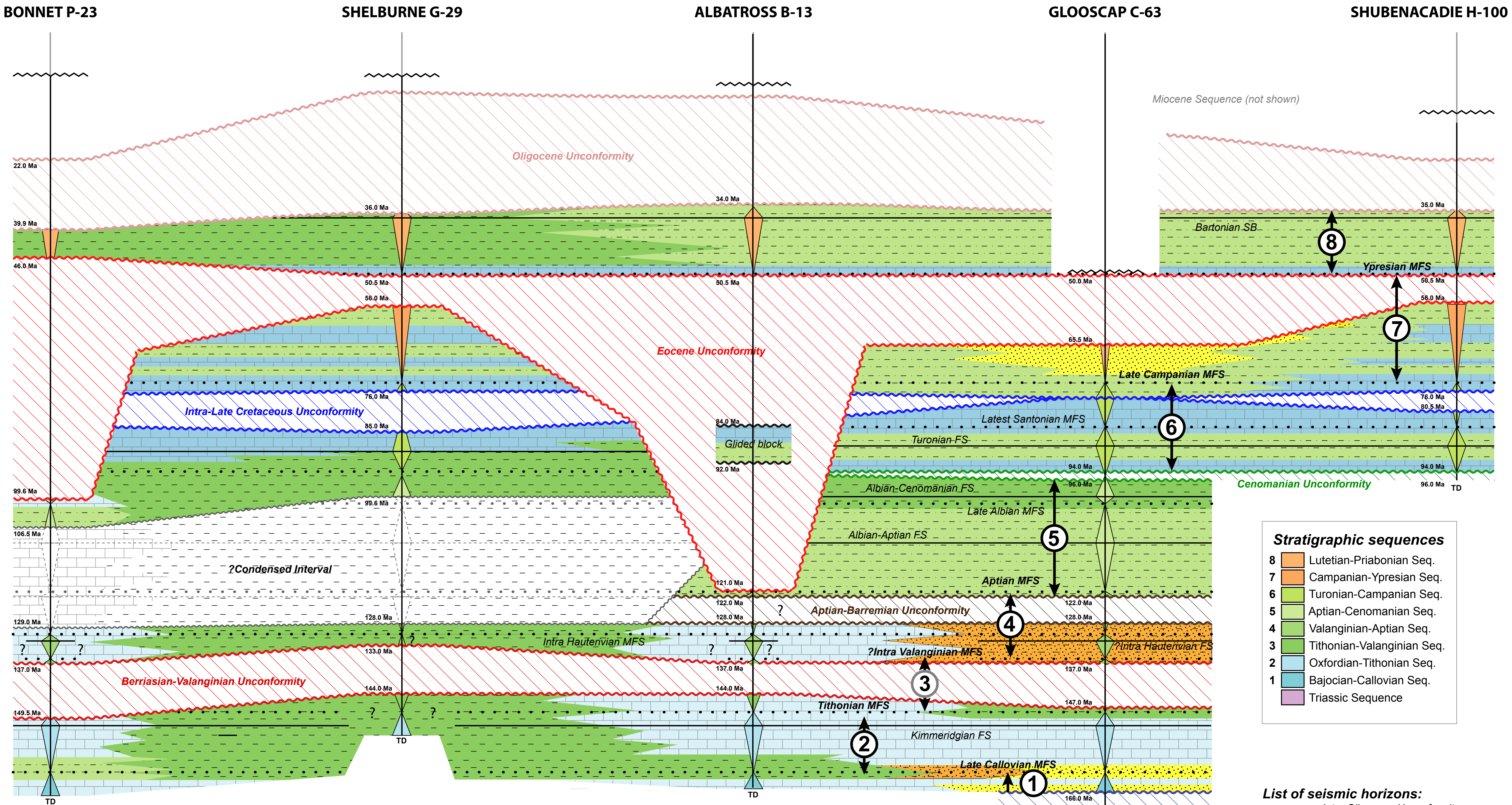


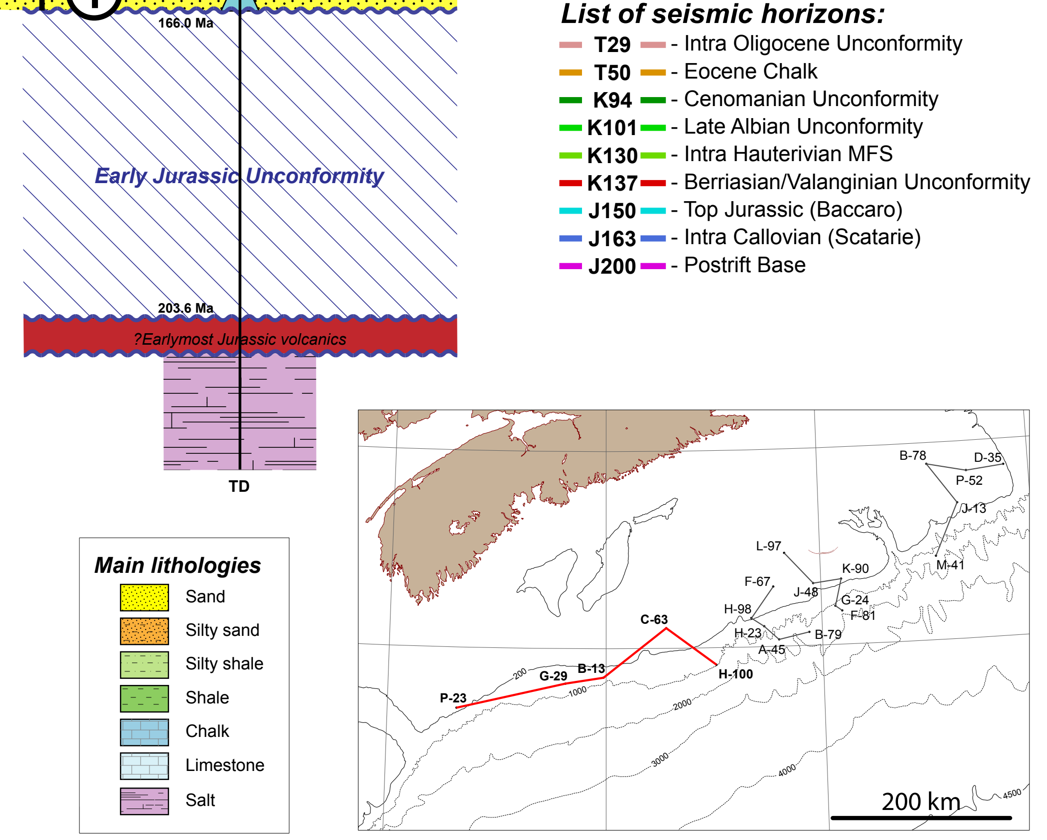


CHAPTER 3-4

CHRONOSTRATIGRAPHIC CROSS-SECTIONS







Triassic sequence (syn-rift)

The topmost part of the syn-rift sequence, biostratigraphically dated as Late Triassic, was drilled in Glooscap C-63, where it contains siliciclastics and evaporites deposited under lacustrine to alluvial conditions. The syn-rift sequence is overlain by the break-up unconformity and basalts.

Bajocian-Valanginian sequences (sequences 1 to 3)

The first post-rift sediments deposited on the Western Scotian Shelf are biostratigraphically dated as Bajocian (Glooscap C-63). Overlying the break-up unconformity is a transgressive sequence with non-marine siliciclastics grading into Callovian shallow-marine oolitic carbonates. During Late Callovian, the carbonate platform was drowned and marine shales and sandstones deposited. Carbonate sedimentation reinitiated at the Callovian-Oxfordian boundary with the development of an oolitic carbonate ramp, which subsequently evolved into a reefal platform during Oxfordian (Albatross B-13 and Bonnet P-23). Beyond the reef margin, shales accumulated in a deep open-marine environment (Shelburne G-29). The Demise of the reefal platform started during Tithonian as a result of the increasing prodeltaic influence of the Sable delta (Central Scotian Shelf). The top of Late Jurassic deposits is eroded by the Berriasian-Valanginian unconformity, recognized biostratigraphically along the southwest margin.

Valanginian-Aptian sequence (sequence 4)

The demise of the carbonate platform initiated during Late Jurassic increased during Early Cretaceous. Shallow-marine siliciclastics derived from the Sable delta reached the eastern part of the LaHave Platform. Away from these siliciclastic inputs, shallow-marine sedimentation continued (Albatross B-13 and Bonnet P-23). The Aptian-Barremian unconformity was recognized on most of the LaHave Platform, but could not be biostratigraphically extended to its western end (Shelburne G-29 and Bonnet P-23).

Aptian-Cenomanian sequence (sequence 5)

The sequence was identified on the LaHave Platform up to the Albatross B-13 area. In this region, away from any significant sand sources, shallow water sedimentation was predominantly argillaceous. Southwest to Albatross B-13, sedimentation rates were very low (condensed section?) both in the deep water basin (Shelburne G-29) and on the remnant shallow-water carbonate platform (Bonnet P-23). The Cenomanian unconformity was recognized on the eastern LaHave Platform associated with the 2nd order Late Cenomanian maximum flooding surface.

Turonian-Campanian sequence (sequence 6)

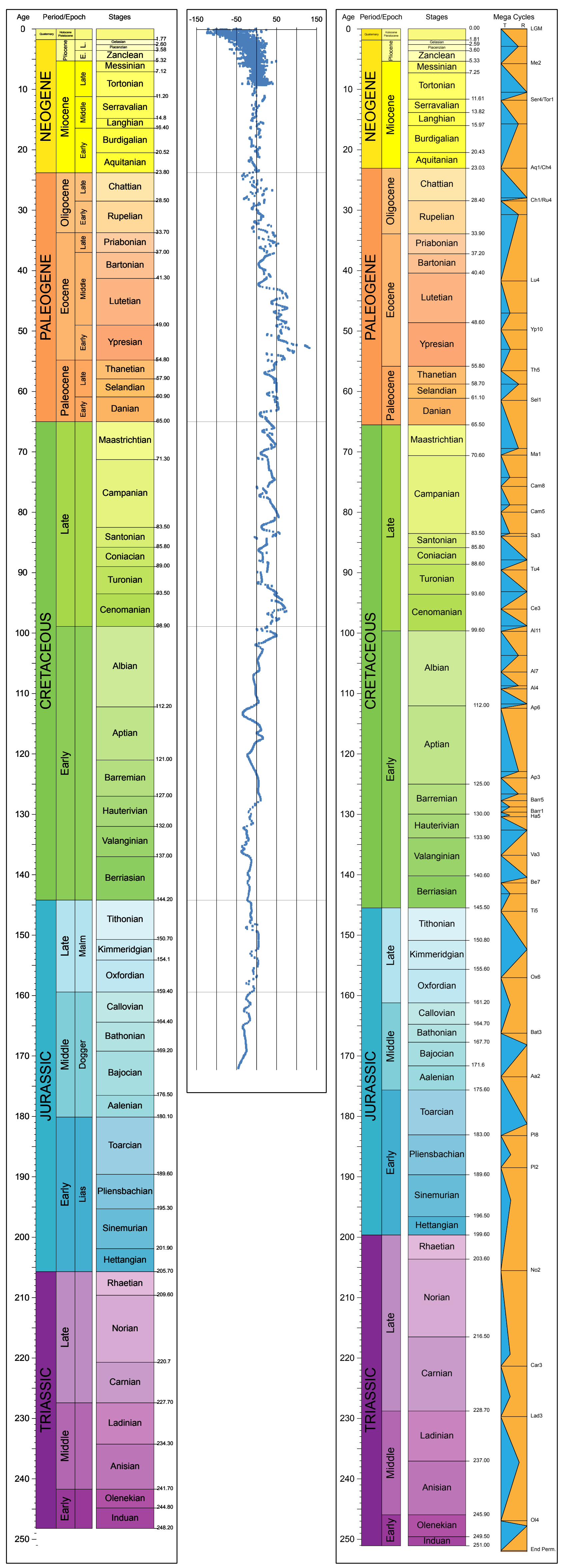
As observed in the Central and Eastern Scotian Shelf, the Turonian-Campanian sequence is characterized by a marked reduction in siliciclastic influx and concomitant chalk sedimentation under deep, open-marine conditions. Pelagic carbonate sedimentation started to deposit during Turonian and it extended over the whole LaHave Platform during Santonian. The top of chalk formation is eroded by the intra Late Cretaceous unconformity.

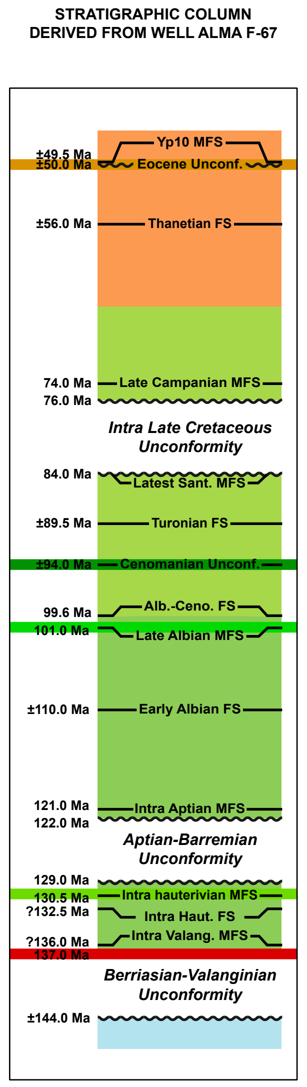
Campanian-Ypresian sequence (sequence 7)

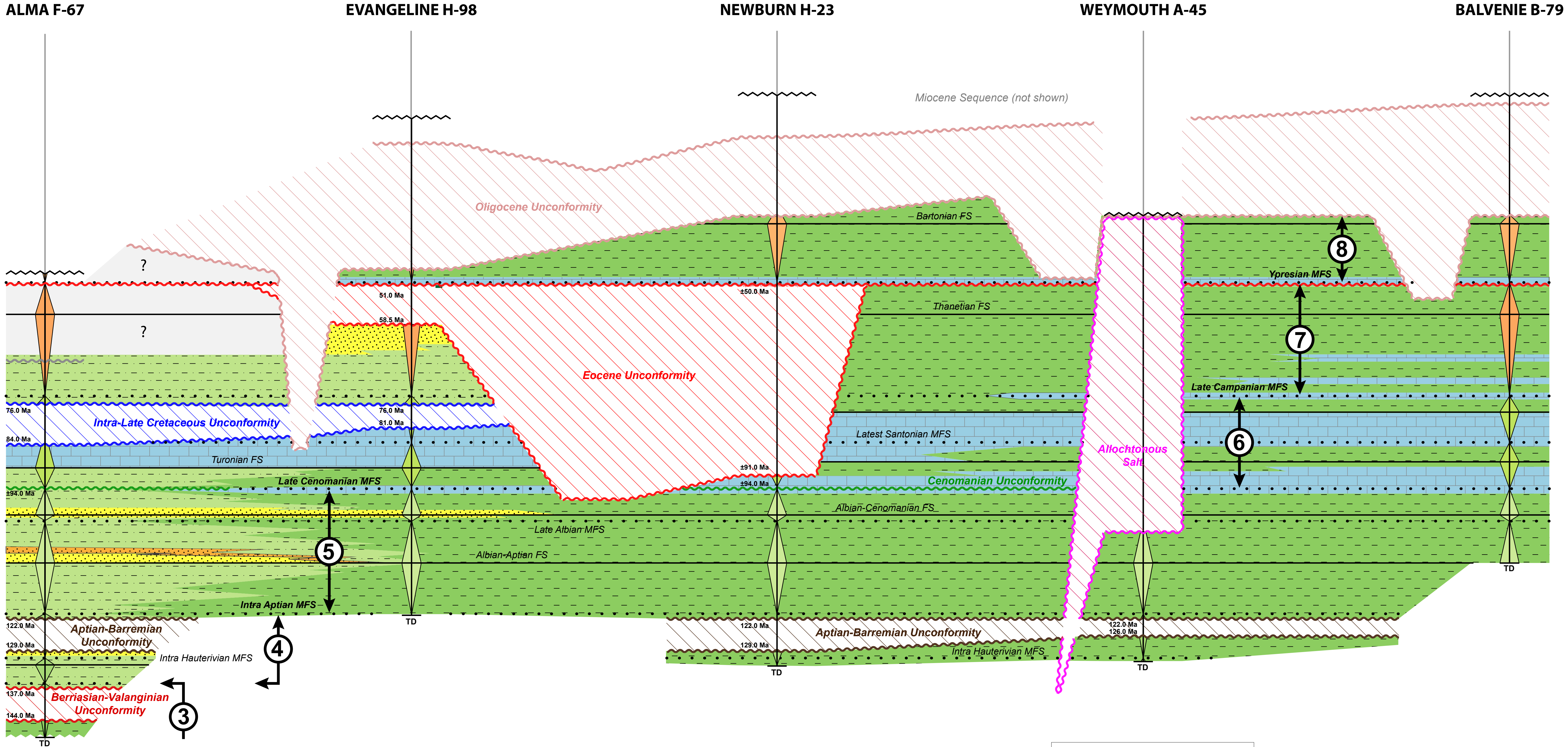
Chalk sedimentation was still predominant over the LaHave Platform, except around Glooscap C-63, where shales and sands derived from a local deltaic system are observed. The sequence is deeply eroded by the Eocene unconformity interpreted as a major slope failure caused by the Montagnais meteorite impact at 50.50 ± 0.76 Myrs. The largest and deepest erosion is observed in Albatross B-13 and Bonnet P-23, where Late to even Early Cretaceous sediments were removed over the rupture surface and transported downward into the adjacent basin area. Down to the slope margin, removed sediment volumes were smaller resulting in a shorter time gap above the scarp (Shelburne G-29 and Shubenacadie H-100). A similar short time gap is documented on the inner shelf (Glooscap C-63), and the razor effect of waves generated by the meteorite impact could be a plausible mechanism for the erosion observed on the shelf. The Eocene unconformity is overlain by the Ypresian chalk, deposited during the 2nd order sea level maximum.

Lutetian-Priabonian sequence (sequence 8)

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







Callovian-Aptian sequences (sequences 3 and 4)

On the cross-section, the Late Jurassic and Early Cretaceous sequences are only documented close to the bottom depth of Alma F-67, Newburn H-23 and Weymouth A-45, and are poorly known. In Alma F-67, the Tithonian interval contains open-marine shales deposited beyond the shallow-marine carbonate platform margin setting to the North (not shown on this section). It is overlain by the Berriasian-Valanginian unconformity. The Early Cretaceous sedimentary system is also dominated by prodeltaic to open-marine shales. In Alma F-67, the prodeltaic shales grade into sandstones deposited under shallower marine conditions, illustrating the progradation of the Sable delta toward the basin. Deltaic sediments are topped by the Aptian-Barremian unconformity.

Aptian-Cenomanian megasequence (sequences 5)

During the Aptian, the Early Cretaceous deltaic deposits were flooded (intra Aptian maximum flooding surface) and regional open-marine conditions established due to decreased sand supplies. At the Aptian-Albian boundary, renewed shallow-marine siliciclastic sedimentation took place on the Central Scotian Shelf with estuarine and shallow-marine shales and sandstones. These shallow-marine conditions prevailed up to the Albian-Cenomanian boundary, when the platform was flooded (2nd order Late Cenomanian maximum flooding surface). In this transgressive context, chalk sedimentation initiated during the Late Cenomanian. The Late Cenomanian unconformity was identified in the wells, but the associated time gap associated is short.

Turonian-Campanian sequence (sequence 6)

The Late Cretaceous sequence is characterized by predominant chalk sedimentation associated to high sea levels and a marked reduction in siliciclastic influx. On the shelf, the top of the chalk is diachronous and eroded by the intra Late Cretaceous unconformity (Alma F-67 and Evangeline H-98). The magnitude of the unconformity decreases basinward so that no time gap was biostratigraphically documented in more distal wells such as Balvenie B-79. The unconformity was interpreted as submarine erosion.

Campanian-Ypresian megasequence (sequence 7)

The sequence is characterized by renewed terrigenous influx on the Scotia Shelf. Open marine shales deposited on the shelf gradually passed to chalk deposits in more offshore area where suitable conditions for pelagic carbonate production still maintained. The vertical transition from shale to sandstone at Evangeline H-98 suggests shallowing-up trend, consistent with the observation of prograding clinoforms over the shelf (close to Alma F-67). Siliciclastics are capped the Eocene unconformity, interpreted as a major erosion surface associated with the Montagnais meteorite impact at 50.50 ± 0.76 Myrs. The time gap related to the Eocene unconformity is a major feature of the paleoslope margin (Evangeline H-98 and Newburn H-23) where most of the Late Cretaceous deposits were removed by large scale submarine landslides. Above the unconformity, the sequence is draped by the laterally persistent Ypresian chalk, deposited during the 2nd order sea level maximum.

Lutetian to Priabonian sequence (sequence 8)

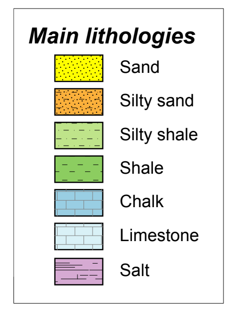
This sequence is poorly documented at wells, and only open-marine shales are preserved below the Oligocene unconformity.

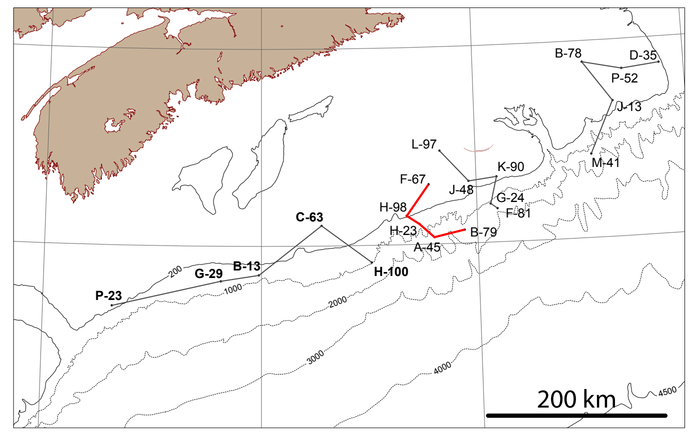
Stratigraphic sequences

8	Lutetian-Priabonian Seq.
7	Campanian-Ypresian Seq.
6	Turonian-Campanian Seq.
5	Aptian-Cenomanian Seq.
4	Valanginian-Aptian Seq.
3	Tithonian-Valanginian Seq.
2	Oxfordian-Tithonian Seq.
1	Bajocian-Callovian Seq.
	Triassic Sequence

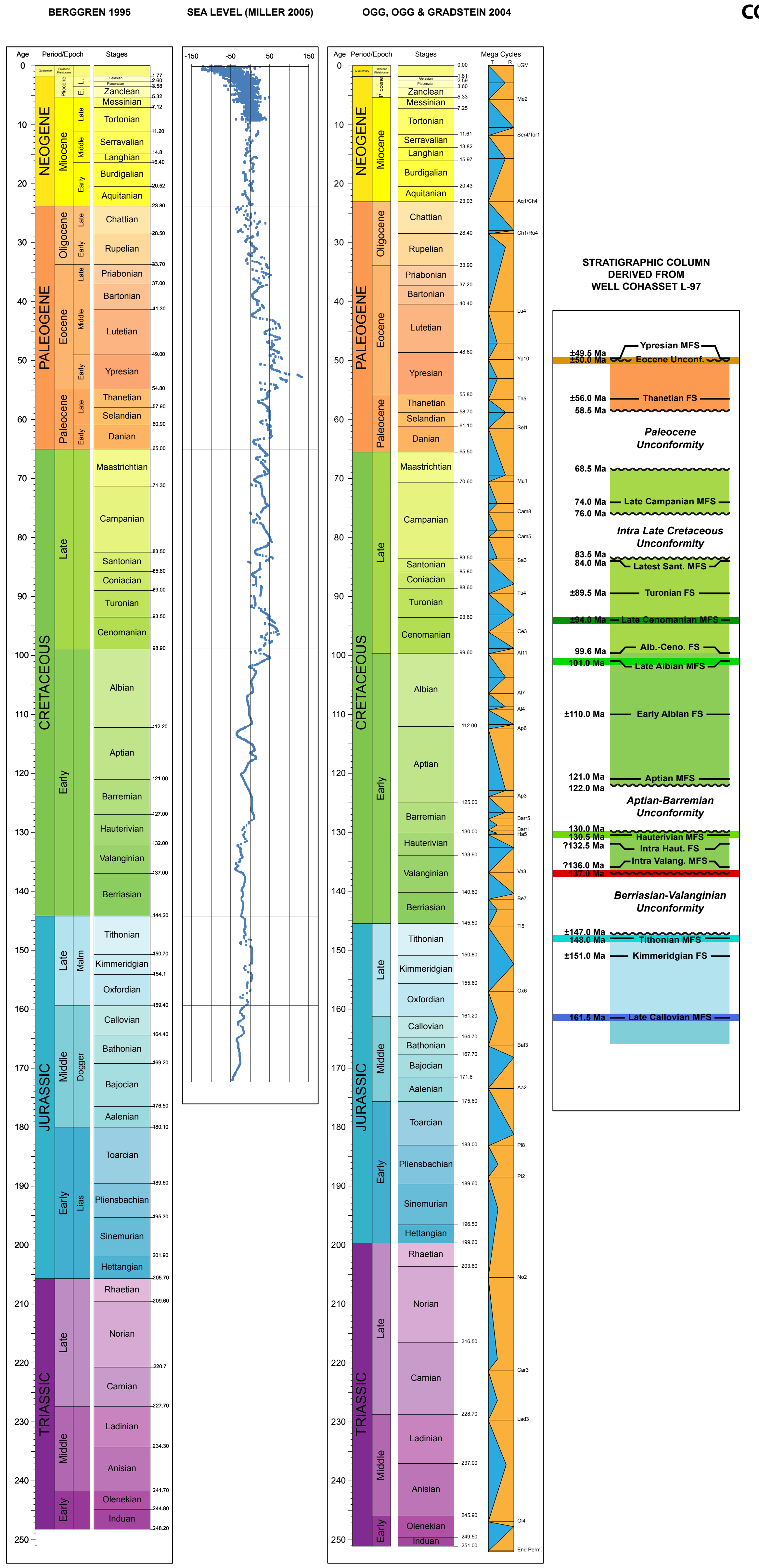
List of seismic horizons:

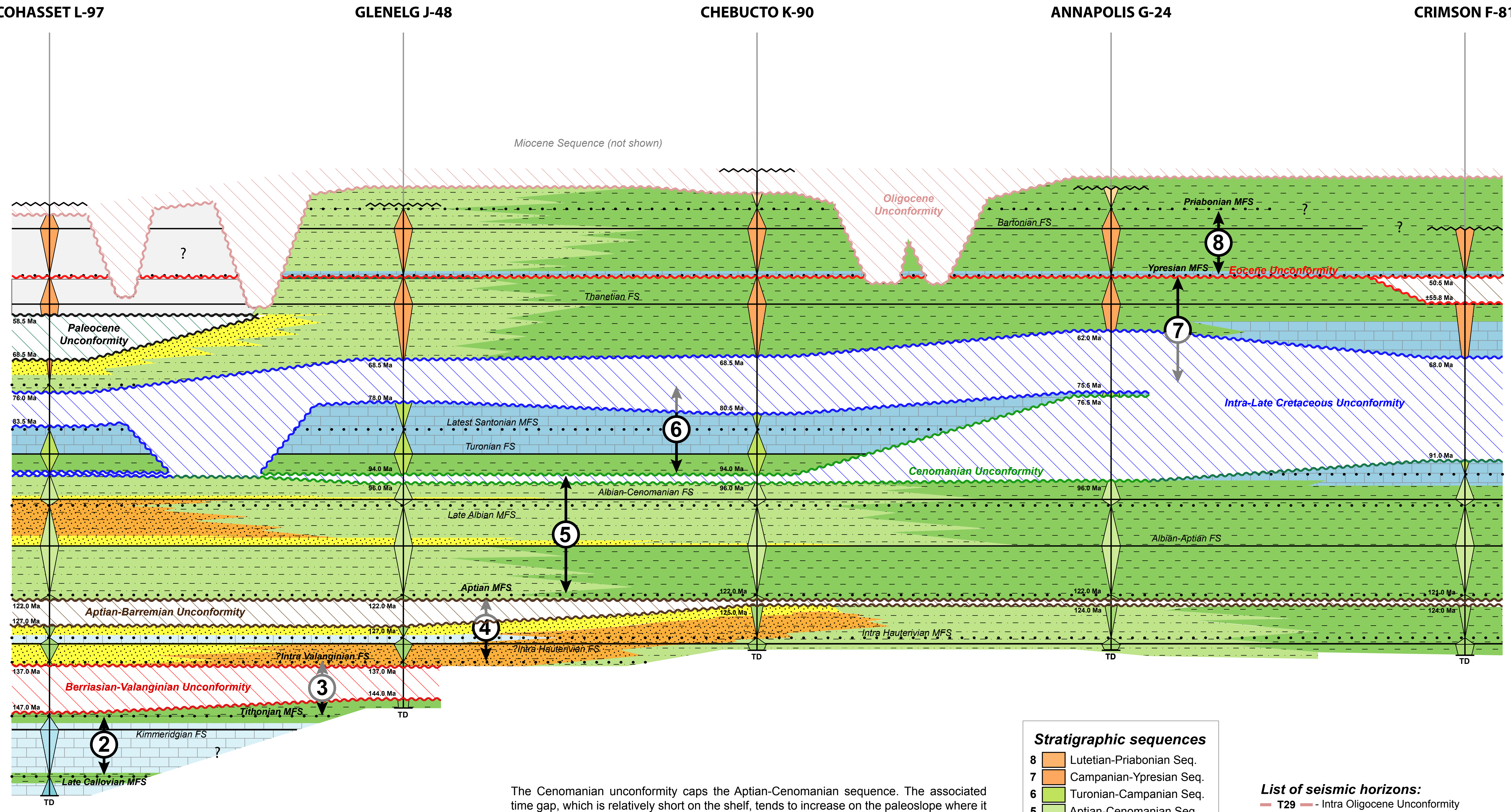
- **T29** - Intra Oligocene Unconformity
- **T50** - Eocene Chalk
- **K94** - Cenomanian Unconformity
- **K101** - Late Albian Unconformity
- **K130** - Intra Hauterivian MFS
- **K137** - Berriasian/Valanginian Unconformity
- **J150** - Top Jurassic (Baccaro)
- **J163** - Intra Callovian (Scatarie)
- **J200** - Postrift Base

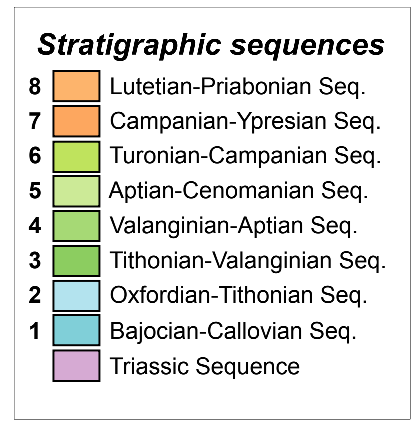




Chronostratigraphic Cross-Section in the Sable Sub-Basin, Central Scotian Margin (1)







List of seismic horizons:

- T29 - Intra Oligocene Unconformity
- T50 - Eocene Chalk
- K94 - Cenomanian Unconformity
- K101 - Late Albian Unconformity
- K130 - Intra Hauterivian MFS
- K137 - Berriasian/Valanginian Unconformity
- J150 - Top Jurassic (Baccaro)
- J163 - Intra Callovian (Scatarie)
- J200 - Postrift Base

Callovian-Valanginian sequences (sequences 2 and 3)

The Late Jurassic sequence (sequence 2) was only penetrated in wells drilled on the shelf, where shallow-marine carbonates are recognized (Cohasset L-97). By Tithonian times, the platform was drowned and overlain by open-marine to prodeltaic shales derived from the adjacent Sable delta. This open-marine to prodeltaic sedimentation continued during the Berriasian, before the Berriasian-Valanginian unconformity.

Valanginian-Aptian sequence (sequences 4)

The sequence is characterized by the deposition of volumetrically significant shallow-marine and delta siliciclastics (both sandstones and claystones) on the shelf edge (Cohasset L-97, Glenelg J-48 and Chebucto K-90). In more distal position (Annapolis G-24 and Crimson F-81), prodeltaic to deep open-marine conditions prevailed with predominant shaly sedimentation. Early Cretaceous deltaic to open-marine deposits are topped by the Aptian-Barremian unconformity.

Aptian-Cenomanian sequence (sequences 5)

The Early Cretaceous shallow-marine sediments were flooded during the Aptian transgressive event (intra Aptian maximum flooding surface), and open-marine shale sedimentation established during that stage over the shelf. Shallow-marine, estuarine sedimentation resumed during the Early Albian, while open-marine conditions continued in more distal parts of the basin. The Albian shallow-marine sedimentary system was flooded at the onset of Cenomanian, when more open and deeper marine conditions reestablished up to the shelf. In the basin, reduced siliciclastic influx and true open-marine conditions provided suitable conditions for chalk sedimentation during the Late Cenomanian (Crimson F-81).

The Cenomanian unconformity caps the Aptian-Cenomanian sequence. The associated time gap, which is relatively short on the shelf, tends to increase on the paleoslope where it goes up to the Campanian at Annapolis G-24. Such a large time gap involves submarine erosion but probably also starved sedimentation or even non-deposition over the paleoslope.

Turonian-Campanian megasequence (sequence 6)

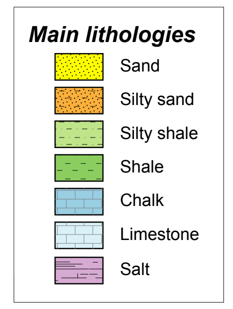
The sequence is characterized by a marked reduction in siliciclastic influx concomitant with chalk deposition under deep, open-marine conditions. Pelagic carbonate sedimentation started to deposit during Turonian and expanded rapidly over the shelf. The top of the Turonian-Campanian sequence is regionally eroded by the intra-Late Cretaceous unconformity. This unconformity locally deeply eroded the Late Cretaceous sequence on the shelf (Cohasset L-97 and Glenelg J-48) and down to the Cenomanian-Turonian on the paleoslope margin (Annapolis G-24 and Crimson F-81). The time gap goes up to Danian, and is probably associated with non-deposition along the paleoslope (downlap surface).

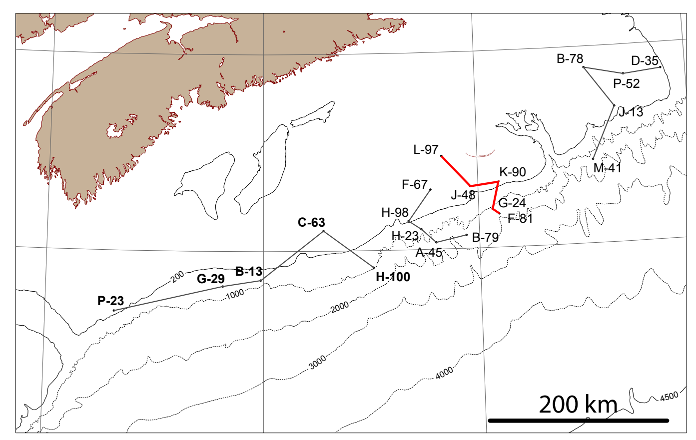
Campanian-Ypresian sequence (sequence 7)

The sequence is characterized by renewed terrigenous influx on the Scotia Shelf. In Cohasset L-97, open-marine shales grade vertically into shallow-marine sandstones, showing a shallowing-up trend associated with prograding clinoforms documented on seismic lines. In more distal parts, sandstones pass laterally into silty shales (Glenelg J-48) and more open marine shales (Annapolis G-24). At the Cretaceous-Paleocene boundary chalk still deposited on the paleoslope margin (Crimson F-81). This regressive sequence was flooded during Thanetian, and open-marine shales deposited before the Ypresian chalk. The Eocene unconformity was identified below the Ypresian chalk, but the time gap was very short except in Crimson F-81.

Lutetian-Priabonian megasequence (sequence 8)

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





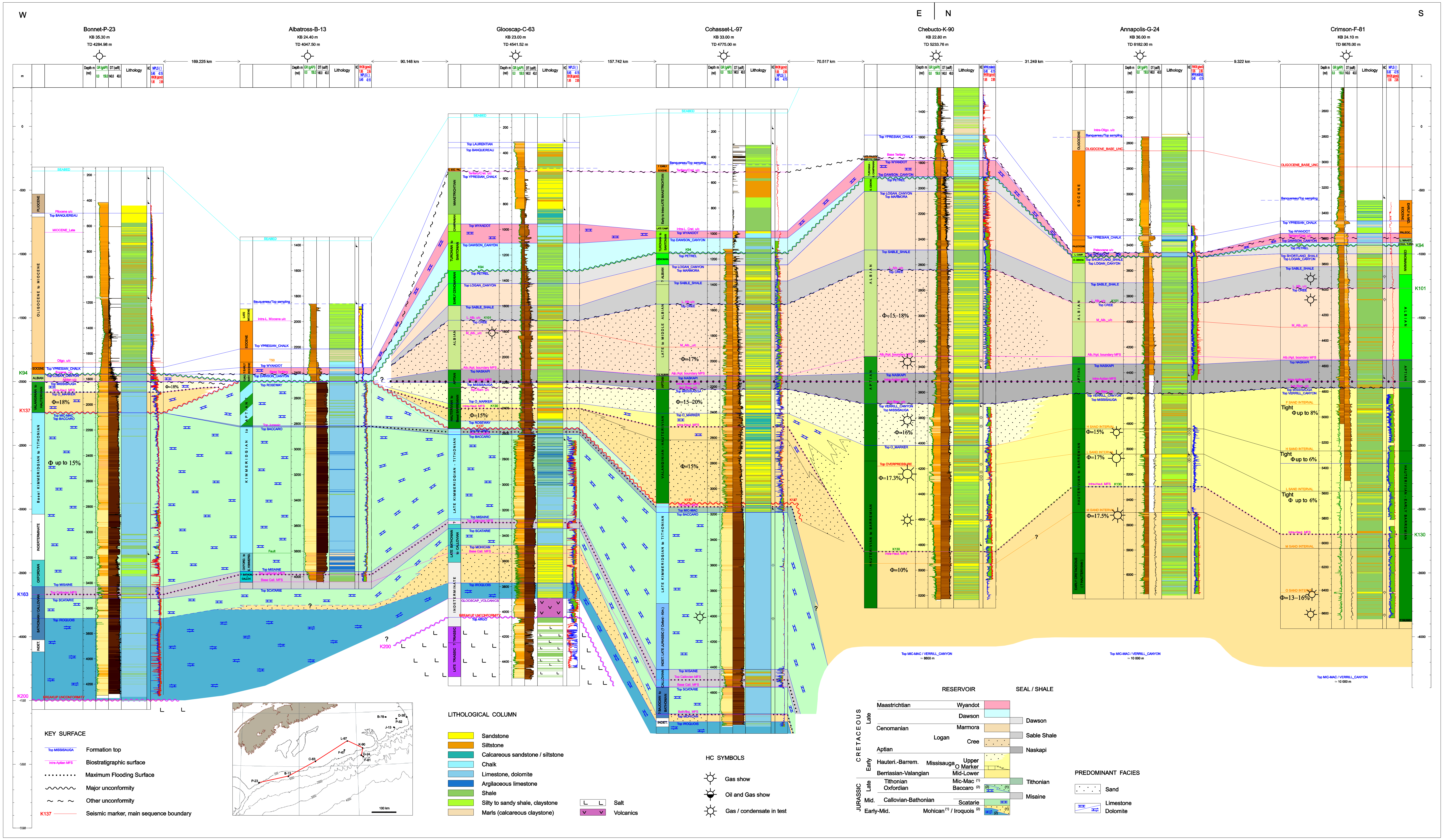
CHAPTER 3-5

STRATIGRAPHY

GEOLOGICAL CROSS SECTIONS

STRATIGRAPHY – GEOLOGICAL CROSS-SECTION

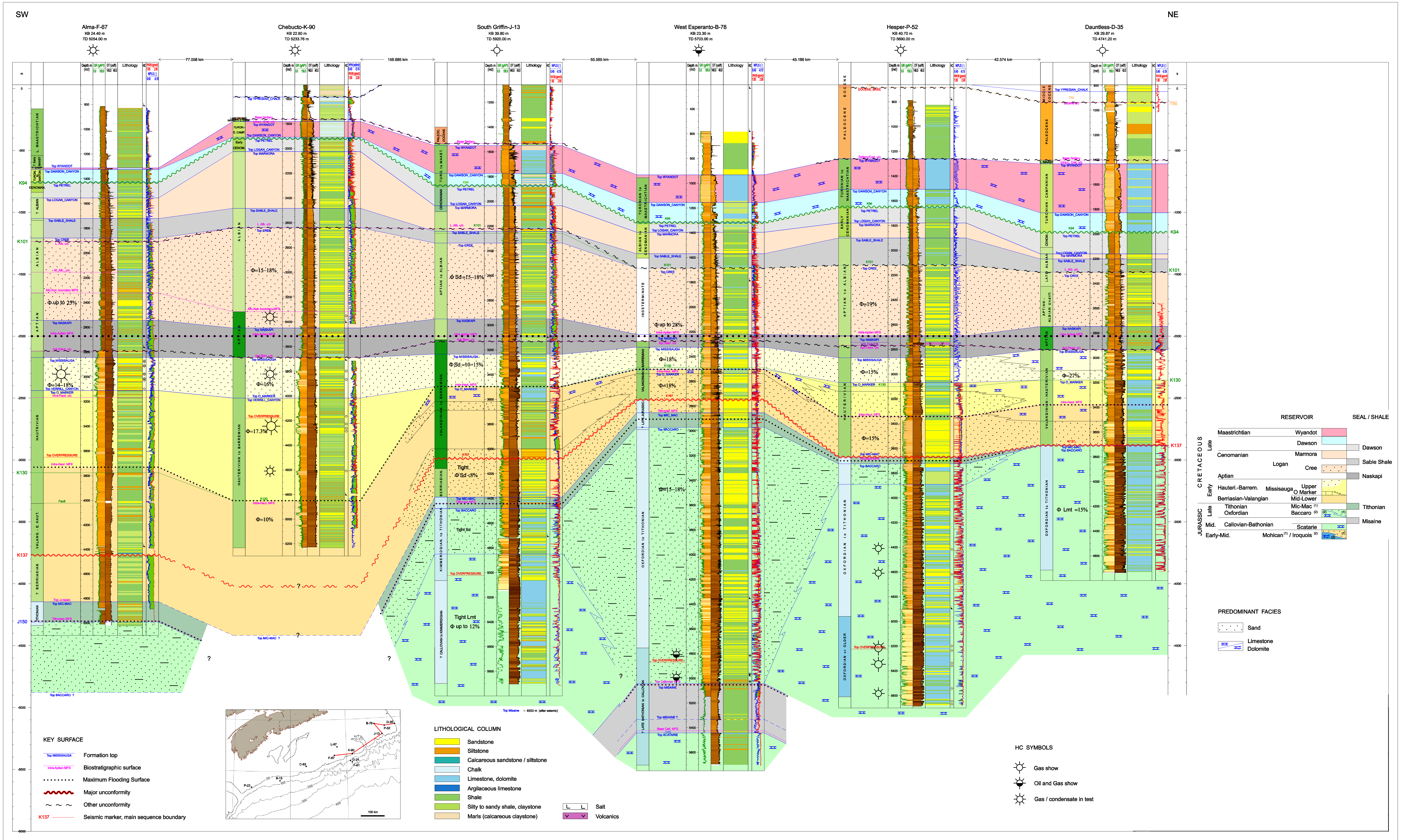
PLAY FAIRWAY ANALYSIS - OFFSHORE NOVA SCOTIA - CANADA - June 2011



The cross-sections illustrated on Plates PL. 3-5-1a (this Plate) and PL. 3-5-1b, flattened on the Intra-Aptian maximum flooding surface (Naskapi) display the lithologies in their new chronostratigraphic context. Along the Jurassic carbonate platform edge, from Bonnet P-23 to Cohasset L-97, the Jurassic section is dominated by the development of a shallow marine carbonate platform topped by the K137 unconformity. Above, the Early Cretaceous section records the siliciclastic sedimentation of the Sable Delta complex (Missisauga Formation) capped by the Naskapi shale. In the North-South direction, the cross-section displays the basinward thickening of the Sable Delta. The Albian-Cenomanian delta (Logan Canyon Formation) shows a rather constant thickness with a sand content decreasing toward the basin and capped by the Late Cretaceous chalk of the Petrel Member and the Wyandot Formations.

STRATIGRAPHY – GEOLOGICAL CROSS-SECTION

PLAY FAIRWAY ANALYSIS - OFFSHORE NOVA SCOTIA - CANADA - June 2011

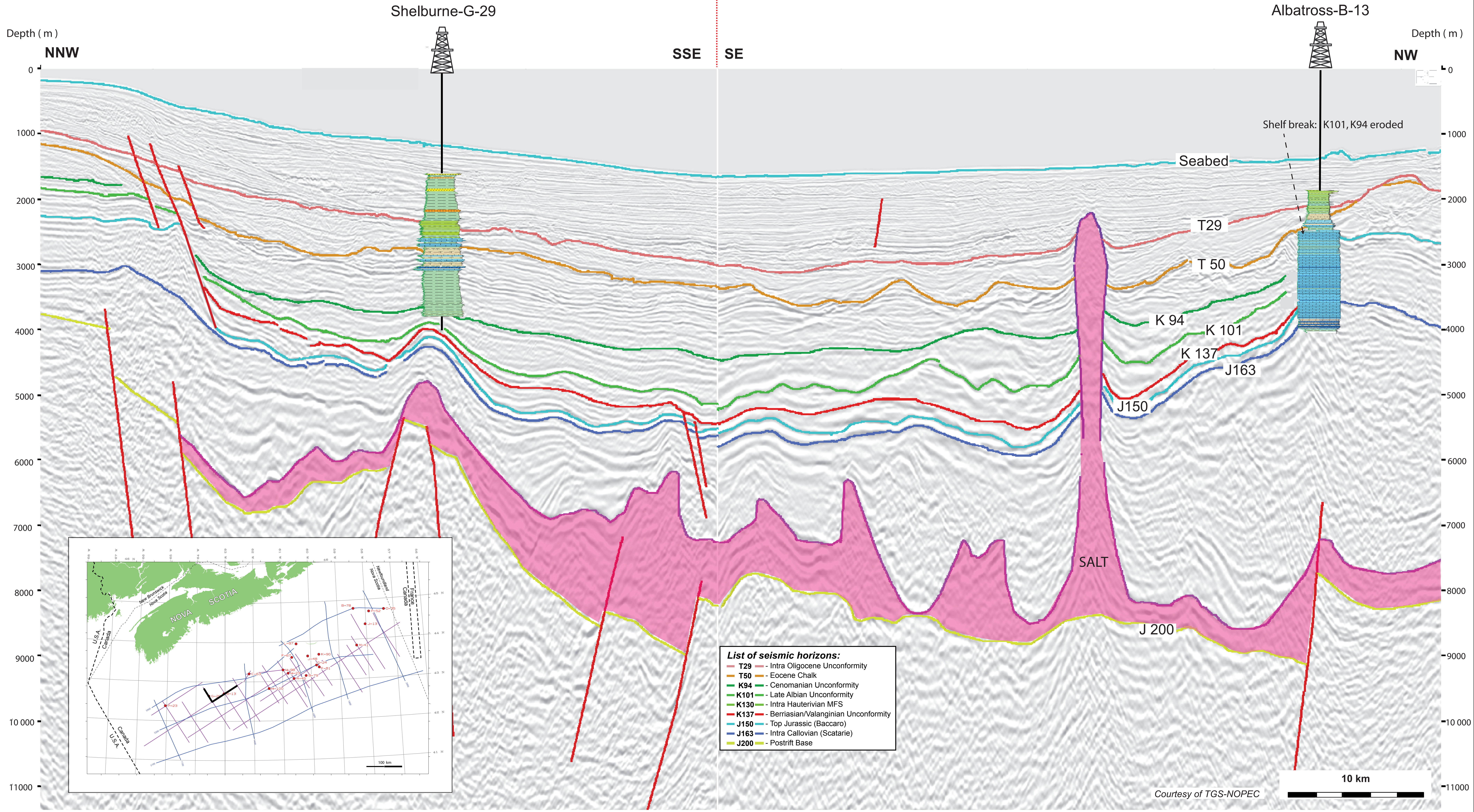


Further East (this Plate), the Late Jurassic deltaic complex of the Mic Mac Formation interfringes as a lateral equivalent of the carbonate platform and is best developed between South Griffin J-13 and Hesper P-52. Above the Tithonian MFS, the Sable Delta complex (Missisauga) thins out eastward and is still capped by the Naskapi shale. The Albian-Cenomanian (Logan Canyon Formation) shows again both relatively constant thickness and sand content. It is also capped like on the western shelf by the Late Cretaceous chalk of the Petrel Member and the Wyandot Formations.

Regional Lithostratigraphic Cross-Section 2 - East

PL. 3-5-1b

STRATIGRAPHY - GEOLOGICAL CROSS-SECTION

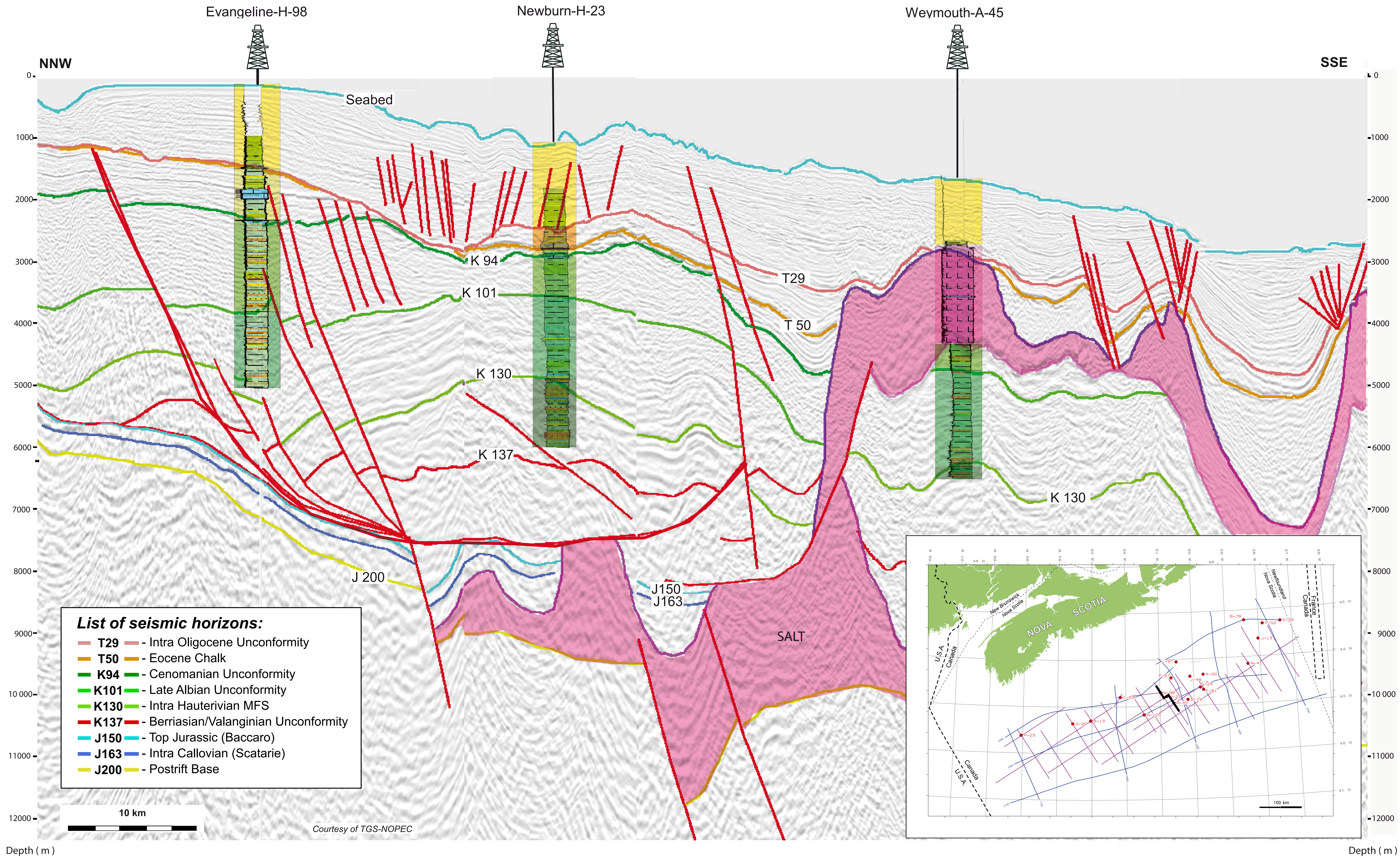


This architectural cross-section illustrates the slope area of the southwestern Scotian margin (LaHave Platform). The deepest part of the cross-section shows the major structural components of the Salt Basin identified above the break-up unconformity (J200 seismic horizon). Autochthonous salt was deposited in an extensional basin limited by major basement faults rooted in the continental crust. Salt deposits encompassed deformation due to sedimentary loading of the up to 4-km-thick Early to Middle Jurassic sediments, which have not been penetrated by wells (between top of salt and J163 seismic horizon). Above top Middle Jurassic (J-163 seismic horizon), the section is along strike the 1-km-thick Late Jurassic shallow-marine carbonate platform, which is penetrated at Albatross B-13 (J163 to K-137 seismic horizons). Beyond the steep margin, shallow-water carbonates pass abruptly into thin deep-water facies found close to Shelburne G-29 TD. Above the carbonates, Cretaceous deposits (K-137 to T50 seismic horizons) are dominated by thick basinal shales (Shelburne G-29), while thinner outer shelf deposits are preserved on the shelf. The T50 seismic horizon outlines the Eocene unconformity, which erodes the Cretaceous shelf margin deposits (slope failure). Above, the Oligocene unconformity (T29 seismic horizon) eroded part of the Eocene to Early Oligocene sediments, leaving a much preserved series on the slope compared to the shelf, where nearly all the sediments were removed. The unconformity surface is capped by a 1-km-thick series of outer shelf to slope siliciclastics deposited during Neogene.

Architectural Cross-Section Dip Shelburne G-29 - Albatross B-13 on Bible Lines 352, 408-100

STRATIGRAPHY - GEOLOGICAL CROSS-SECTION

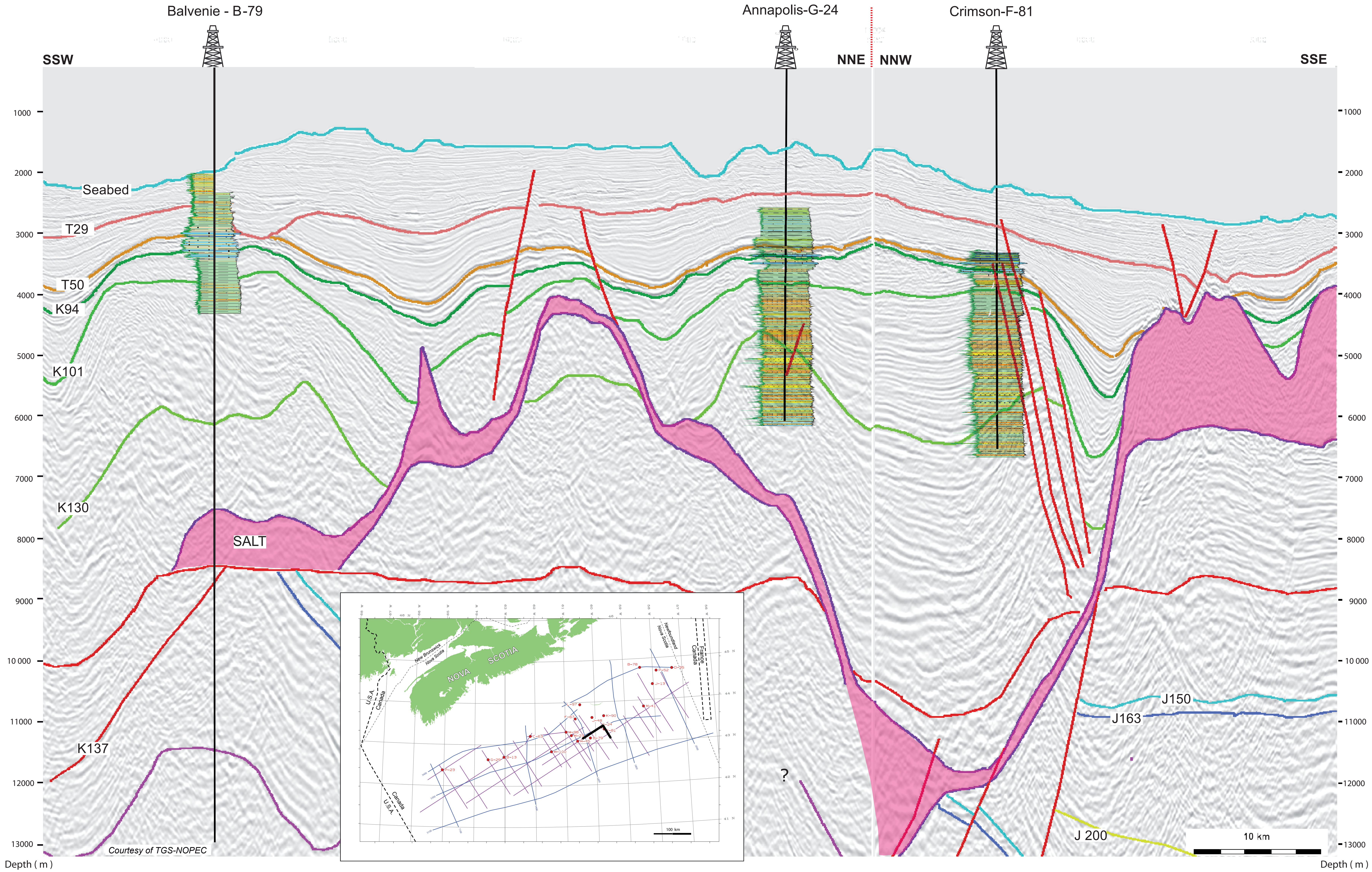
PLAY FAIRWAY ANALYSIS - OFFSHORE NOVA SCOTIA - CANADA - June 2011



This NNW-SSE Bible line about 100km long crosses the central part of the Nova Scotia Basin in a dip direction from the shelf hinge (EvangelineH-98), south of the Moheida ridge through the deep offshore basin (Weymouth A-45).
Listric major faults, associated roll over and antithetic tilted blocks are prominent structural features along the northwestern segment (Evangeline area). The salt tectonics creates pronounced diapir structures between which Jurassic to Cretaceous series (J163- J150) were preserved as observed at the vertical of Newburn area. Southward, over the Weymouth area, the salt canopy province developed and disrupted the Cretaceous – Tertiary deposits.
For the Geo-tectonic environment, see also : Major Tectonic Elements of the Scotian Basin (PL. 1-1b) and J 163 Depth Structure Map (PL. 5-3-11b)

Architectural Cross-Section Dip Tied to Wells on Bible Lines 644, 245, 660-10

STRATIGRAPHY - GEOLOGICAL CROSS-SECTION



This Bible line montage is tied to the Balvenie-B-79, Annapolis G-24 and-Crimson F-81 wells over a length of about 100 km presenting strike and dip sections. The deep and thick Jurassic-Cretaceous Basin (Annapolis sub-basin) whose Jurassic base is estimated at about 13000m deep (J200) developed in front of the Alma ridge. These deepwater wells (near 2000m sea bottom) penetrated the Early Cretaceous Valanginian/Hauterivian Verrill Canyon (distal equivalent of the Middle Missisauga) and the Upper Cretaceous Shortland shales formations (distal equivalent of the Logan Canyon) described as a thick uniform shaly series (highlighted by a uniform seismic facies) with repeated sand/silt thin intervals, some of them gas bearing. The Upper most Cretaceous to Lower Tertiary (Cenomanian – Eocene) shows alternating marls, shales and chalk (Wyandot, Ypresian Formations) presenting well differentiated seismic horizons. Balvenie is the deepest well ever drilled in the Nova Scotia Basin with TD at 6670m.

The salt canopies widely present invades the full sedimentary.

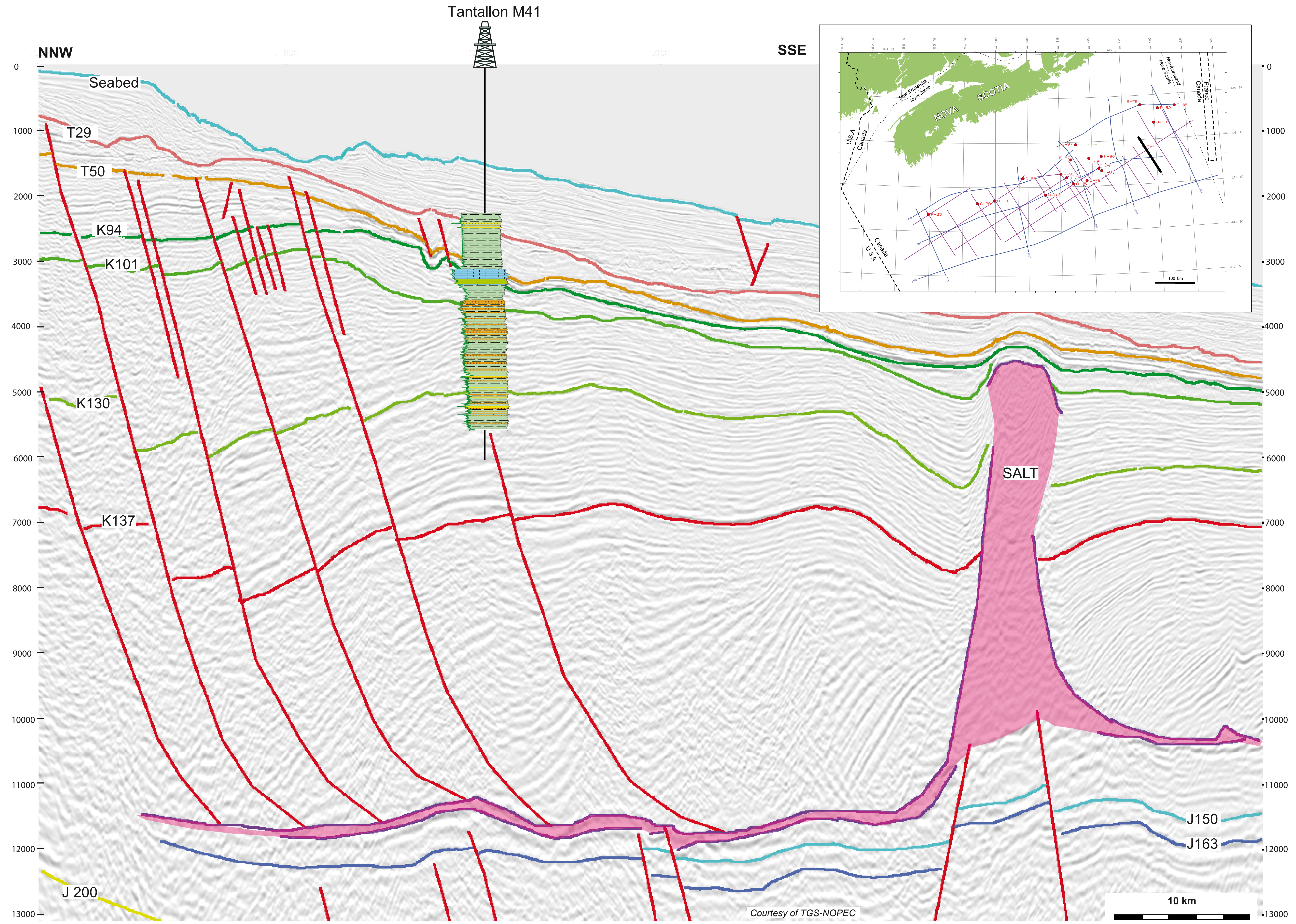
It is observed that fault density and activity is less important in the deep basin than on the margin or the shelf break.

For the Geo-tectonic environment, see also : Major Tectonic Elements of the Scotian Basin (PL. 1-1b) and J 163 Depth Structure Map (PL. 5-3-11b)

Architectural Cross-Section Dip Tied to Wells on Bible Lines 716, 764-100

STRATIGRAPHY - GEOLOGICAL CROSS-SECTION

PLAY FAIRWAY ANALYSIS - OFFSHORE NOVA SCOTIA - CANADA - June 2011



This Bible line montage is tied to the Balvenie-B-79, Annapolis G-24 and-Crimson F-81 wells over a length of about 100 km presenting strike and dip sections. The deep and thick Jurassic-Cretaceous Basin (Annapolis sub-basin) whose Jurassic base is estimated at about 13000m deep (J200) developed in front of the Alma ridge. These deepwater wells (near 2000m sea bottom) penetrated the Early Cretaceous Valanginian/Hauterivian Verrill Canyon (distal equivalent of the Middle Missisauga) and the Upper Cretaceous Shortland shales formations (distal equivalent of the Logan Canyon) described as a thick uniform shaly series (highlighted by a uniform seismic facies) with repeated sand/silt thin intervals, some of them gas bearing. The Upper most Cretaceous to Lower Tertiary (Cenomanian – Eocene) shows alternating marls, shales and chalk (Wyandot, Ypresian Formations) presenting well differentiated seismic horizons. Balvenie is the deepest well ever drilled in the Nova Scotia Basin with TD at 6670m.
The salt canopies widely present invades the full sedimentary.
It is observed that fault density and activity is less important in the deep basin than on the margin or the shelf break.
For the Geo-tectonic environment, see also : Major Tectonic Elements of the Scotian Basin (PL. 1-1b) and J 163 Depth Structure Map (PL. 5-3-11b)

Architectural Cross-Section Dip Tantallon M-41 on Bible Line 924-100