

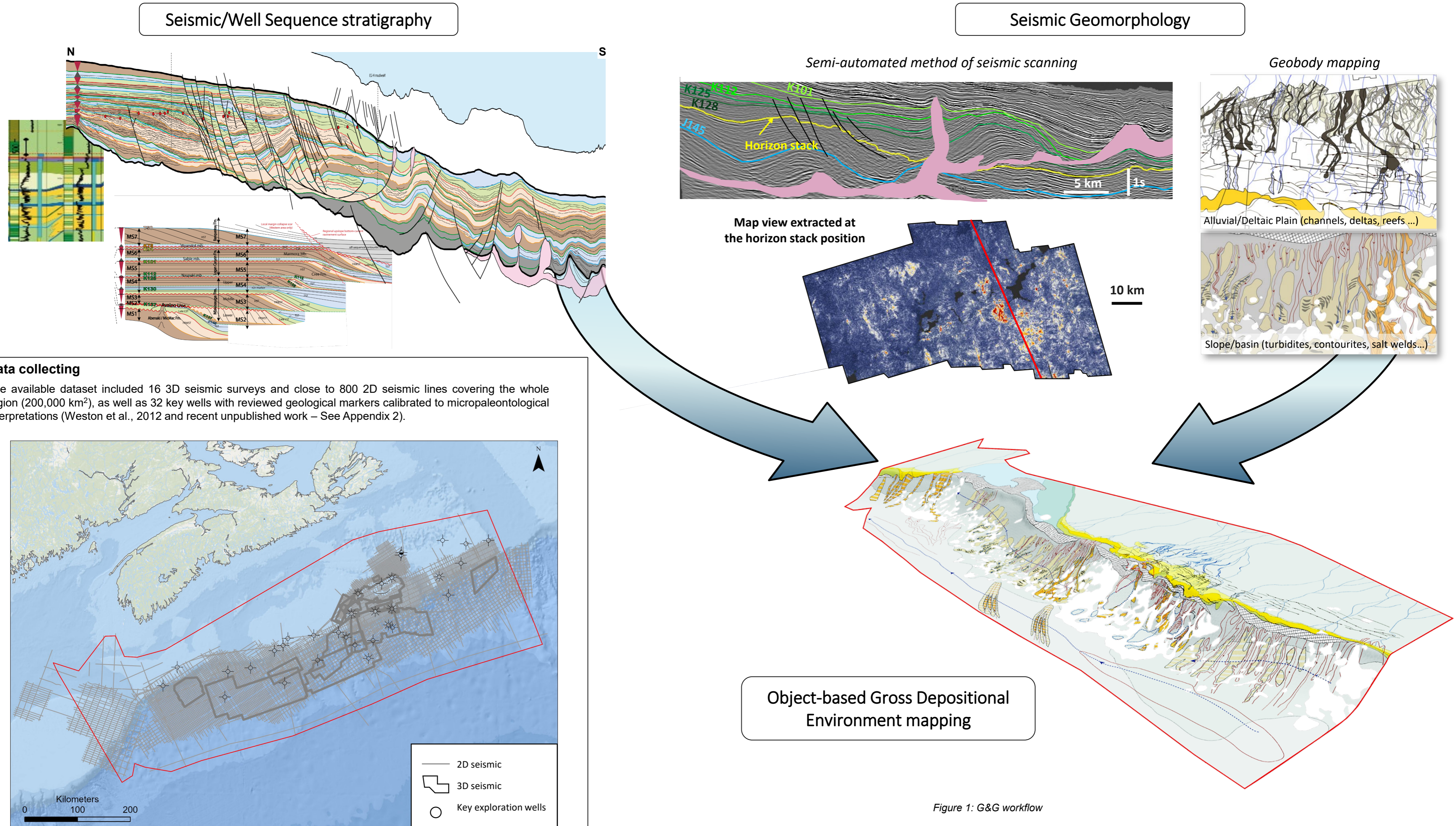
**CHAPTER 3**  
**GEOLOGY & GEOPHYSICAL ANALYSIS**



## Geology and Geophysical Workflow

In order to provide a sound depositional model and gross depositional mapping of the offshore Nova Scotian region, a Geological & Geophysical workflow combining both sequence stratigraphic and geomorphological analyses was developed. These two workflows consisted of:

- A detailed sequence stratigraphy analysis based on well stacking patterns and on the seismic stratal geometries.
- Coupling of sequence stratigraphy with the geomorphological approach, using 2D and 3D seismic, and in this case, with the help of semi-automated seismic scanning (*Paleoscan™*). This analysis led to the mapping of the seismic geobodies with unprecedented precision, from the shelf to the basin and in a constrained stratigraphic framework.

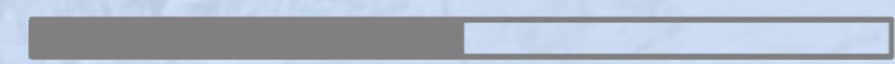




# CHAPTER 3.1 SEQUENCE STRATIGRAPHY

Kilometers

0 100 200



## Objectives

This study aimed at integrating information from observed geometries in seismic with well information to improve the chronostratigraphic framework of the offshore Nova Scotian margin. This involved the combination of various geological and geophysical methodologies, integrating seismic sequence stratigraphic and seismic geomorphological analysis with well stacking patterns and biostratigraphic analysis.

This workflow lead initially to the update of the chronostratigraphic chart, focusing on the system tracts, which are the building blocks of the sedimentary architecture of the basin. Understanding the spatial organization of such elements is key to predicting reservoir presence and efficiency at various scales.

The proposed sequence breakdown was then used as a framework for the regional gross depositional environment (GDE) mapping. The seven generated maps are both descriptions of the greater scale depositional environments and object-based, focusing on the key reservoir prone geobodies extracted from the seismic database.

## Methodology of Seismic Sequence Stratigraphy Analysis

This methodology follows the stratal unit breakdown developed by Hunt & Tucker (1992), Embry & Johannessen (1992) and revised by Catuneanu *et al.* (2009). The method involved:

1. The picking of successive positions of the offlap break and associated stratal terminations is performed
2. Picking the key stratigraphic surfaces (ie. Maximum Flooding Surface, Basal Surface of Forced Regression, Maximum Forced Regressive Surface and Transgressive Surface are assigned ,
3. Picking the regional systems tracts bounded by those horizons
4. Assigning ages to the successive sequences using well biostratigraphic data

The workflow was performed on five key representative sections alongside the depositional profile.

The correlation between each section lead to the definition of megasequences with regional expression, with each megasequence reflecting a unique prograding-retrograding regional trend. The amplitude of such T/R cycle varies laterally with respect to the balance between accommodation and sedimentary flux.

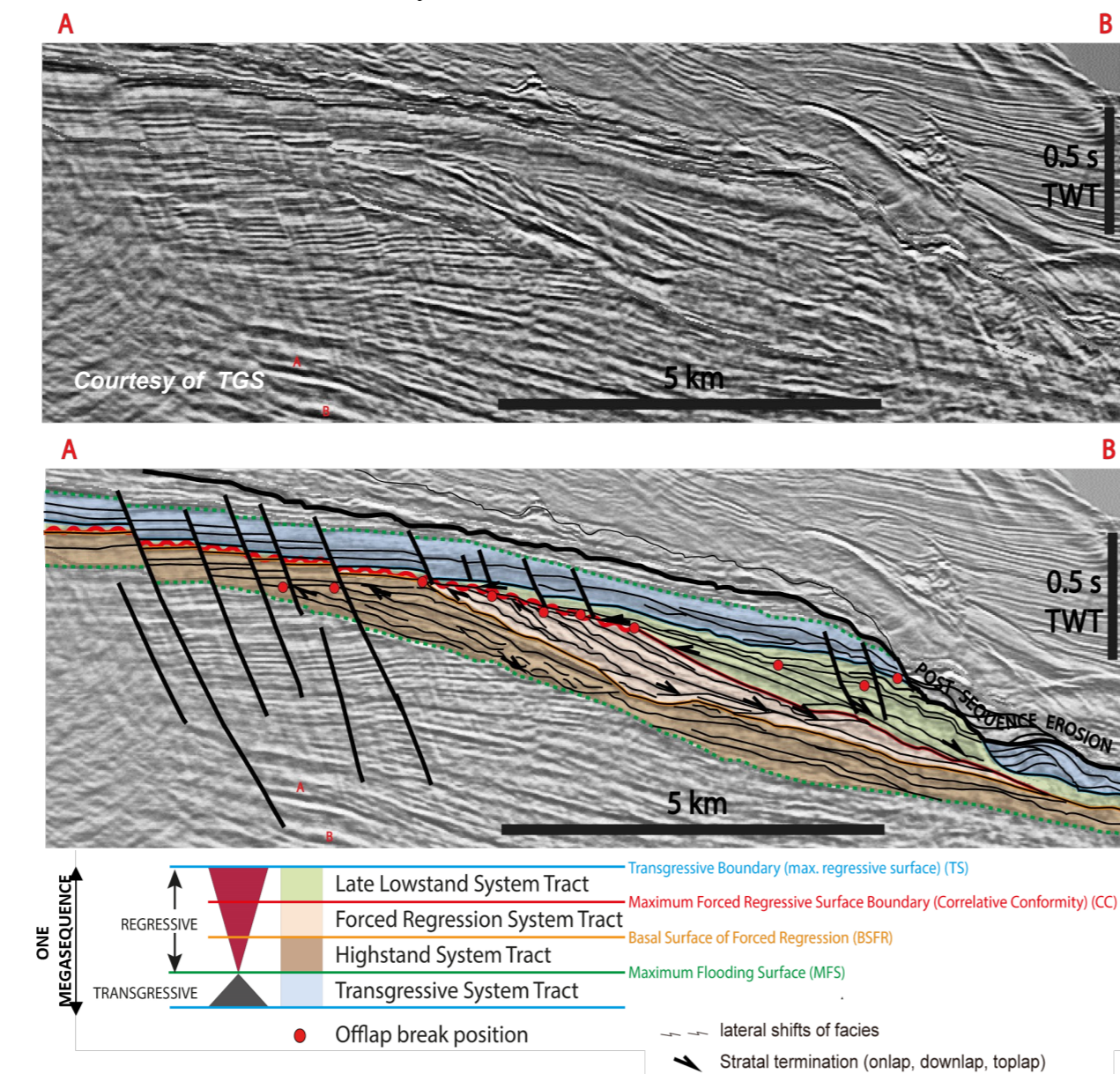
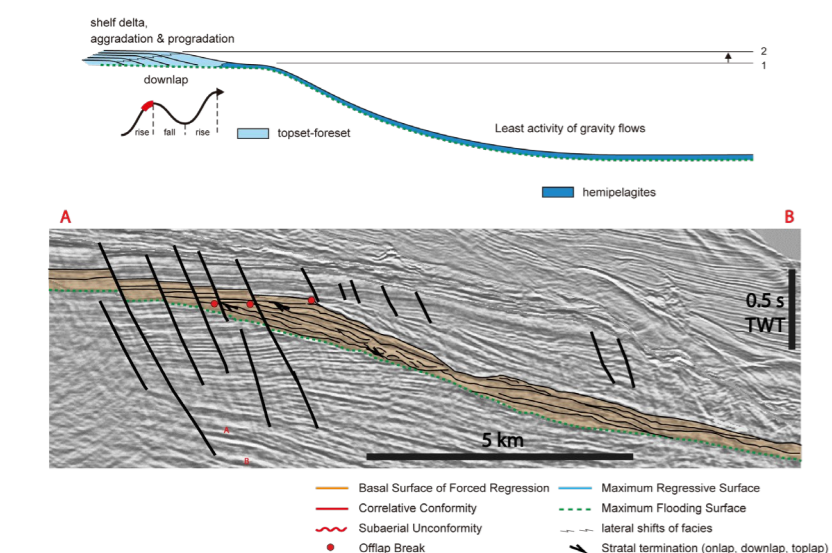
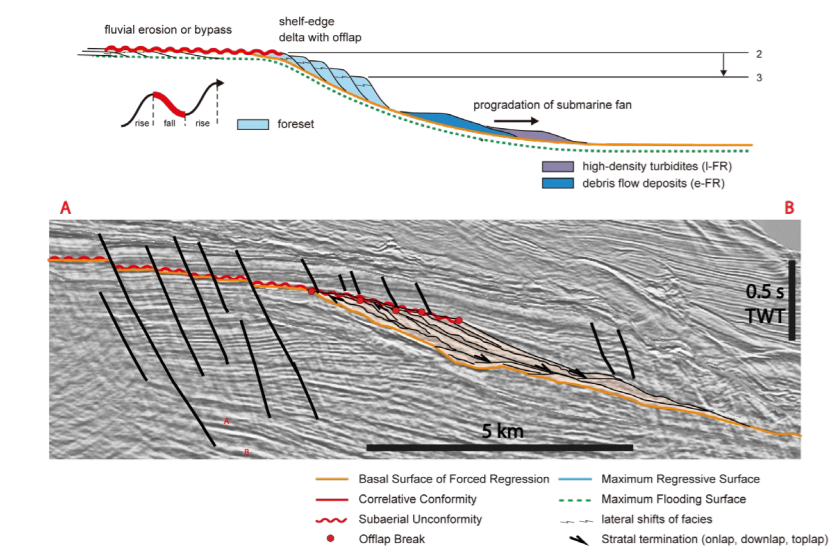


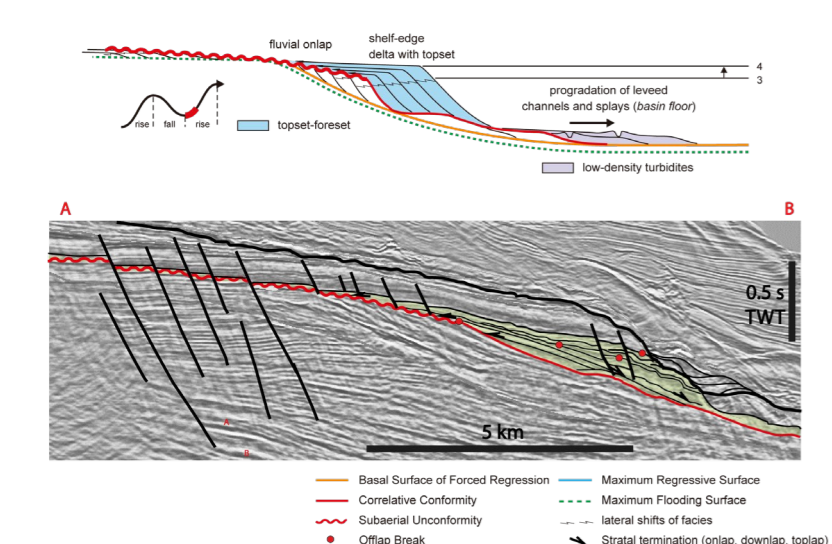
Figure 2: Seismic sequence stratigraphy method (extracted from TGS 916-100)



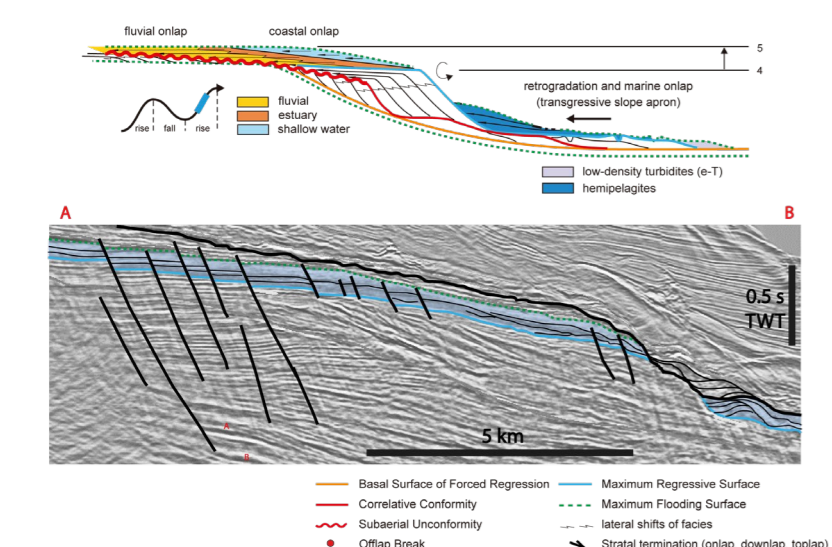
Highstand System Tract: low rate progradation and aggradation (base-level rise at the shoreline and normal regression)



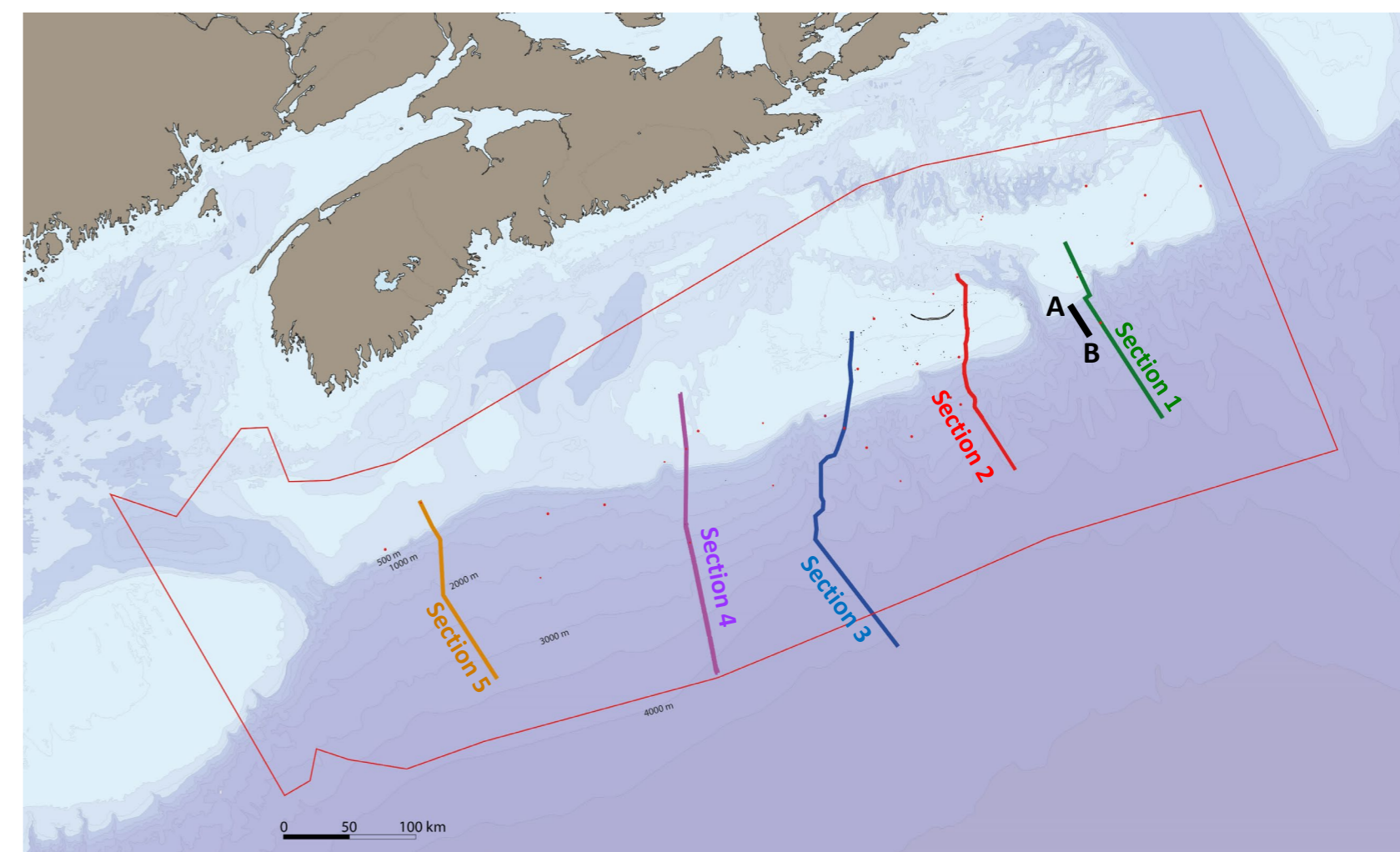
Falling Stage System Tract: high rate progradation and offlap (base-level fall at the shoreline and forced regression)



Late Lowstand System Tract: low rate progradation and aggradation (base-level rise at the shoreline and normal regression)



Transgressive System Tract: retrogradation and aggradation (base-level rise at the shoreline and transgression)



← SSE

NNW →

Studied interval (J160-T50)

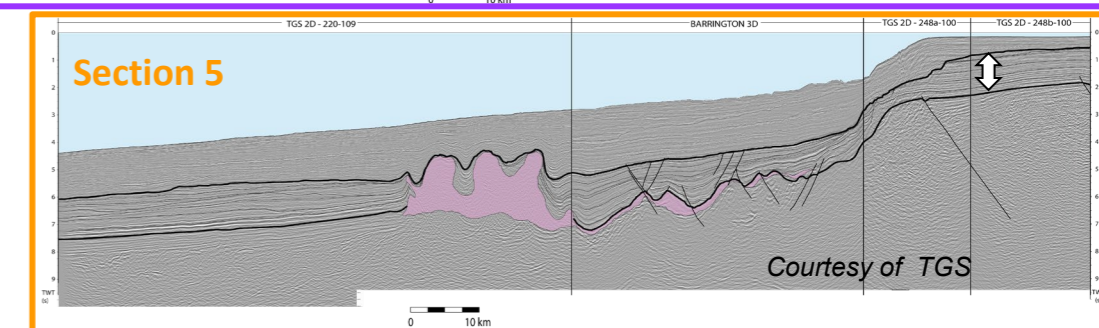
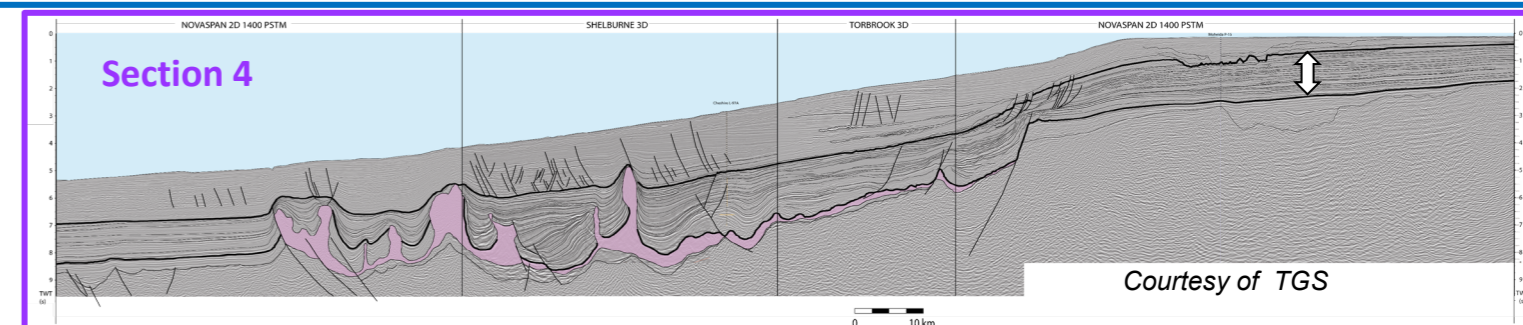
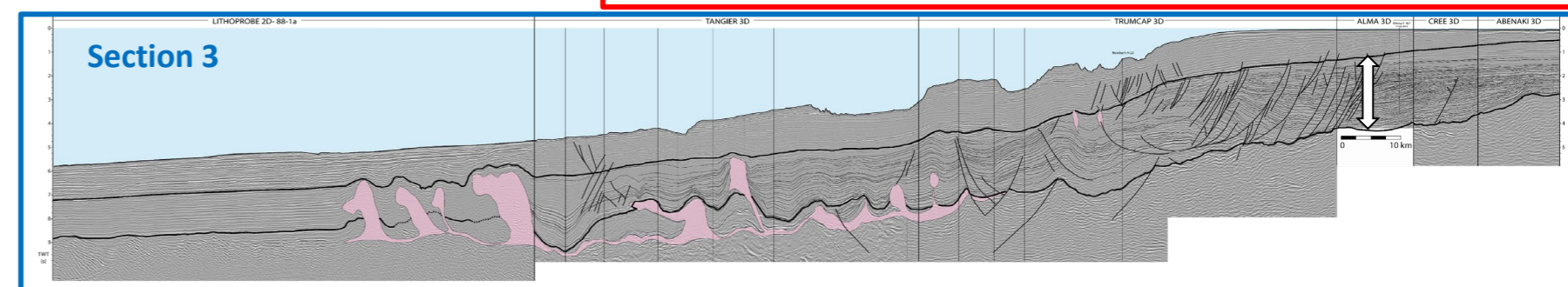
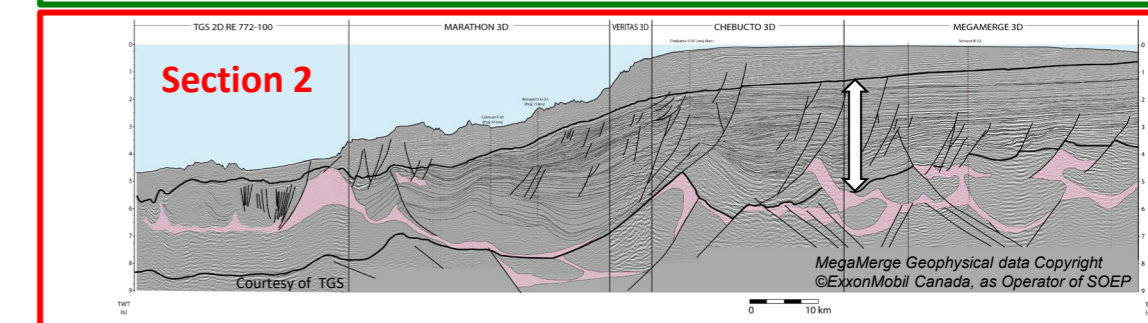
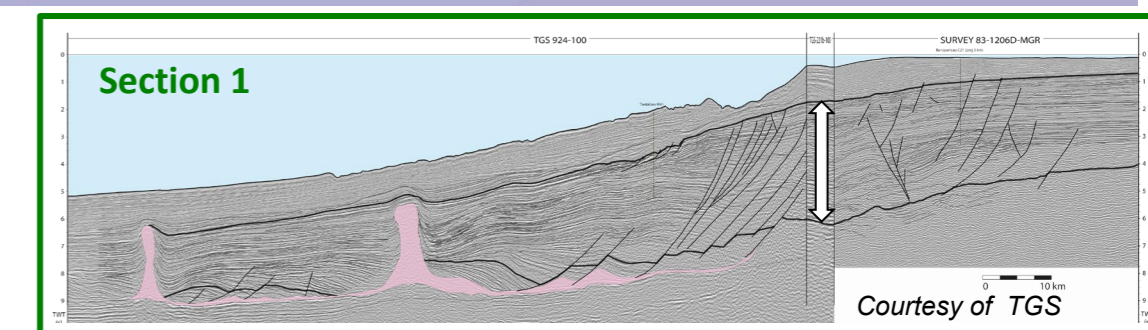


Figure 3: Selected dip-oriented regional sections (see next slide for details on seismic surveys)

## Section 1 – Eastern Banquereau area

This section goes through the Banquereau margin and displays the typical chronostratigraphic succession of the Eastern Sable Subbasin. The deepest part shows the autochthonous salt that started to be deformed during the Jurassic, leading to the creation of the Banquereau Synkinematic Wedge, affecting mainly the slope downstream of the Mic Mac delta. The significant clastic sediment loading during the Upper Jurassic lead to the formation of successive rollover and turtleback structures following a salt gravity gliding process. Such intense deformation persists until the Jurassic/Cretaceous transition, and then drastically diminishes during the Lower Cretaceous, with deformation limited to proximal normal faults with limited offsets, and distal isolated salt diapirs.

The sedimentation rate on the slope remains high until the Lower Aptian (Upper Missisauga) in this region, suggesting that a significant river system is feeding the basin toward the lowermost part of the Cretaceous. This observation is re-enforced by the system tract breakdown that shows thick successions of forced regressive wedges connected with significantly thick lowstand fans (MS1 to MS4).

Sediment distribution changes during the Albian and Cenomanian with less sediment transfer to the deep basin and more aggrading highstand system tract deposits on the shelf. This system is then sealed on the shelf by retrograding Upper Cretaceous deposits, while the slope is dominated by bypass conditions.

The end of the stratigraphic succession is characterized by an overall prograding and aggrading system in the Eocene.

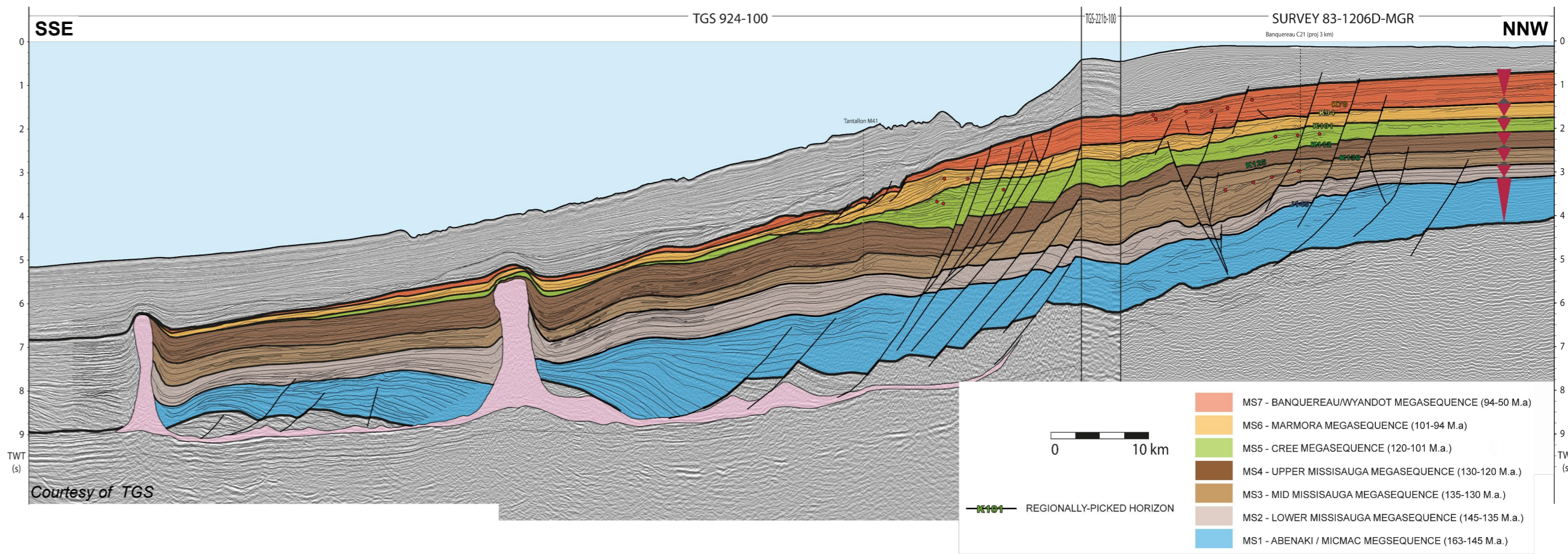
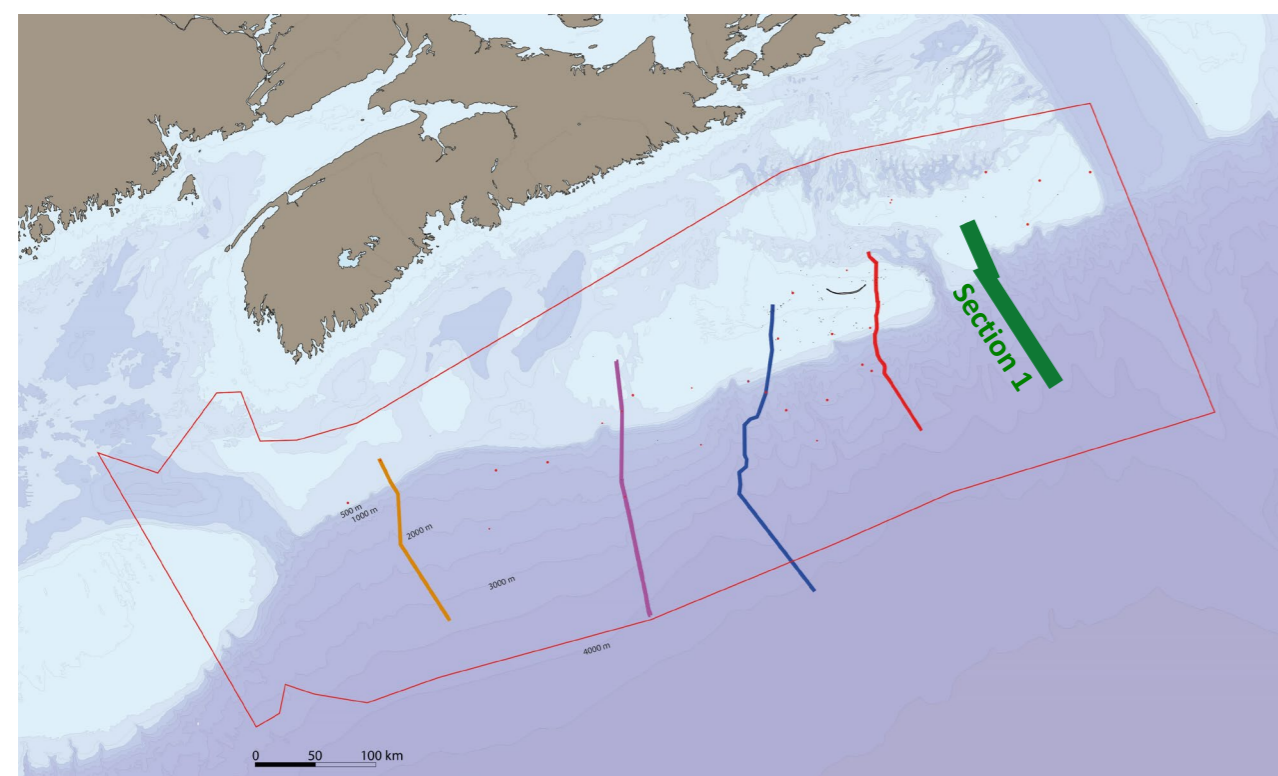
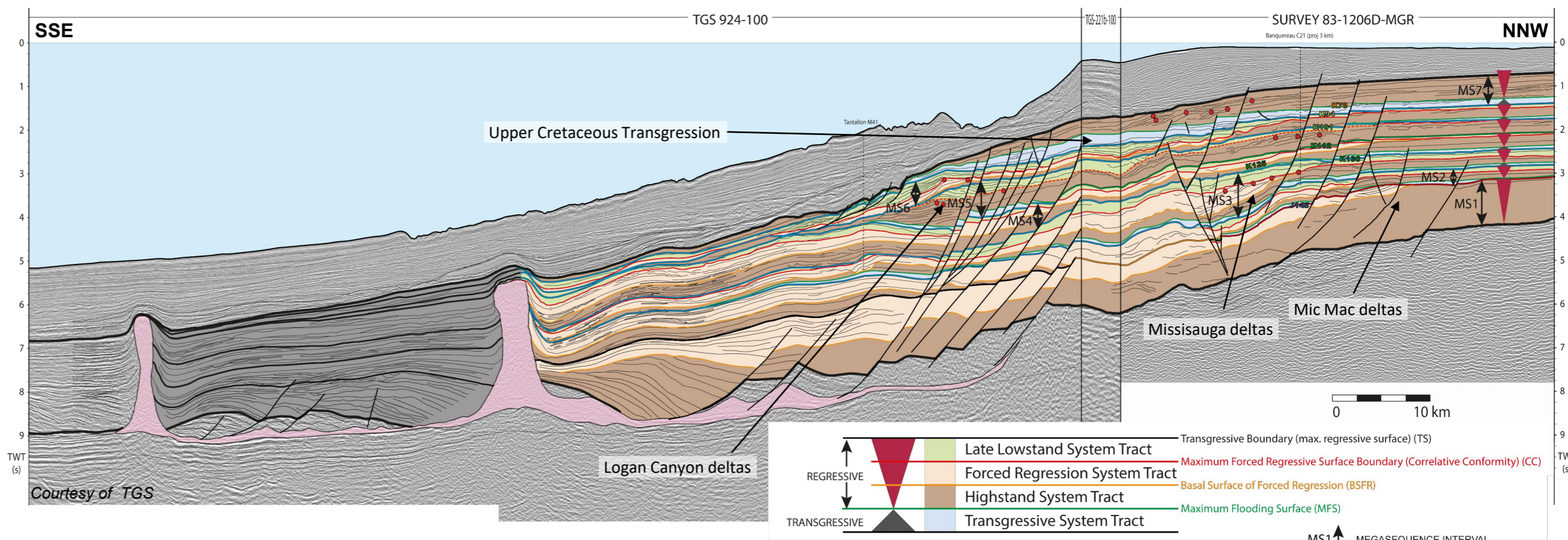
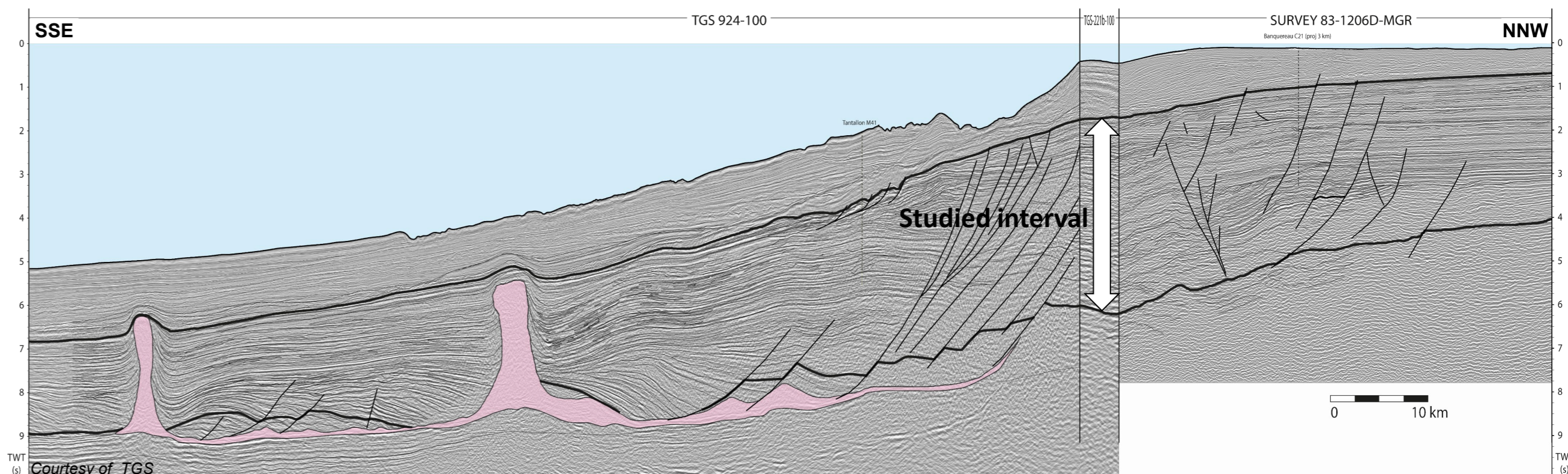


Figure 4: Chronostratigraphic views of Section 1 (seismic extracted from TGS 2D survey & 8620-S014-006E)

# Sequence Stratigraphy

Offshore Nova Scotia Velocity Modeling – CANADA – January 2022

## Section 2 – Central/Eastern Sable area

This section is going through the central Sable Subbasin region and displays the typical settings of a structurally complex area with polyphasic salt deformation events affecting the shelf edges and the slope.

The Mic Mac delta and subsequent Missisauga deltas are cut by a succession of normal/listric faults linked with the proximal extension above salt deformation. The progradation continues in the Logan Canyon stratigraphic succession until the Marmora Member with a maximum advance of the delta a few kilometers north of the Annapolis G-24 well.

Beneath the present-day slope, a prominent salt canopy intersects the Megasequence 4, which indicates a strong halokinesis phase during the Barremian/Aptian. Such deformation continues until the Cenozoic, as indicated by complex turtle-back and anticline structures affecting the sediments from the Albian to the Eocene.

The Upper Cenozoic transgression is clear on this section with a significant backstepping of the shoreline.

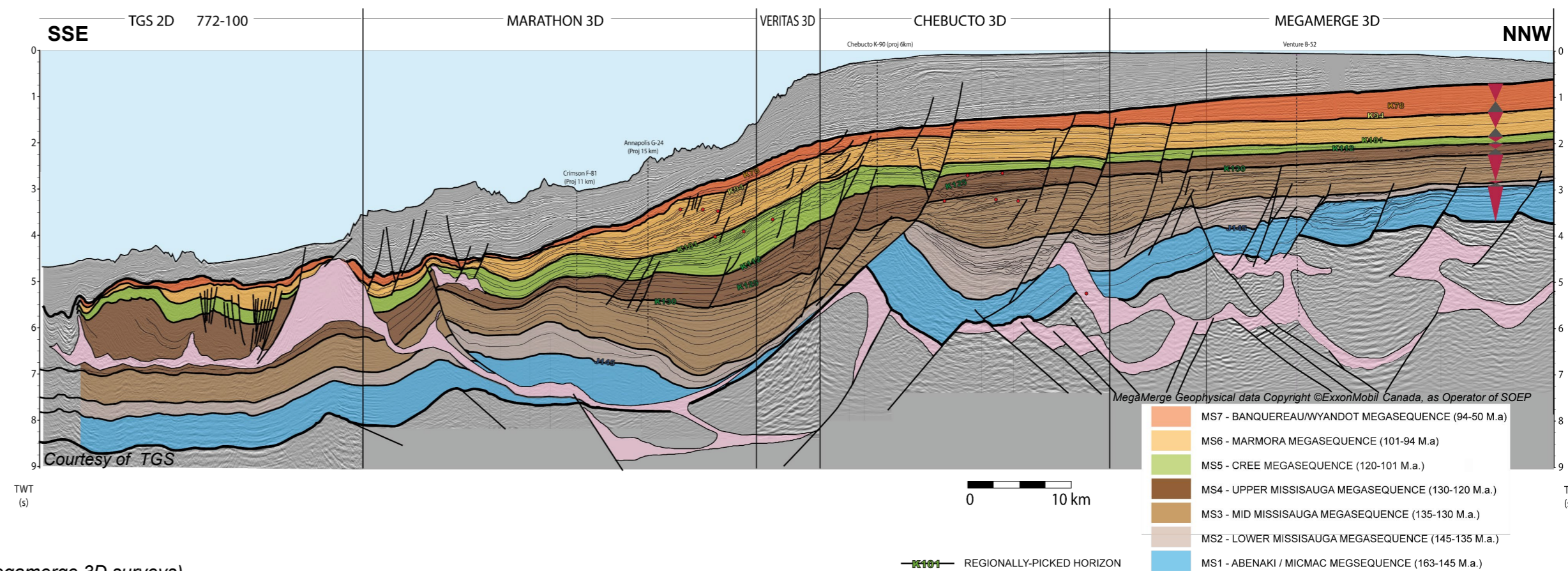
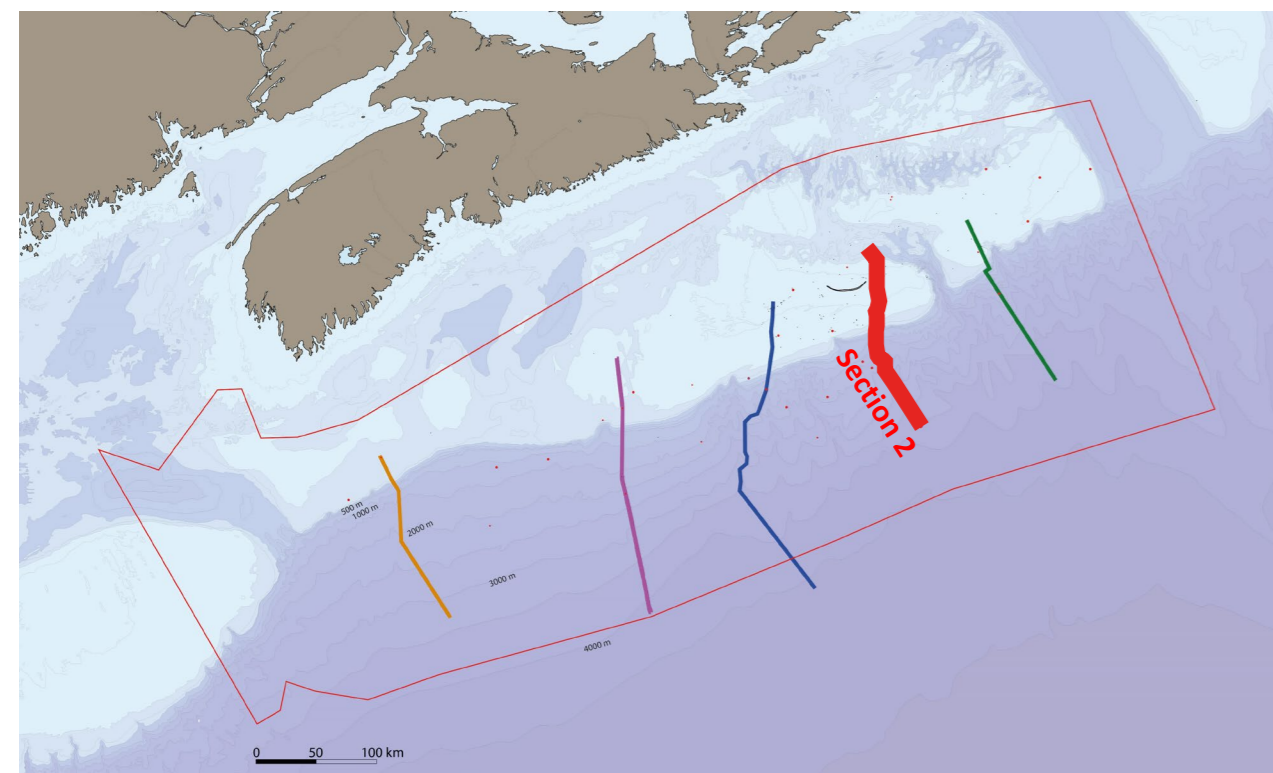
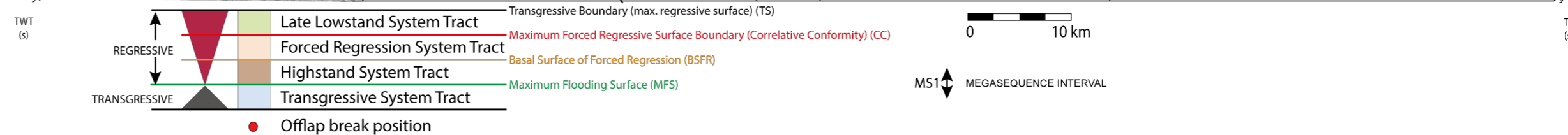
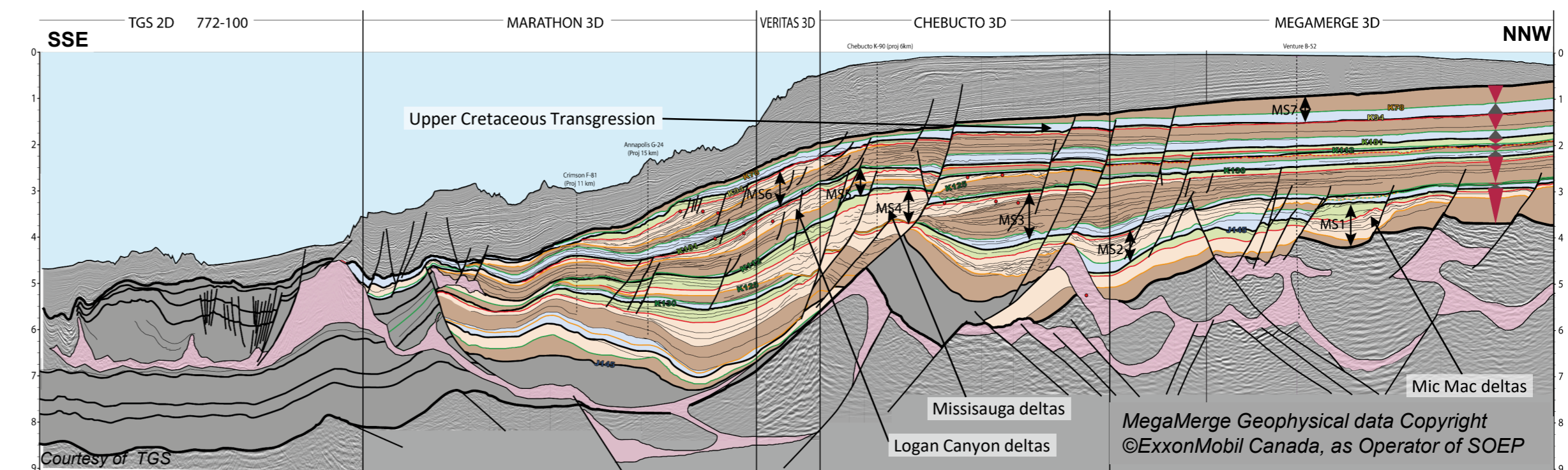
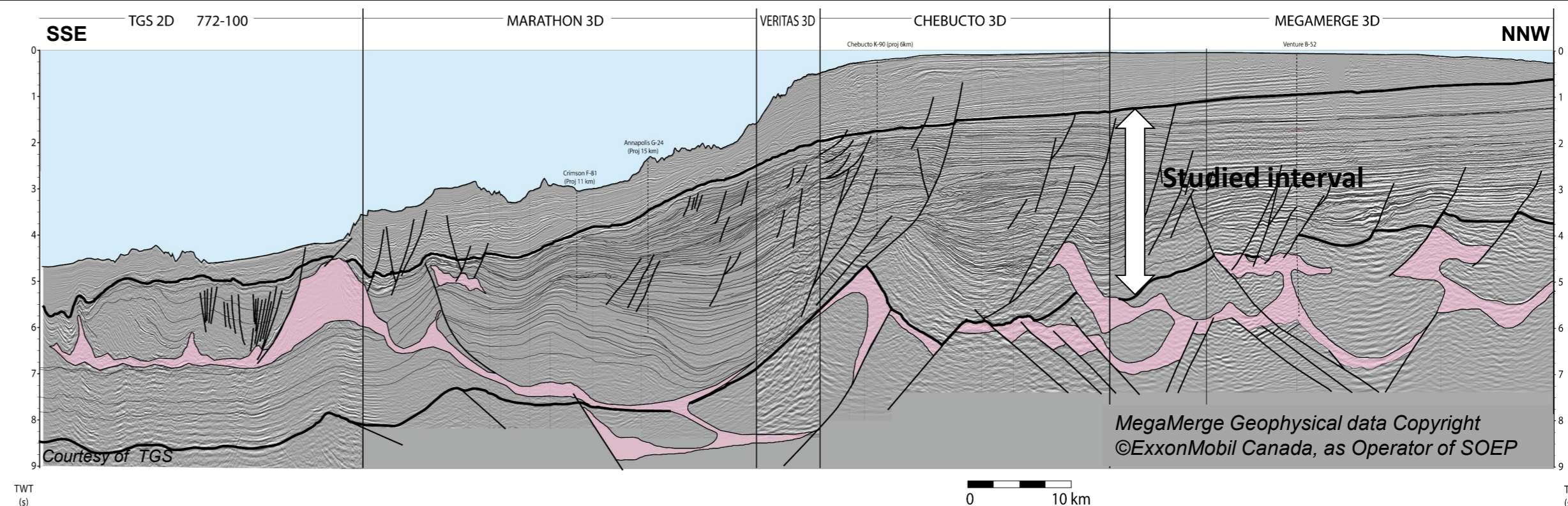
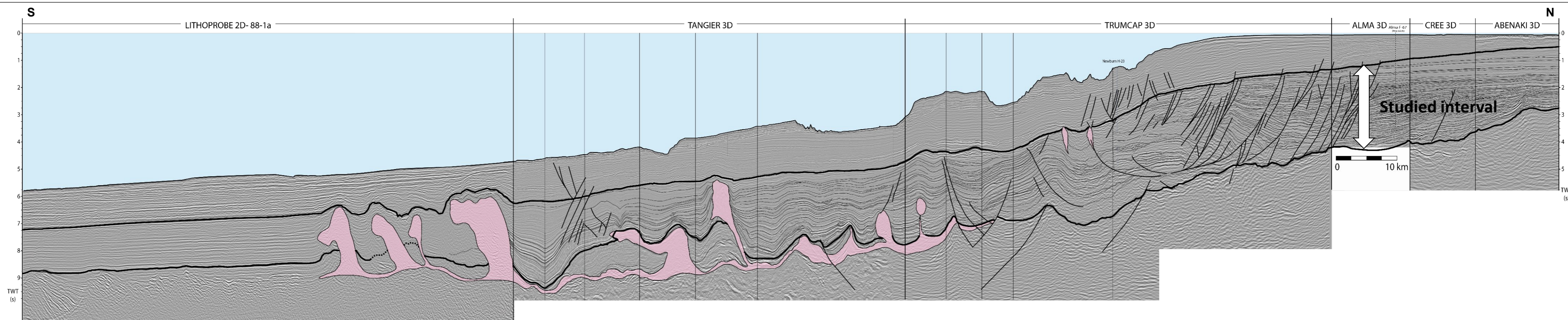


Figure 5: Chronostratigraphic views of Section 2 (seismic extracted from TGS 2D survey & Marathon, Veritas, Chebucto and Megamerge 3D surveys)



### Section 3 – Western Sable region

The central part of the margin (west of Sable region) displays a structurally segmented margin, with an extensional domain to the north and a compressional domain to the south. The successive shelf edges are highly affected by normal/listric faulting, while the basinal domain is cut by autochthonous to para-autochthonous salt diapirs.

The Upper Jurassic sediment thickness decreases to the west. A more significant slope-apron shelf edge, with aggrading sedimentation, is present in the right and side of the section.

The lowermost Cretaceous depositional profile (Berriasian to Lower Aptian) displays a typical shelf deltaic prograding clinoform-shaped configuration with normal progradations alternating with downward shift of the deltaic systems during forced regressive time intervals. This results in the transport of a significant amount of sediments to the basin with a sedimentation rate around 80 m/Myr (locally 2 km of sediments deposited in 20 Myrs).

The end of the Lower Cretaceous interval is characterized by the continuation of the deltaic progradation, until reaching a maximum of advance of the delta front during the Cenomanian (clinoforms are described 70 km North of Newburn H-23 well).

Finally, the whole Upper Cretaceous and Lower Cenozoic are starved with overall transgressive and highstand conditions, and condensed layers observed on the platform.

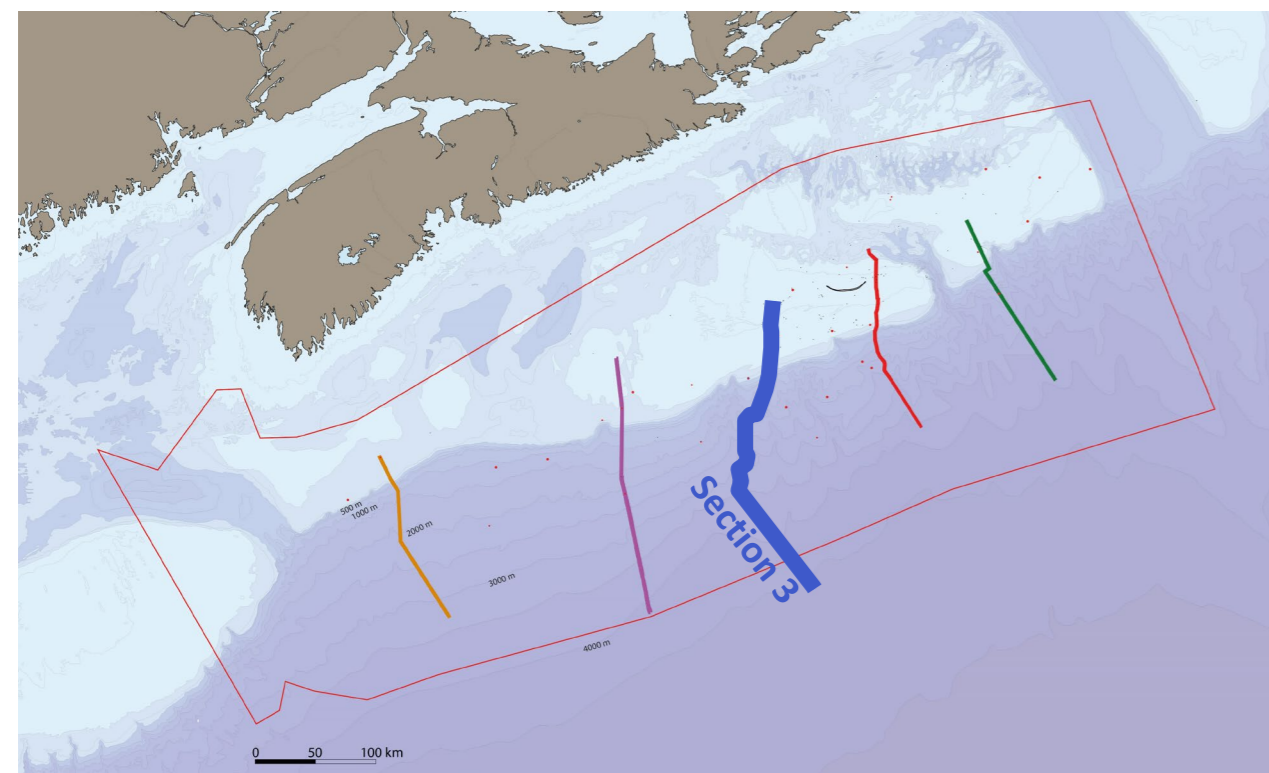
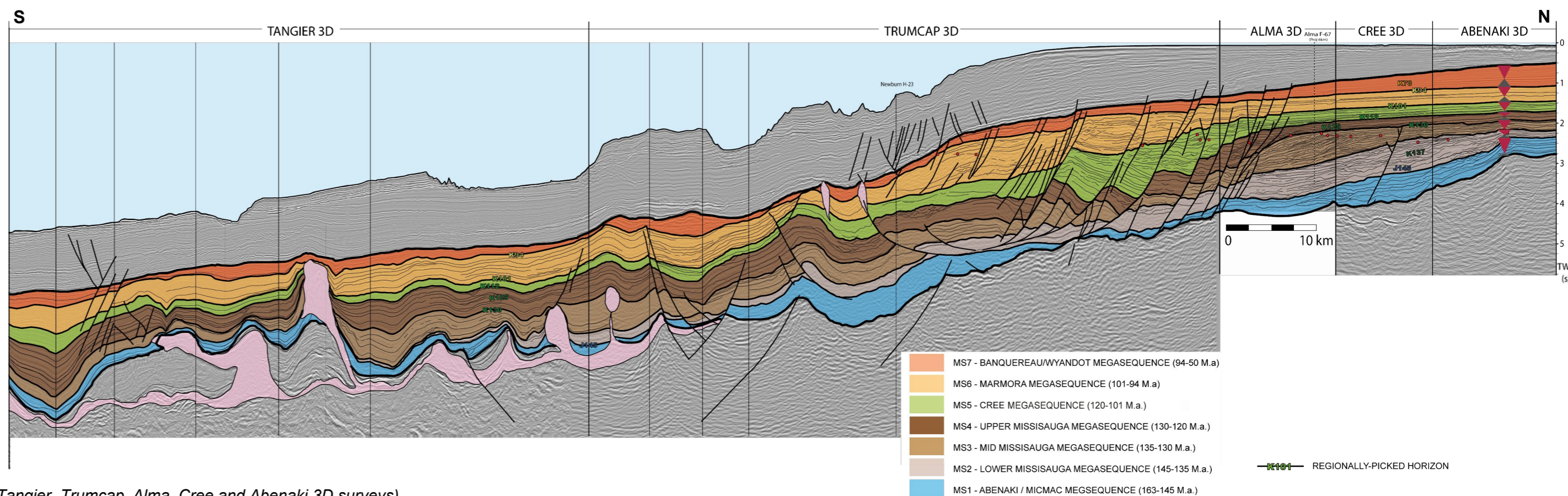
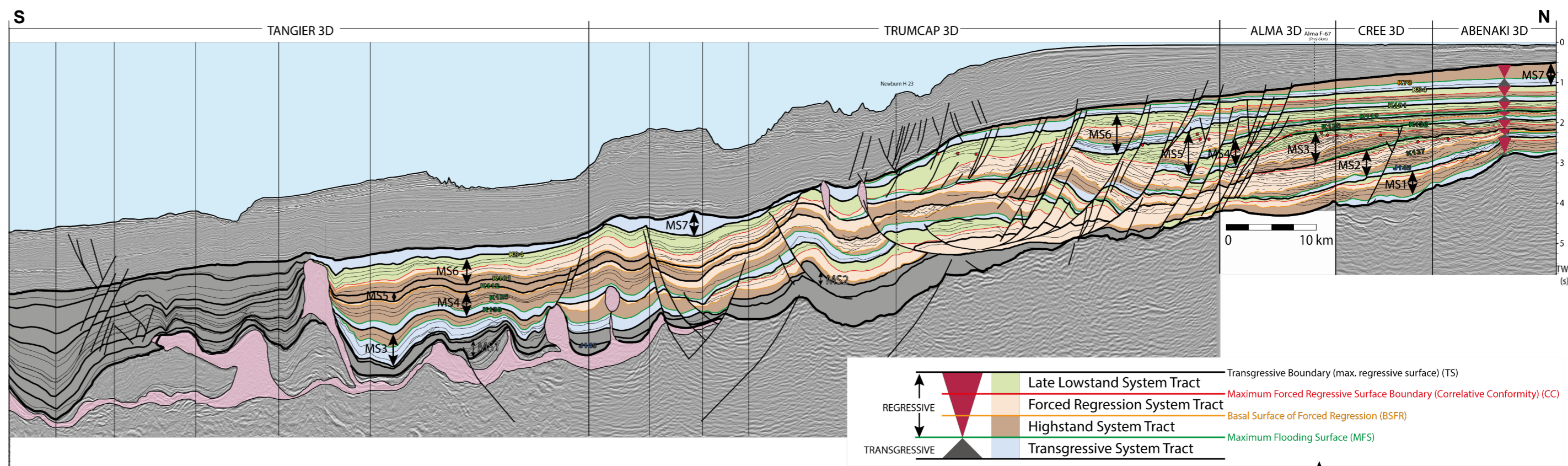
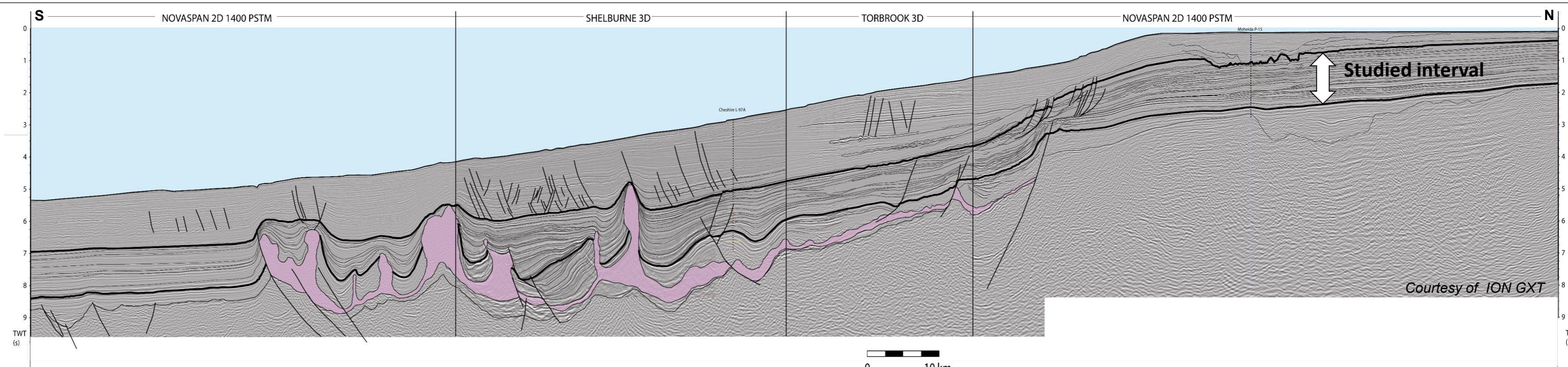


Figure 6: Chronostratigraphic views of Section 3 (seismic extracted from Lithoprobe 2D survey & Tangier, Trumcap, Alma, Cree and Abenaki 3D surveys)

# Sequence Stratigraphy

Offshore Nova Scotia Velocity Modeling – CANADA – January 2022



## Section 4 – Central area / Eastern LaHave Platform

The central Nova Scotian domain displays many different sedimentary successions for the studied stratigraphic interval.

The Upper Jurassic displays a significant slope apron configuration and mostly highstand deposits on the shelf.

Much thinner deposits are then observed during the lowermost Cretaceous with condensed/bypass environment on the shelf and a starved slope.

Renewed deltaic progradation is visible later in the Cenomanian with ramp to low-angle clinoform.

The Upper Cretaceous and Lower Cenozoic is more aggrading with sediments distributed in a homoclinal configuration.

The salt tectonics is mostly active in the lower slope domain with continuous deformation of the Mesozoic and Lower Cenozoic strata by vertical diapirs.

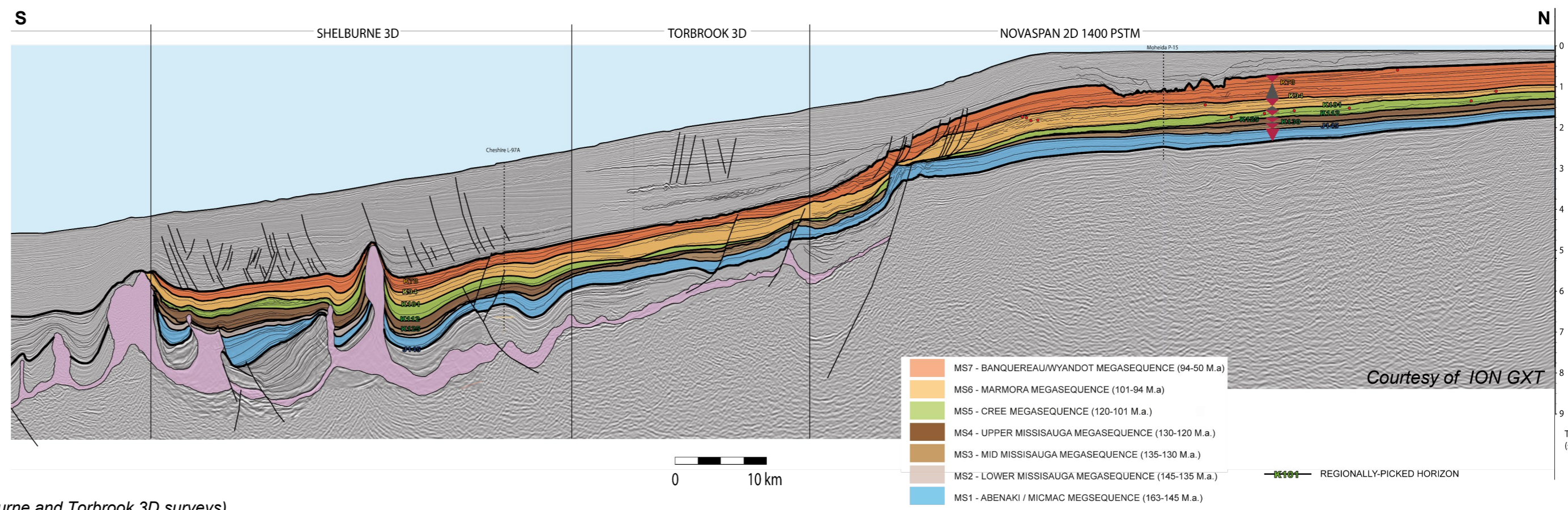
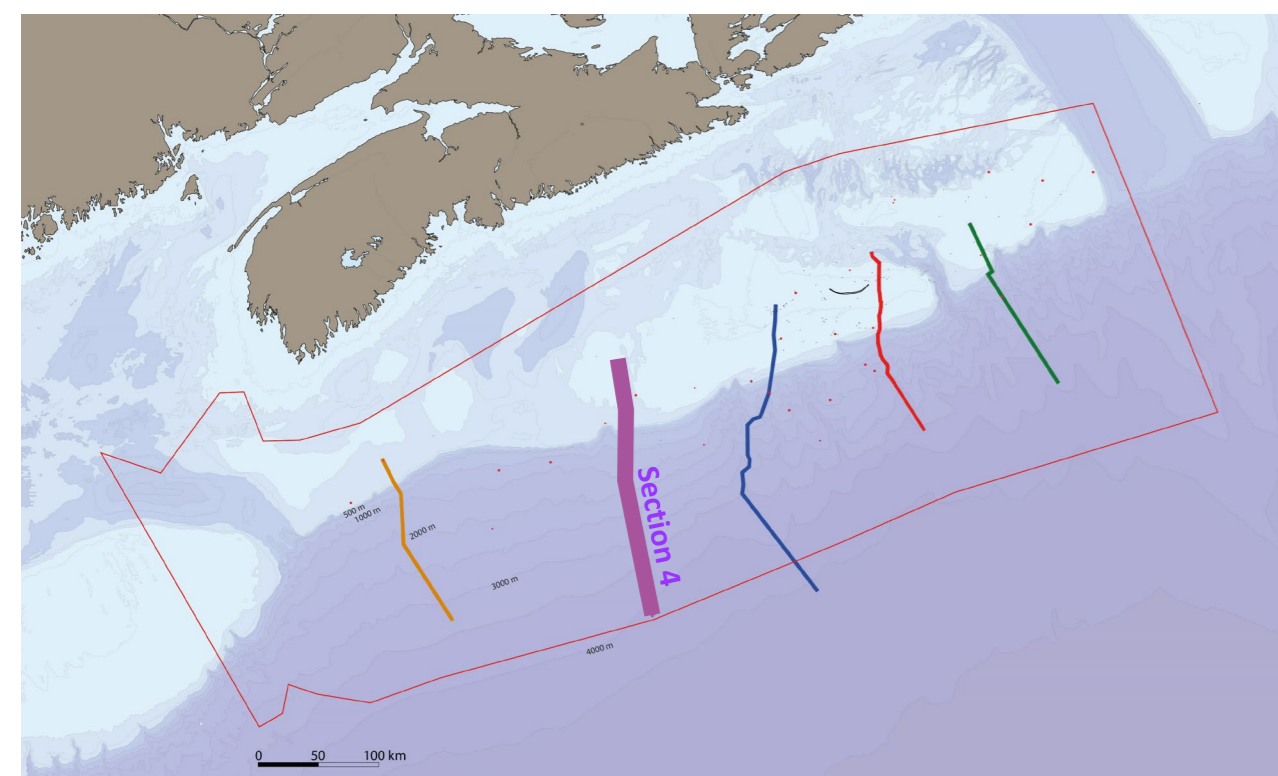
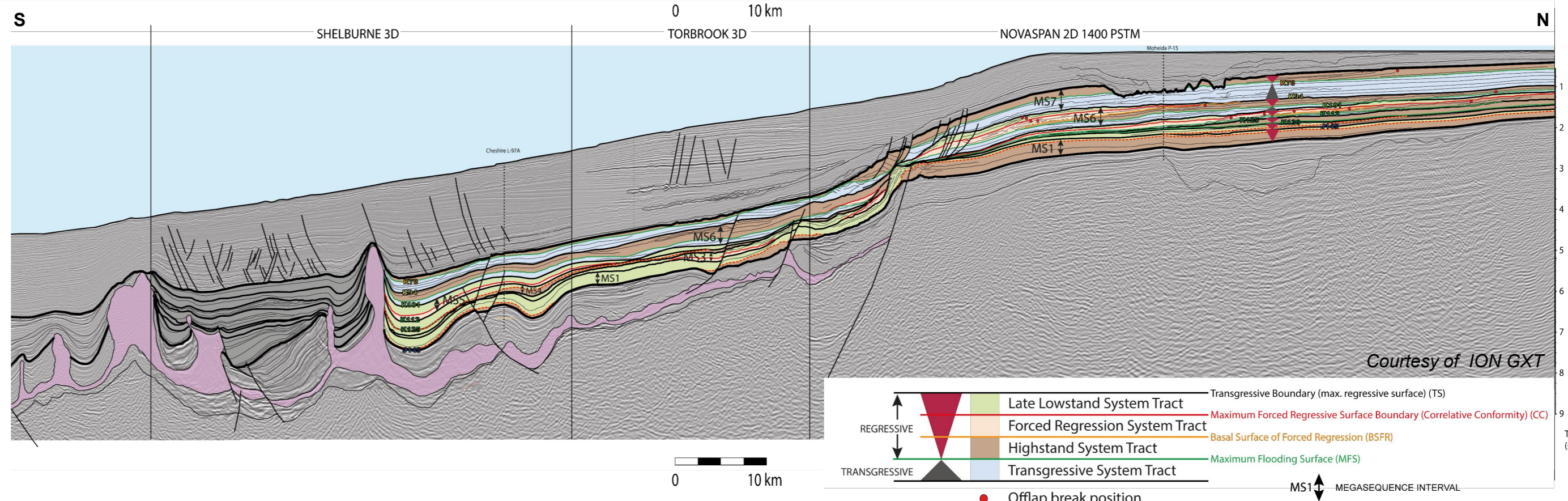


Figure 7: Chronostratigraphic views of Section 4 (seismic extracted from NovaSpan 2D survey & Shelburne and Torbrook 3D surveys)

## Section 5 – Western LaHave Platform

This western regional section crosses the shelf to deep offshore domain along the western LaHave Platform, 50 km to the west of the Montagnais Impact crater. The Upper Jurassic and Cretaceous margin appears starved:

The Upper Jurassic deposits display a tabular platform with slope apron shelf edge and a starved slope.

The Lower Cretaceous is characterized by a condensed interval on the platform with less than 250 m of preserved sediments on the platform, and even less on the slope, for the whole Lower Cretaceous (estimated sedimentation rate below 5m/Myr). The basal part located beyond the salt diapirs displays more important volume of sediments which suggests the hypothesis of lateral sedimentary supply from the western Shelburne delta.

The Upper Cretaceous interval is thicker on the shelf, with mainly aggrading to retrograding sedimentation, which suggests an overall transgressive to highstand configuration during this time interval.

The Lower Cenozoic looks deeply affected by shelf and slope erosion processes, with probable effects of long-term ravinements by contour currents, and short-term catastrophic events such as the nearby Montagnais astrobleme impact dated upper Ypresian (Jansa & Pe-Piper (1987); Deptuck & Campbell (2012)).

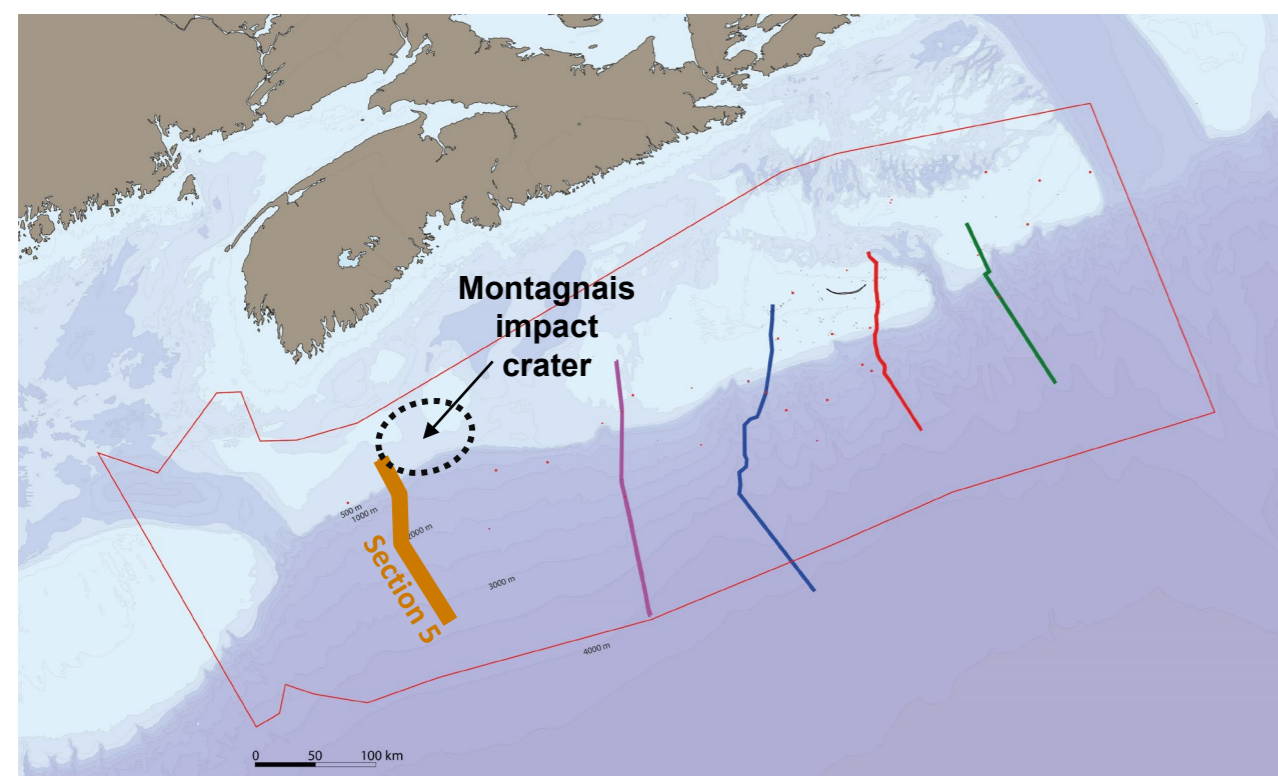
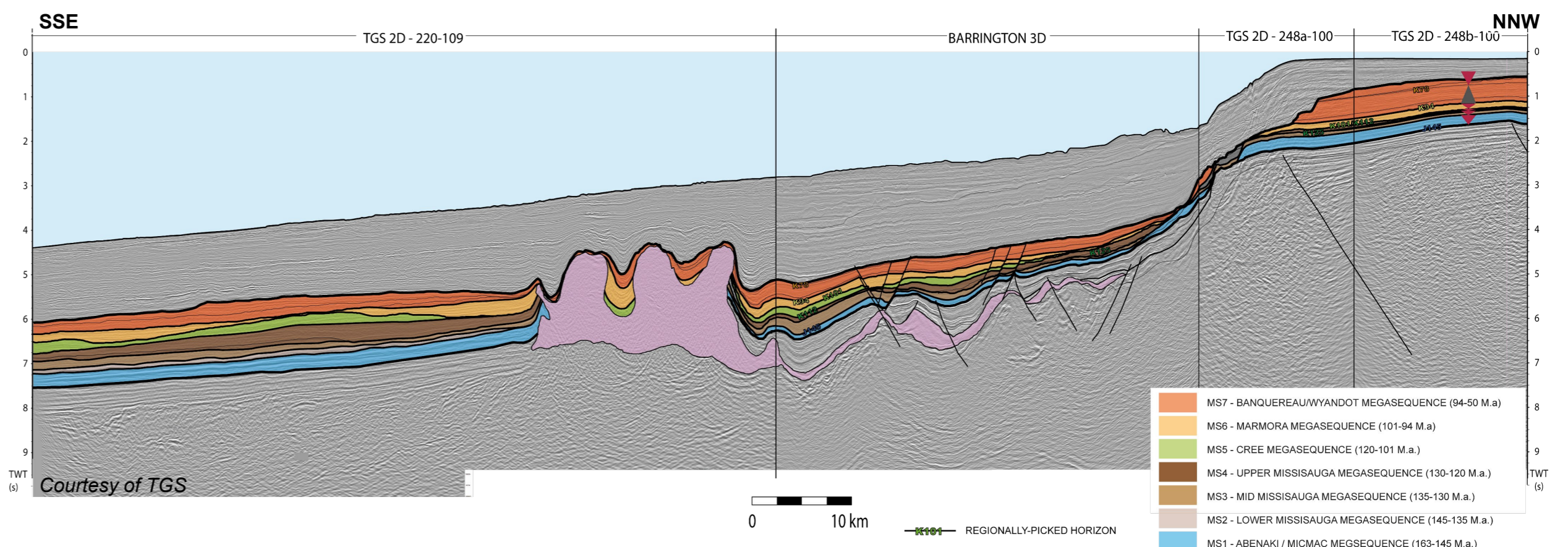
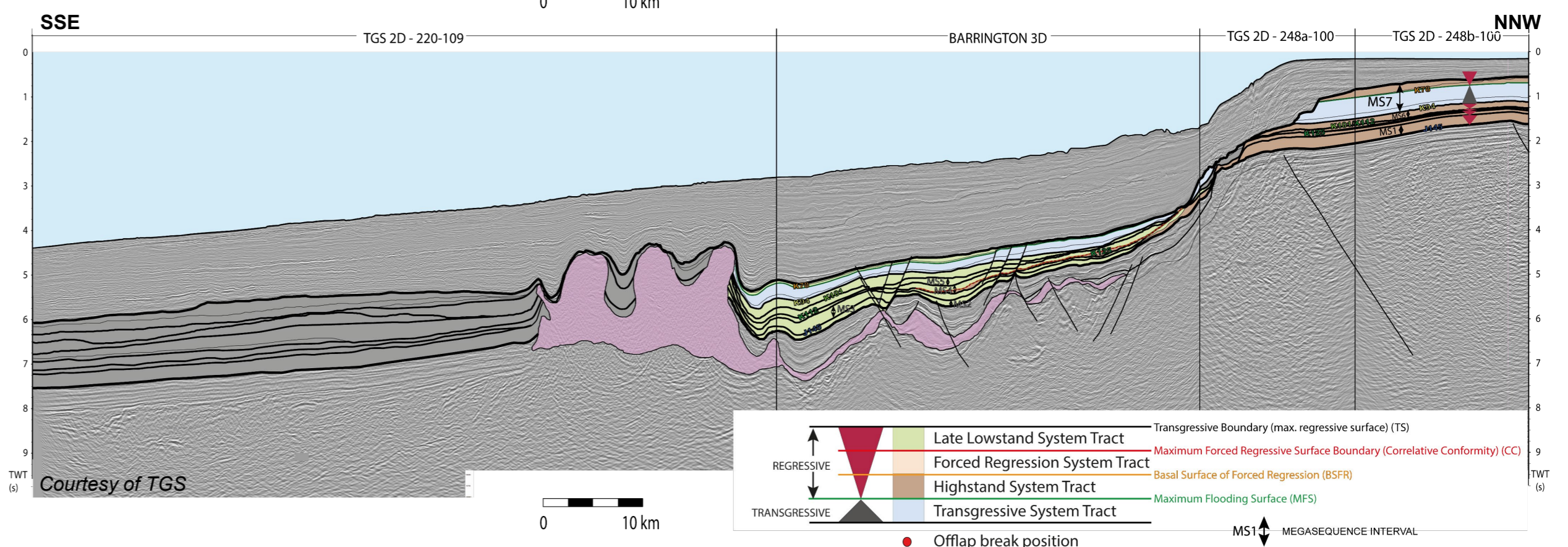
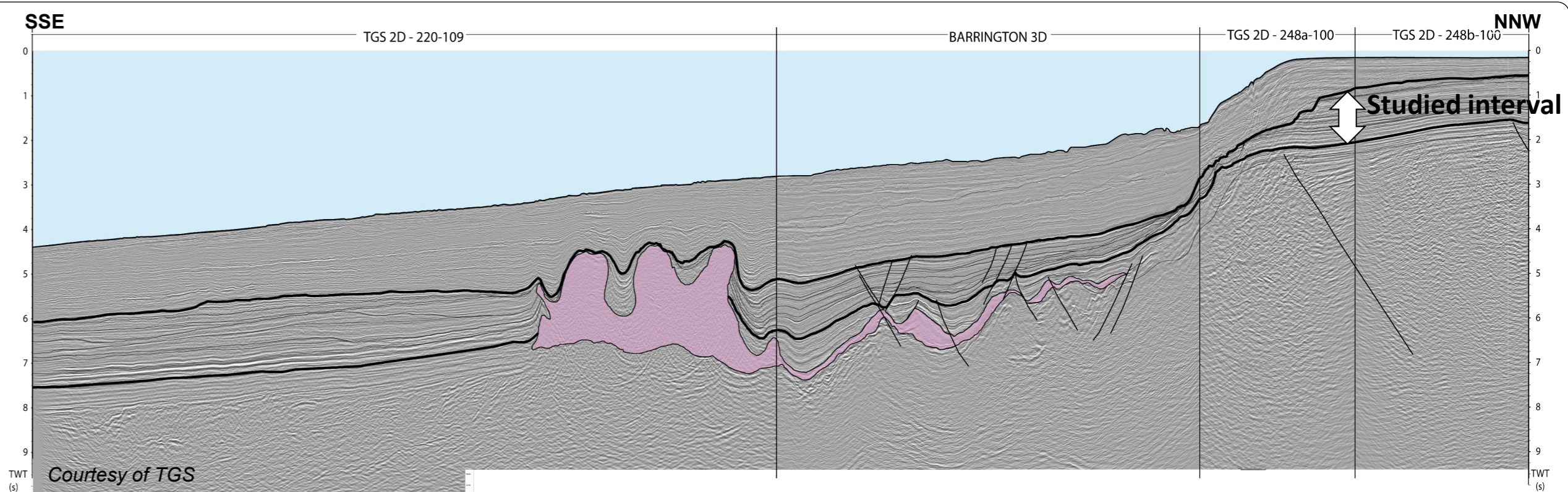


Figure 8: Chronostratigraphic views of Section 5 (seismic extracted from TGS 2D survey and Barrington 3D survey)

**Additional Section – Westernmost Georges Bank / Shelburne Deltas**

This westernmost regional section crosses the shelf to deep offshore domain along the Georges Bank area, and the presented stratigraphic and facies configurations are extracted from the Southwest Nova Scotia Extension Play Fairway Atlas published in 2015.

Although no stratigraphic update was done for this part of the study area in this study, the work carried out in 2015 has nevertheless been integrated into this G&G synthesis, in order to better populate the GDE maps in this more frontier region.

This dip-oriented section illustrates the architecture of the Georges Bank's margin since the Breakup unconformity around 200 Myr ago.

The deepest part of the cross-section shows the autochthonous and allochthonous salt identified above basement. The salt is overlapped by thick early to middle Jurassic carbonate sediments (J200 – J163).

Around J163 time, deltaic and prodeltaic sediments prograded on the shelf and fed early turbidite systems on the basin slope and rise. This interval corresponds to the development of an early Shelburne delta system.

Near the top Jurassic, the sedimentation is dominated by carbonate sediments and marine shale related to the transgressive trend. Calciturbidites are inferred to be significant in deep water during the early to Mid Jurassic as well as during the J150 – K137 interval.

Sediment accumulation during the Cretaceous is dominated by prodeltaic sediment interbedded with limestone on the shelf, whereas the basin is dominated by clastic turbidites and marine shale. The late Cretaceous until the base Paleocene is composed of chalk and marl sediments.

The Chronostratigraphic transect (2<sup>nd</sup> line) shows thick Jurassic succession on the shelf, whereas Cretaceous succession are thicker downslope due to limited accommodation space on the shelf and extensive base of slope deformation related to salt movement. The Lithostratigraphic transect (3<sup>rd</sup> line) highlights the well-developed Shelburne delta through time and illustrates the change in accommodation space on the shelf and slope from the Jurassic to the Cretaceous.

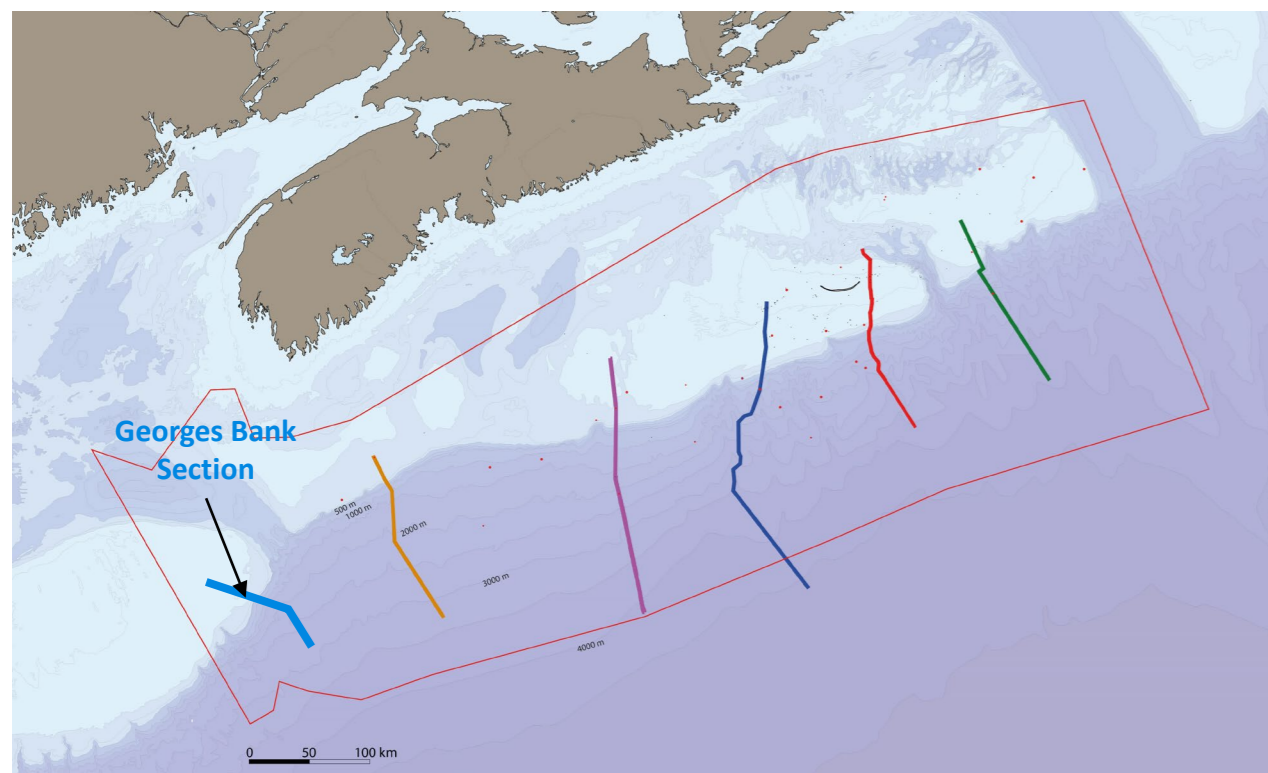
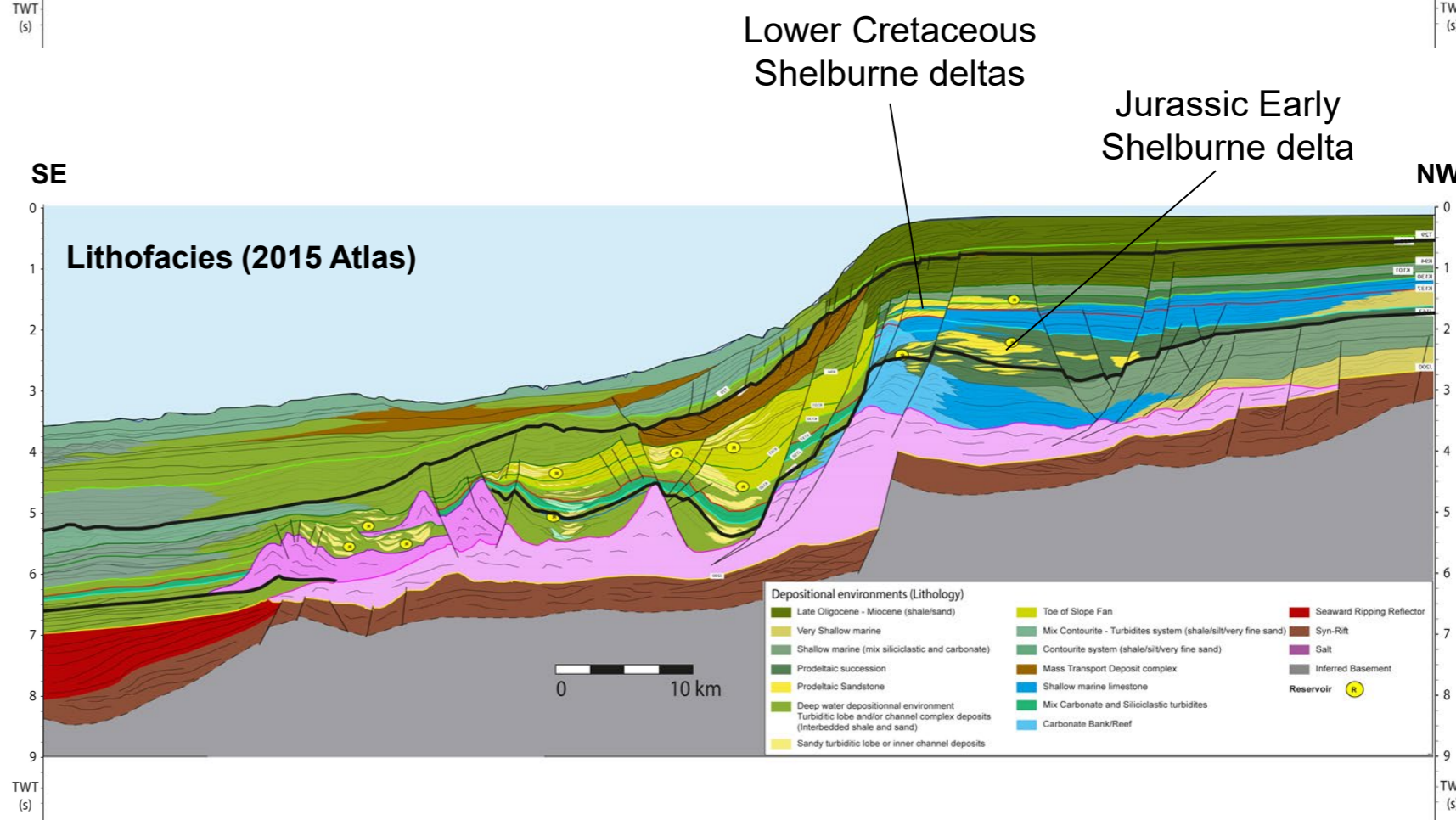
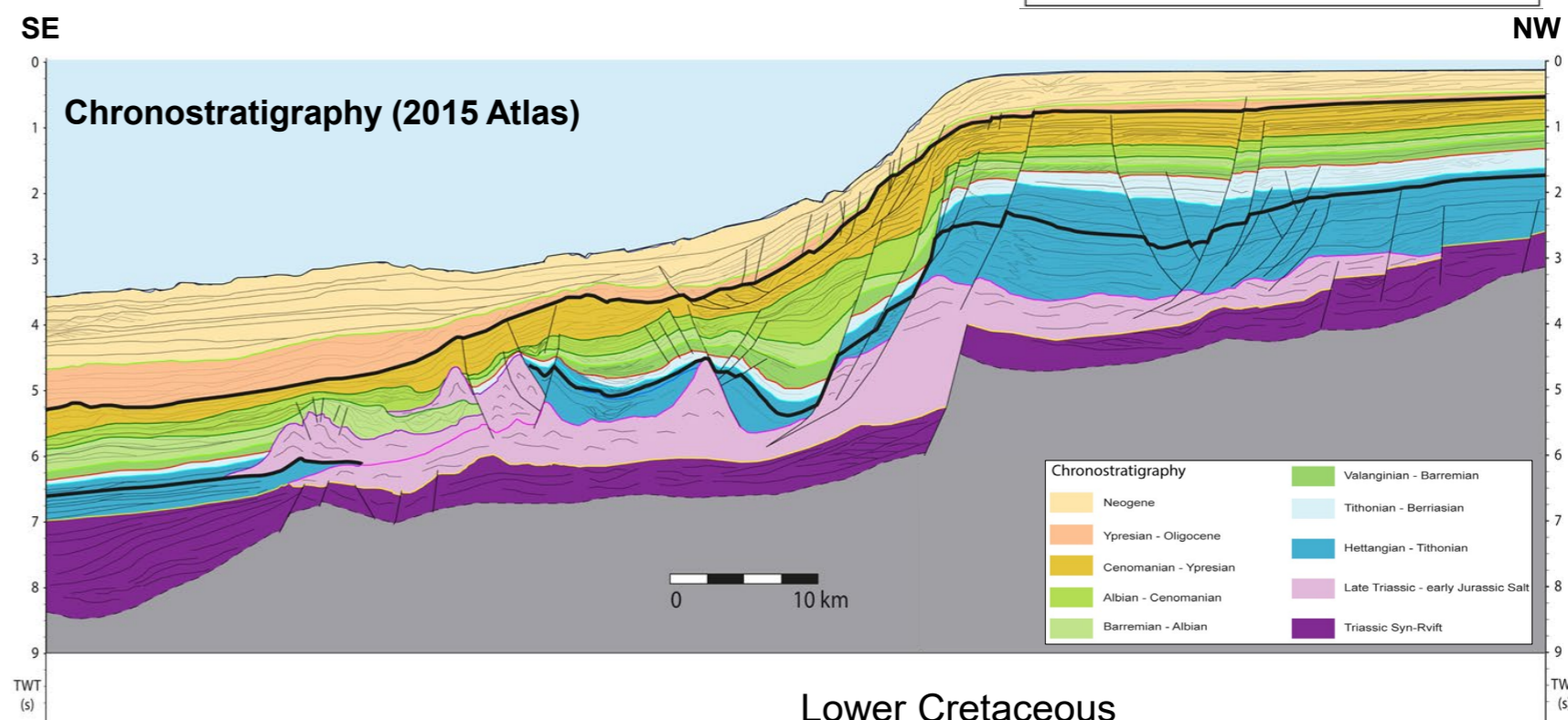
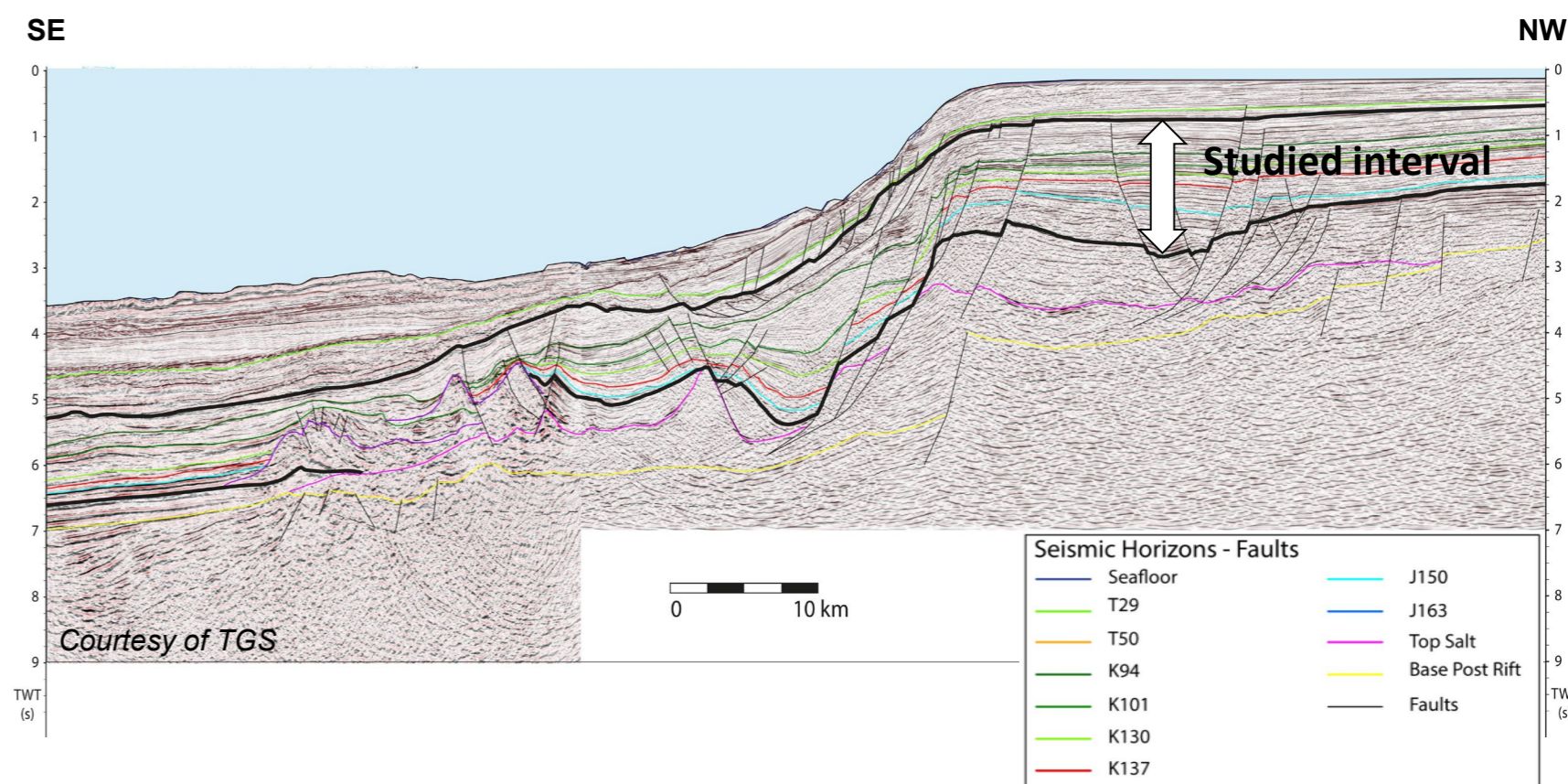


Figure 9: Chronostratigraphic and Lithofacies views of Georges Bank Section (Modified from the South-West Nova Scotia expansion Atlas, 2015) – Seismic extracted from JGM and TGS 2D surveys

## Chronostratigraphic chart

Figure 10 below displays an updated view of the chronostratigraphic chart designed for the whole offshore Nova Scotia margin.

This chart includes the Jurassic at its base and the Paleogene at the top. The sequence stratigraphic breakdown reveals a regional stratigraphic signal observed at different time scales.

The seismic stratigraphic interpretation of the composite lines led to the definition of seven common megasequences (MS1 to MS7). The average duration of the megasequences was around 10 Myrs and each megasequence was characterized by a forced regressive wedge in places where deltaic sedimentation was dominant along the Scotian Shelf (Cummings et al., 2006).

The megasequences stack to form two longer-term depositional cycles (around 50 Myr long cycles), where Jurassic to top Cenomanian strata record the overall progradation of the margin, followed by a widespread marine transgression in the Upper Cretaceous, and renewed progradation during the Paleogene.

The Near Base Cretaceous boundary is marked by a regional unconformity that formed in response to tectonism associated with the Avalon uplift (Wade and MacLean, 1990, BCU in previous OERA/Beicp Atlases). The missing interval documented on the Scotian Shelf both in wells and seismic, is coeval with the sedimentation of a prominent forced regressive wedge (deltaic sandstones of the lower part of the Missisauga Formation) preserved beneath the outer Scotian Shelf (Megasequence 2).

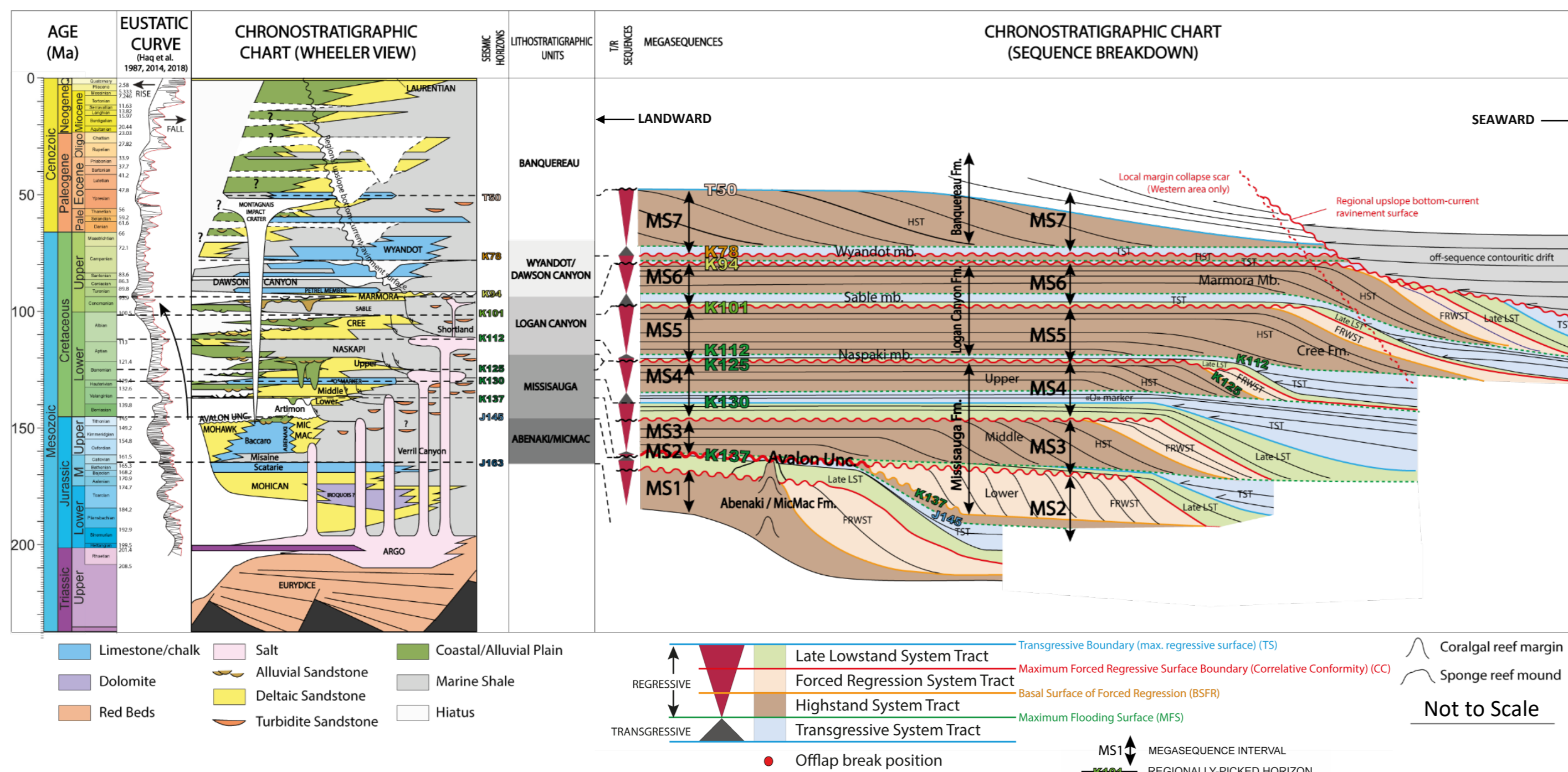


Figure 10: Offshore Nova Scotia Chronostratigraphic chart

During Lower Cretaceous, the long-term prograding trend does not coincide with eustatic curves, which implies a regional tectonic control, causing long wave differential subsidence of the whole margin and drastic increase of sedimentary influx.

The overall prograding behavior observed from the base of Cretaceous up to the top Cenomanian could be the expression of a regional exhumation of the Eastern Canada margin, with a tectonic climax at the Jurassic-Cretaceous transition (Avalon Unconformity). The cause of such uplift/erosion and coeval successive seaward oriented downward shift of the delta fronts is still debated: it might be related to large wavelength lithospheric deformation process either due to kinematic/change of oceanic opening orientation or the onset of a mantle plume/hot spot (Jansa et al., 1975; Wade & McLean, 1990).

At a shorter timescale, however, the observed forced regressive wedges of each megasequences could be explained by eustatic sea level change.

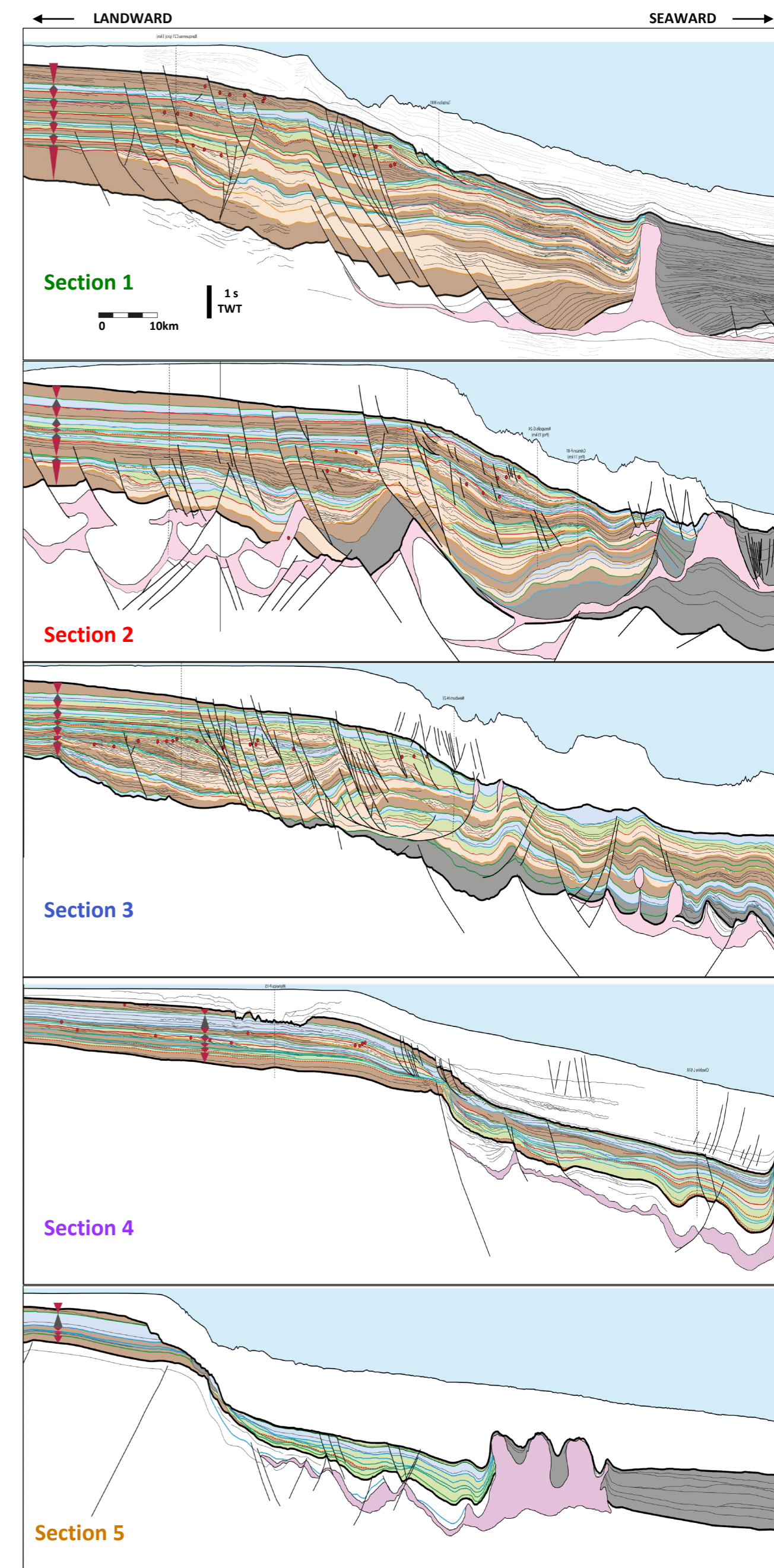
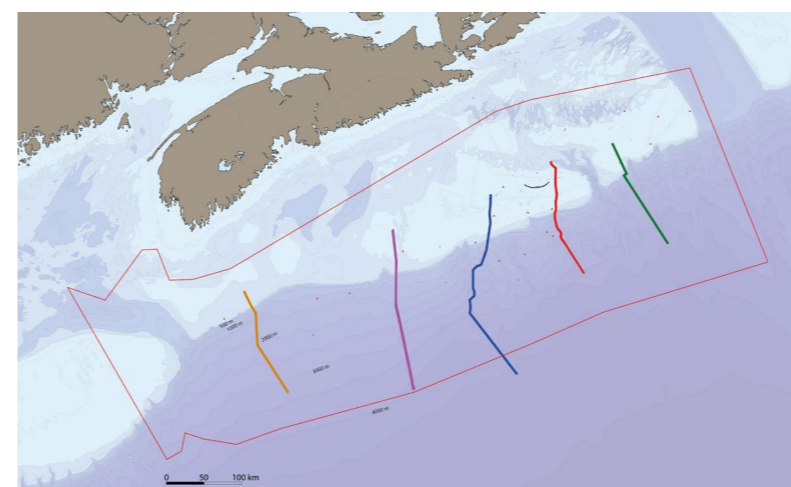
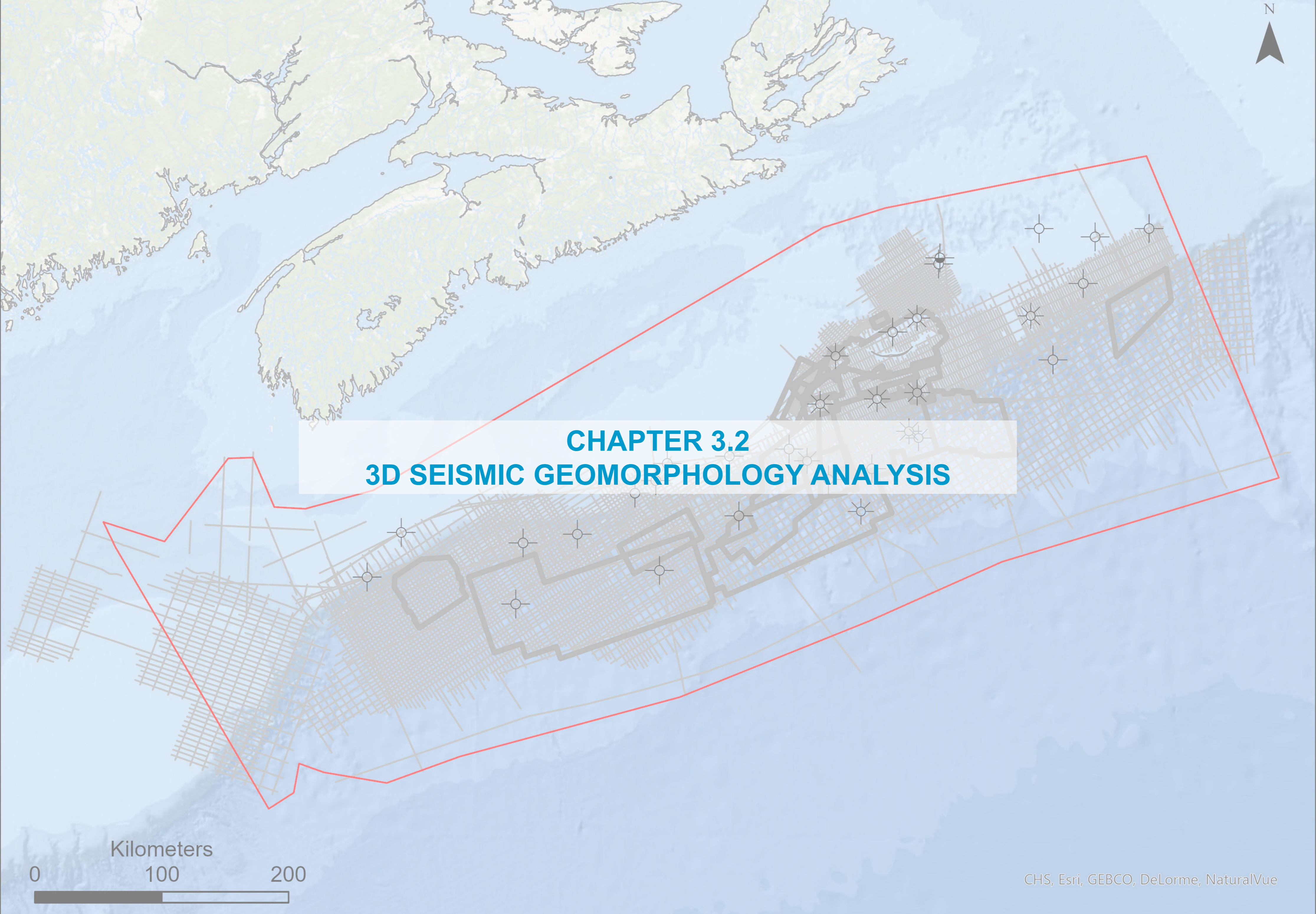


Figure 11: Chronostratigraphic views (with systems tracts) of all sections



**CHAPTER 3.2**  
**3D SEISMIC GEOMORPHOLOGY ANALYSIS**

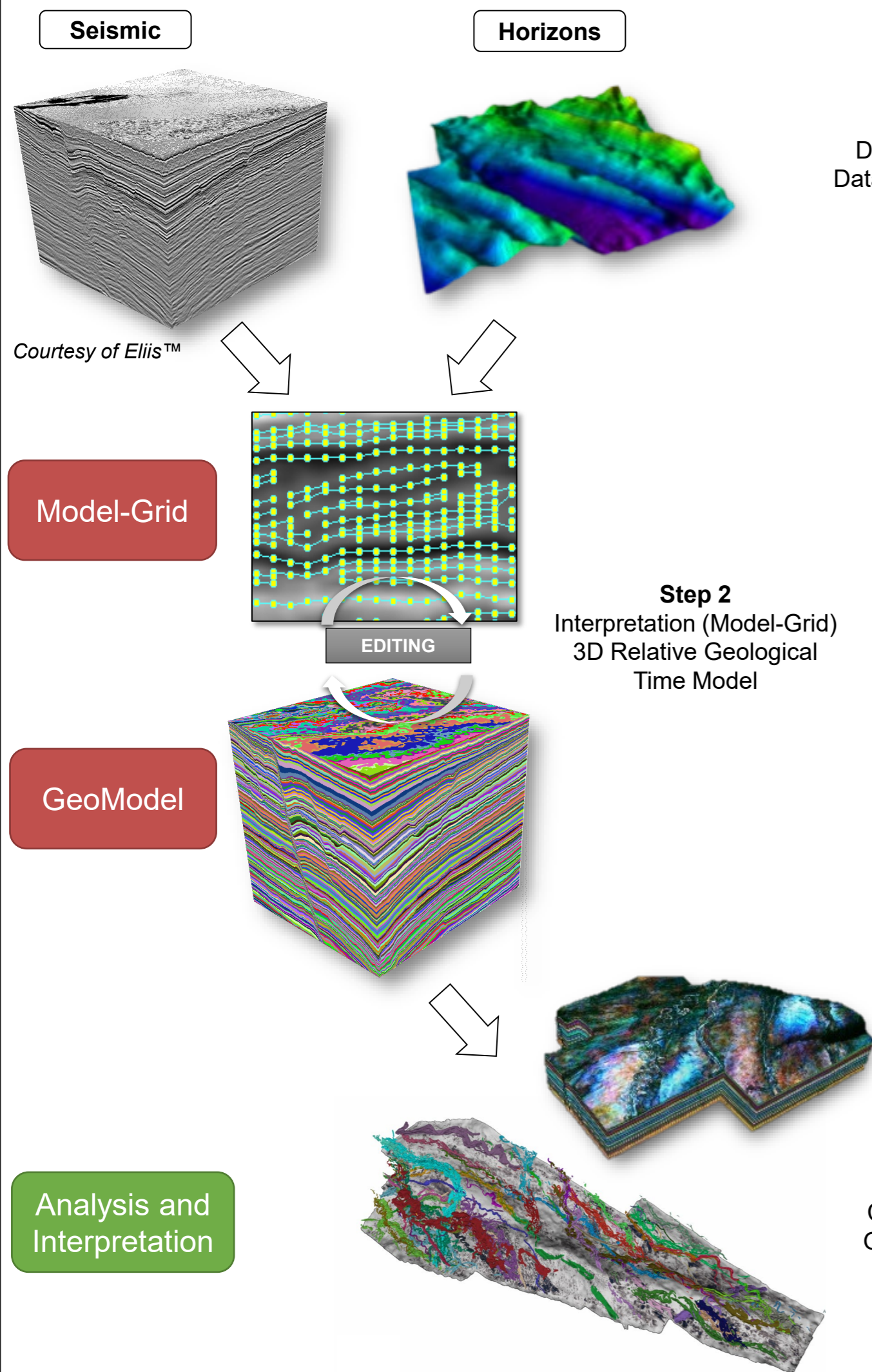
Kilometers

0 100 200

## Objectives

The coupling of detailed sequence stratigraphic analysis with a seismic geomorphological analysis lead to the mapping of seismic geobodies with unprecedented precision, from the shelf to the basin and in a constrained and robust stratigraphic framework.

The geomorphological analysis consisted of the description of geological objects in the available 2D and 3D seismic surveys. In the case of the 3D surveys, semi-automated methods of seismic scanning were used. This relies on computing a model-grid by extracting billions of polarity consistent micro horizons directly from the seismic image. These horizon patches can then be auto-correlated, allowing us to make the decisions in the interpretation process.



**Step 1**  
Import Data  
Data Conditioning  
Data Reconnaissance

The auto-tracked horizons can then be interactively refined within the model grid to rapidly achieve a geologically consistent interpretation. Once validated, we compute a Relative Geological Time (RGT) model from the interpolation of the previously refined horizons within the model-grid.

**Step 2**  
Interpretation (Model-Grid)  
3D Relative Geological Time Model

Since the RGT model is both vertically and spatially continuous, an unlimited number of chronostratigraphic surfaces can be generated. These depositional time surfaces can be extracted as a dynamic series of horizon stacks. The horizon stack enables an interactive stratal slicing through the seismic volume where sedimentary and structural features as well as fluid contact can be highlighted with precision.

**Step 3**  
Creation of Horizon Stack  
Geobody Reconnaissance  
Geobody Picking

Figure 12: Principles of semi-automated method of 3D seismic scanning and multi-horizon extraction

## Example of object mapping based on 3D seismic stratigraphic scanning → output for GDE mapping and lead assessment

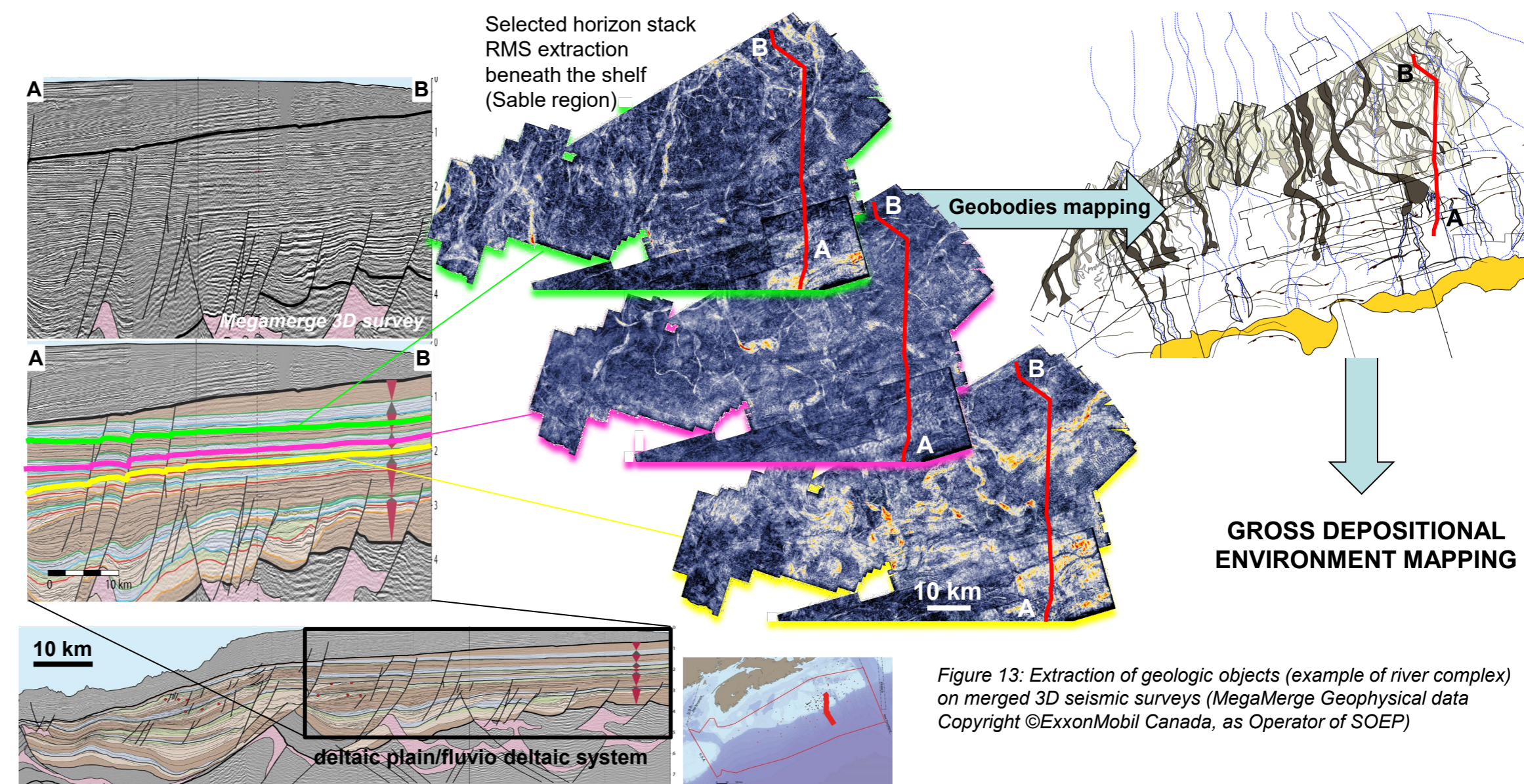


Figure 13: Extraction of geologic objects (example of river complex) on merged 3D seismic surveys (MegaMerge Geophysical data Copyright ©ExxonMobil Canada, as Operator of SOEP)

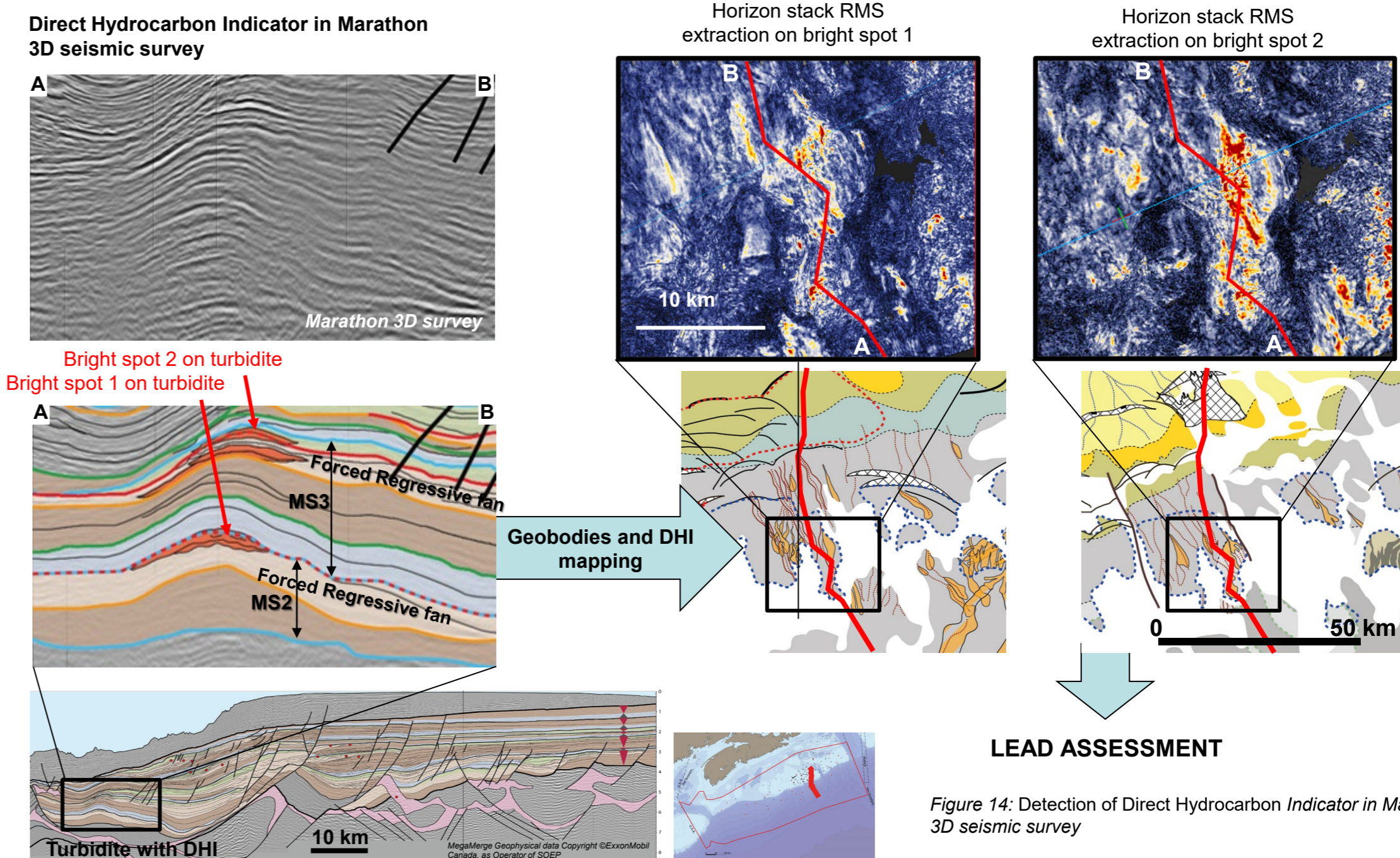


Figure 14: Detection of Direct Hydrocarbon Indicator in Marathon 3D seismic survey

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

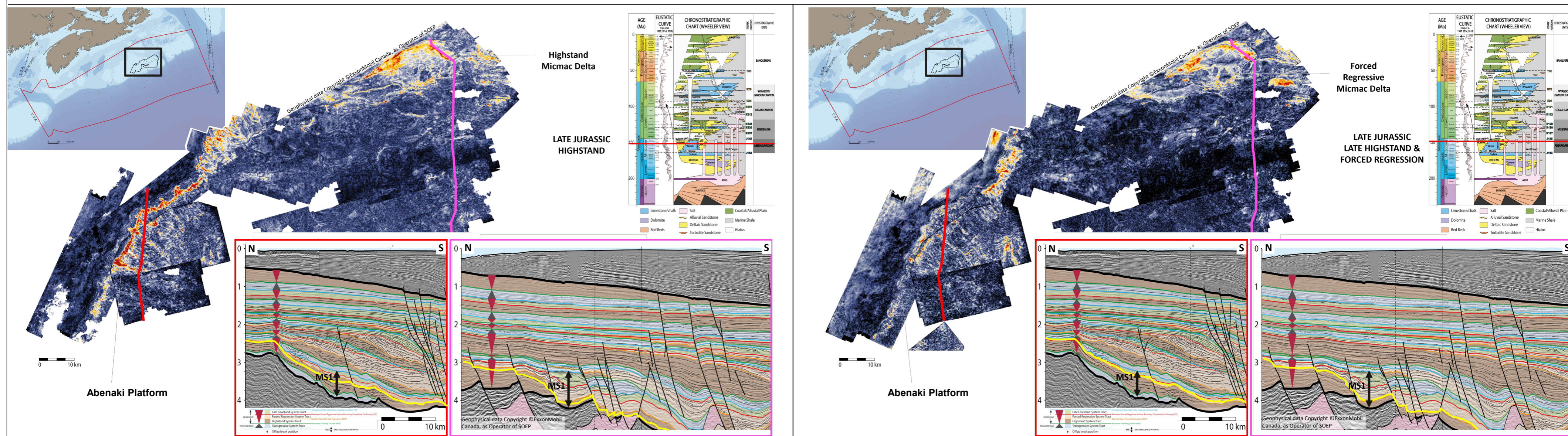
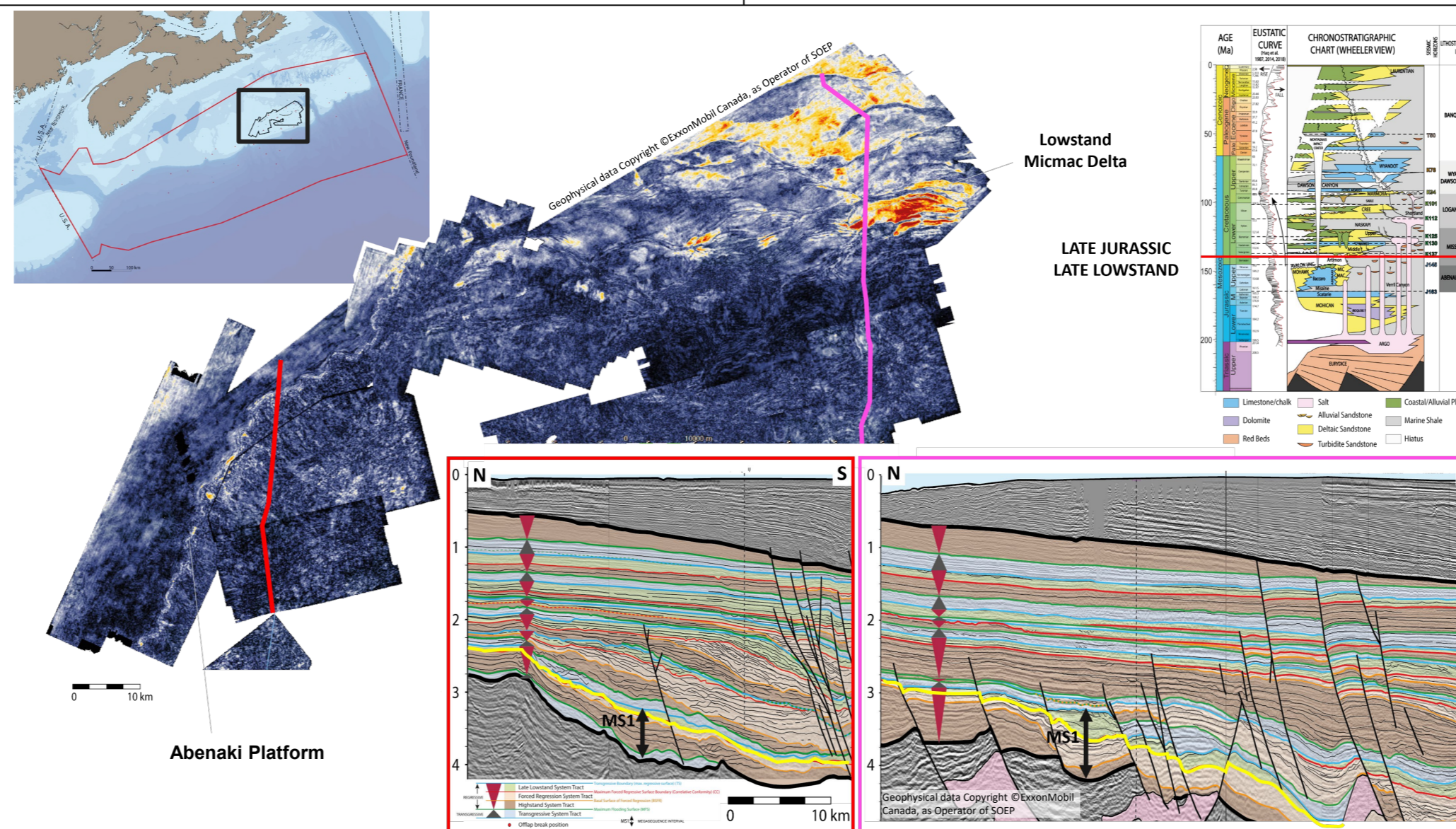


Figure 15a: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for Megasequence 1



# 3D Seismic Geomorphology Analysis

Offshore Nova Scotia Velocity Modeling – CANADA – January 2022

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

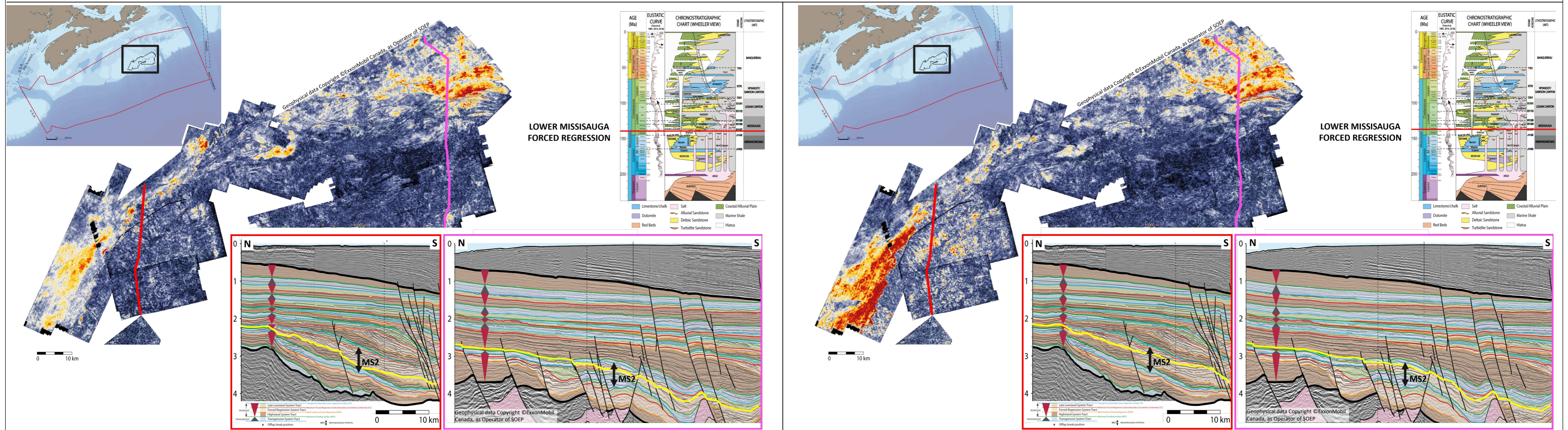


Figure 15b: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for Megasequence 2

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

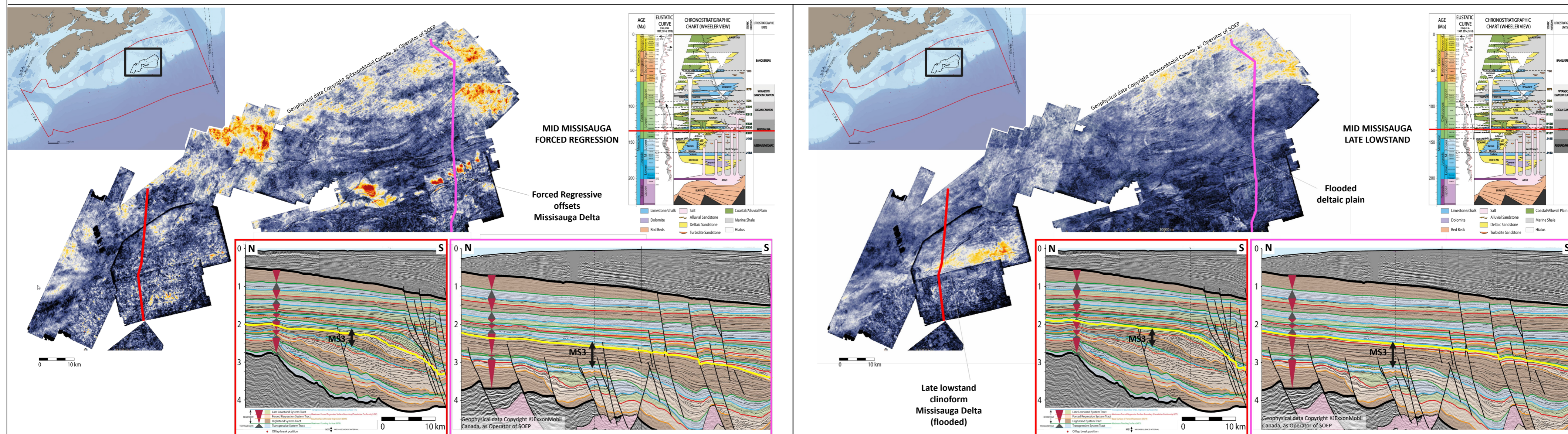


Figure 15c: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for late Megasequence 3

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

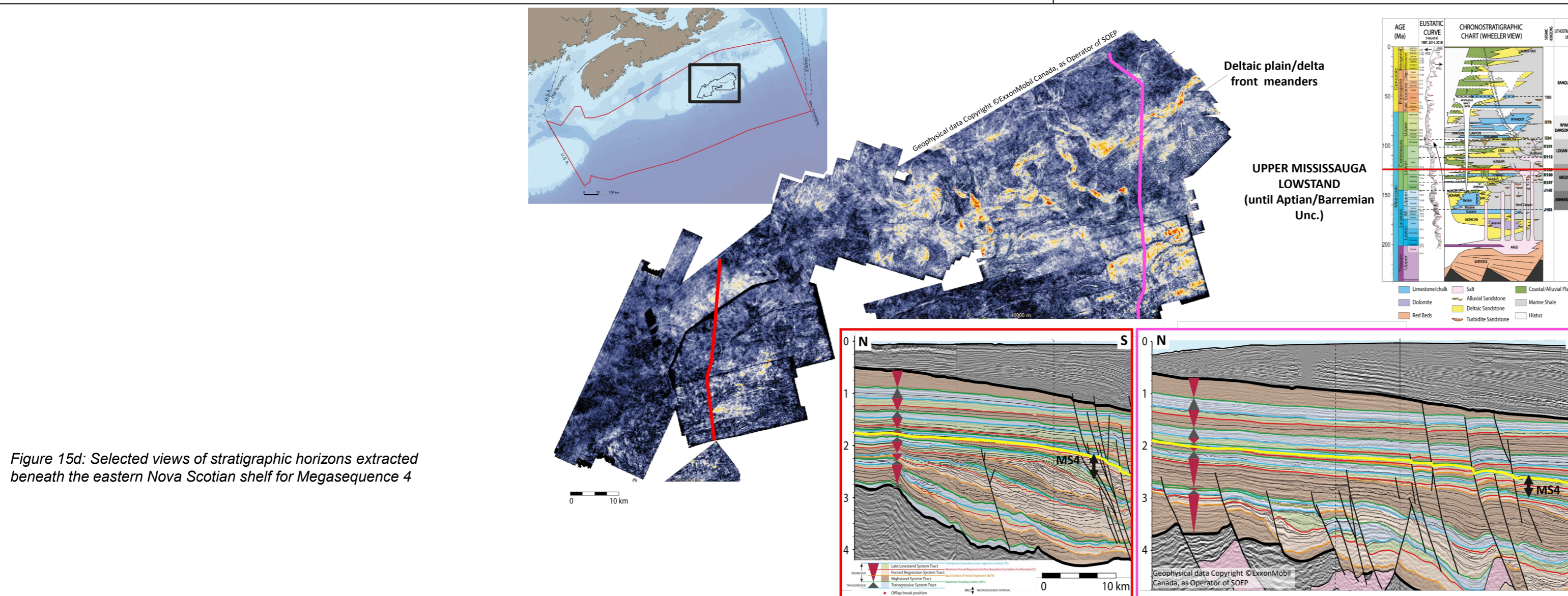
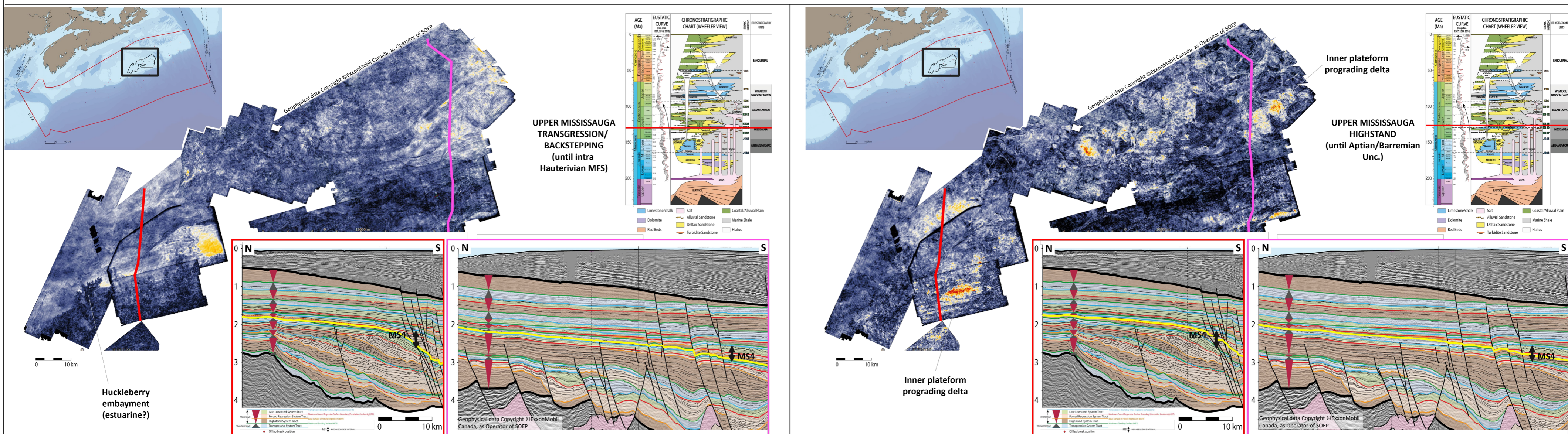


Figure 15d: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for Megasequence 4

# 3D Seismic Geomorphology Analysis

Scotian Basin Integration Atlas 2023 – CANADA – June 2023

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

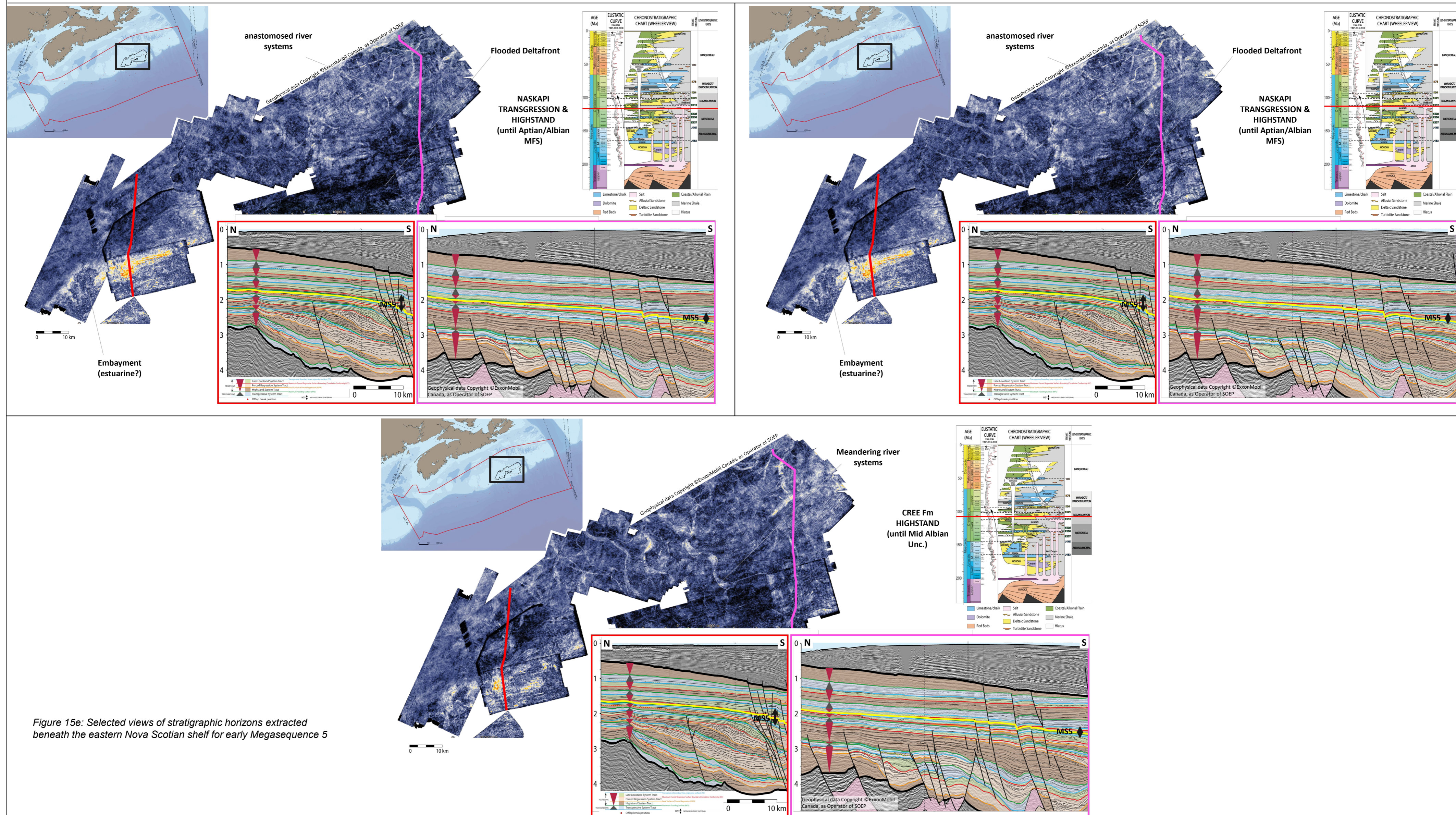


Figure 15e: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for early Megasequence 5

# 3D Seismic Geomorphology Analysis

Offshore Nova Scotia Velocity Modeling – CANADA – January 2022

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

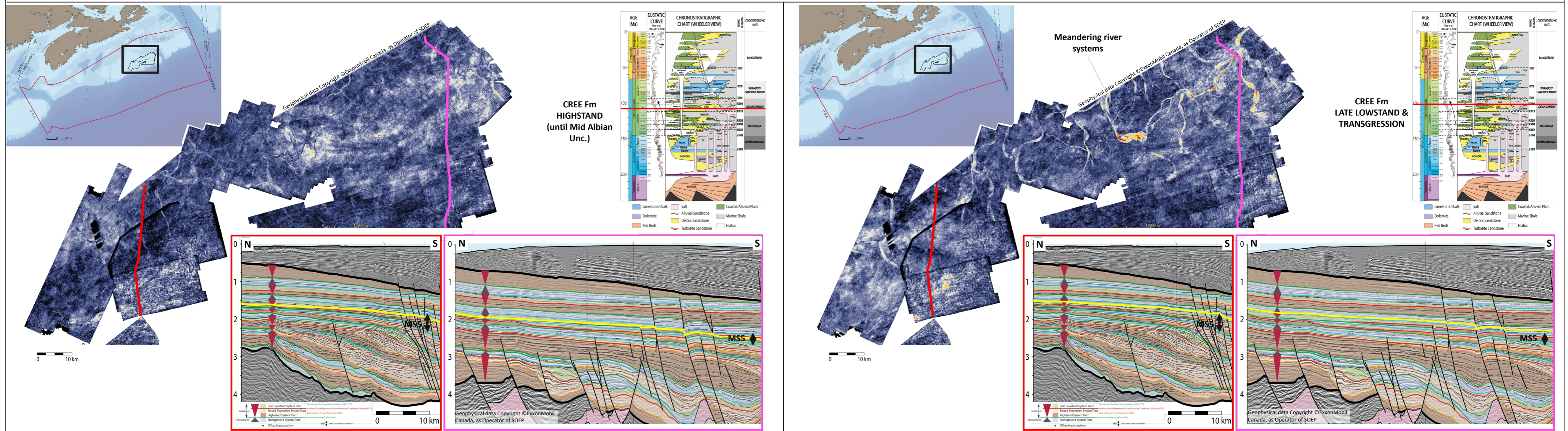


Figure 15f. Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for late Megasequence 5

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

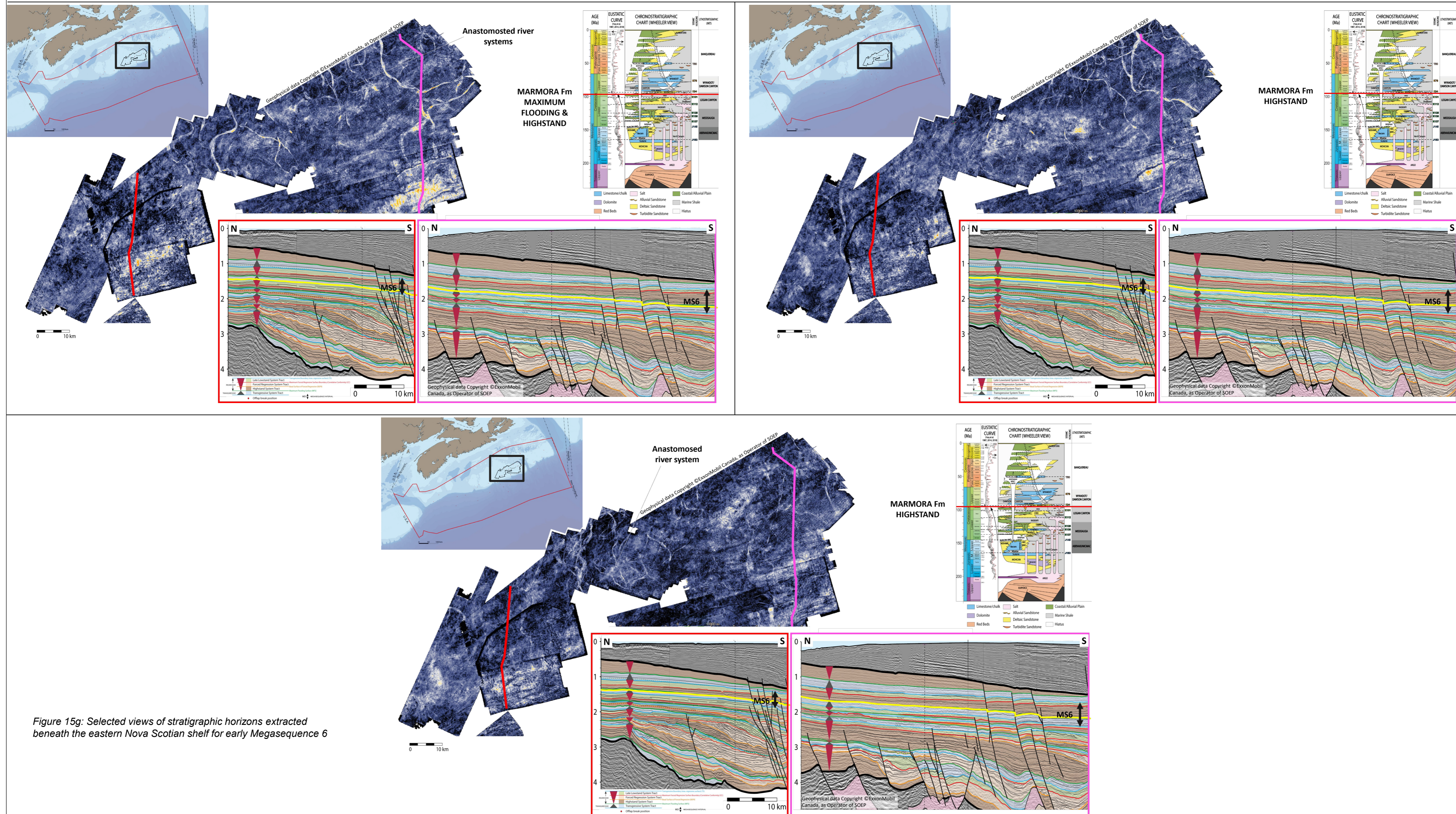


Figure 15g: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for early Megasequence 6

# 3D Seismic Geomorphology Analysis

Offshore Nova Scotia Velocity Modeling – CANADA – January 2022

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

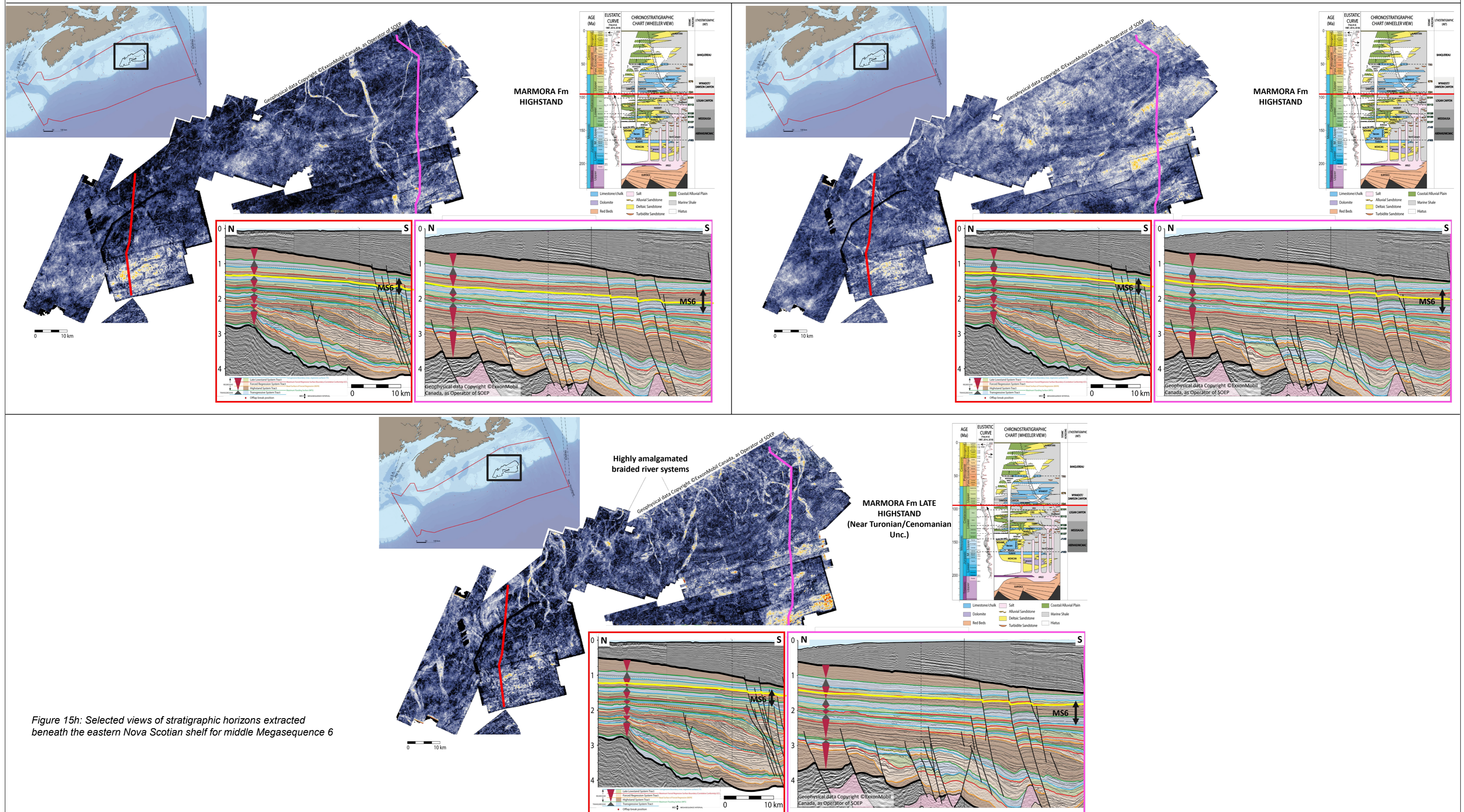


Figure 15h: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for middle Megasequence 6

# 3D Seismic Geomorphology Analysis

Scotian Basin Integration Atlas 2023 – CANADA – June 2023

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

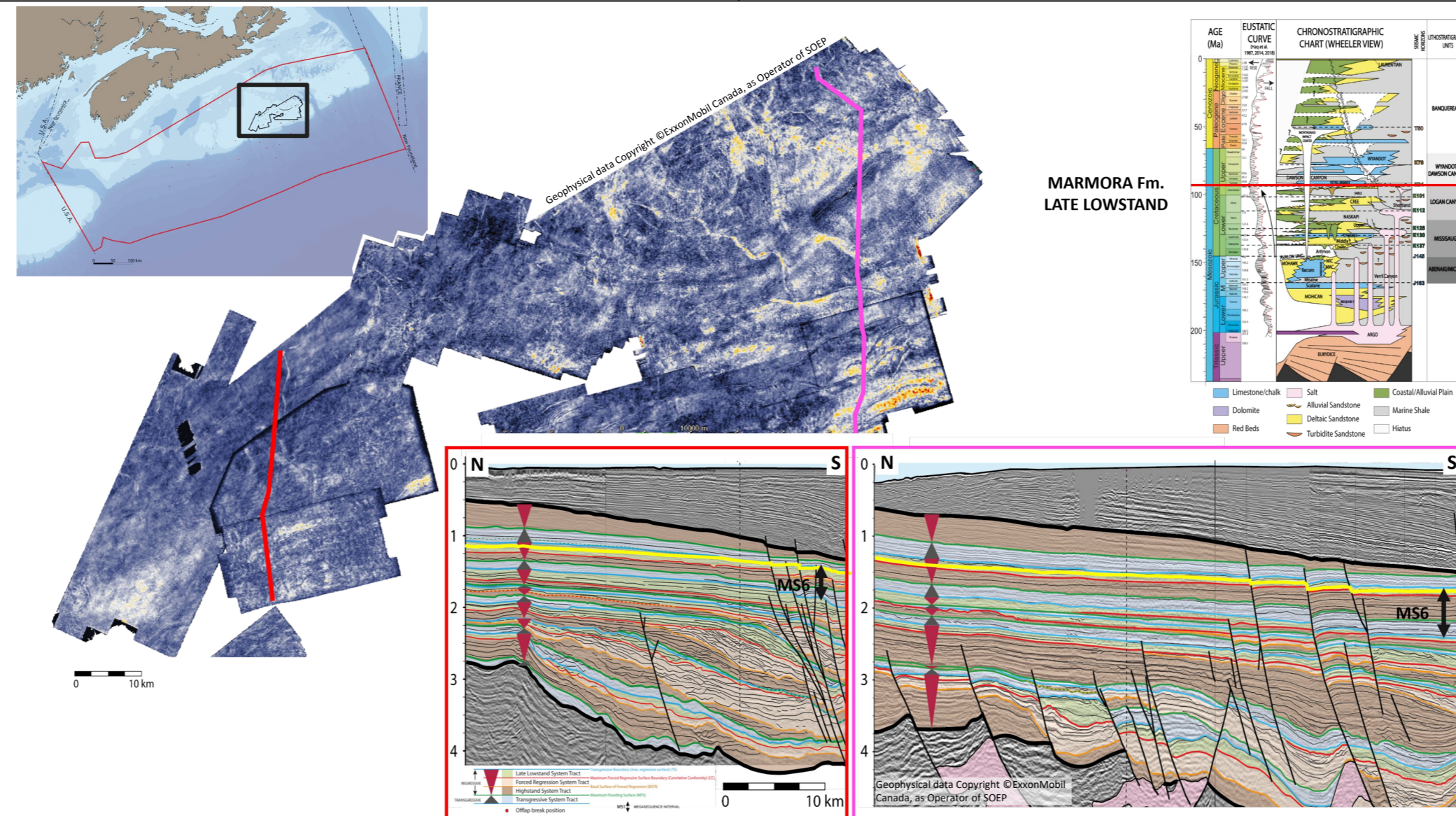
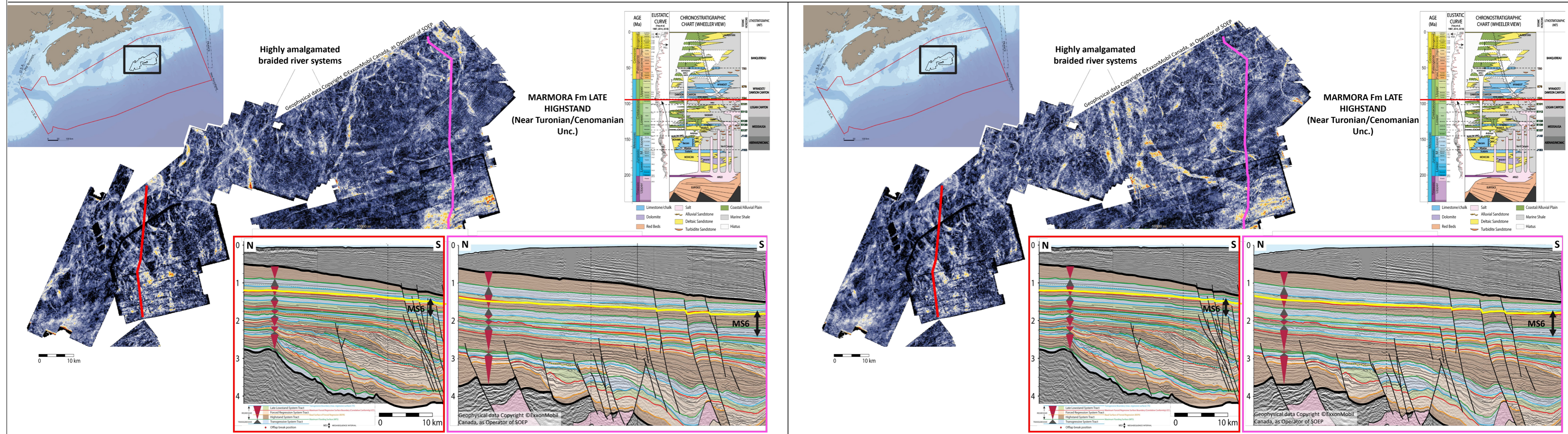


Figure 15i: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for late Megasequence 6

## Geobody description and assignment to a given sequence stratigraphic framework

The application of 3D semi-automated methods of extraction of seismic horizon stacks beneath the present day shelf enabled navigation stratigraphically within the Upper Jurassic and Lower Cretaceous depositional profile. It allowed an estimate of (1) the extension of the Abenaki reefal platform and lateral Mic Mac delta extension during megasequence 1, (2) the progradation of the Missisauga delta from Megasequence 2 to 4, (3) the Alluvial/deltaic systems associated with the Logan Canyon Formation (megasequences 5 and 6), and (4) the Wyandot transgression and subsequent uppermost Cretaceous and Lower Cenozoic prograding bottomsets.

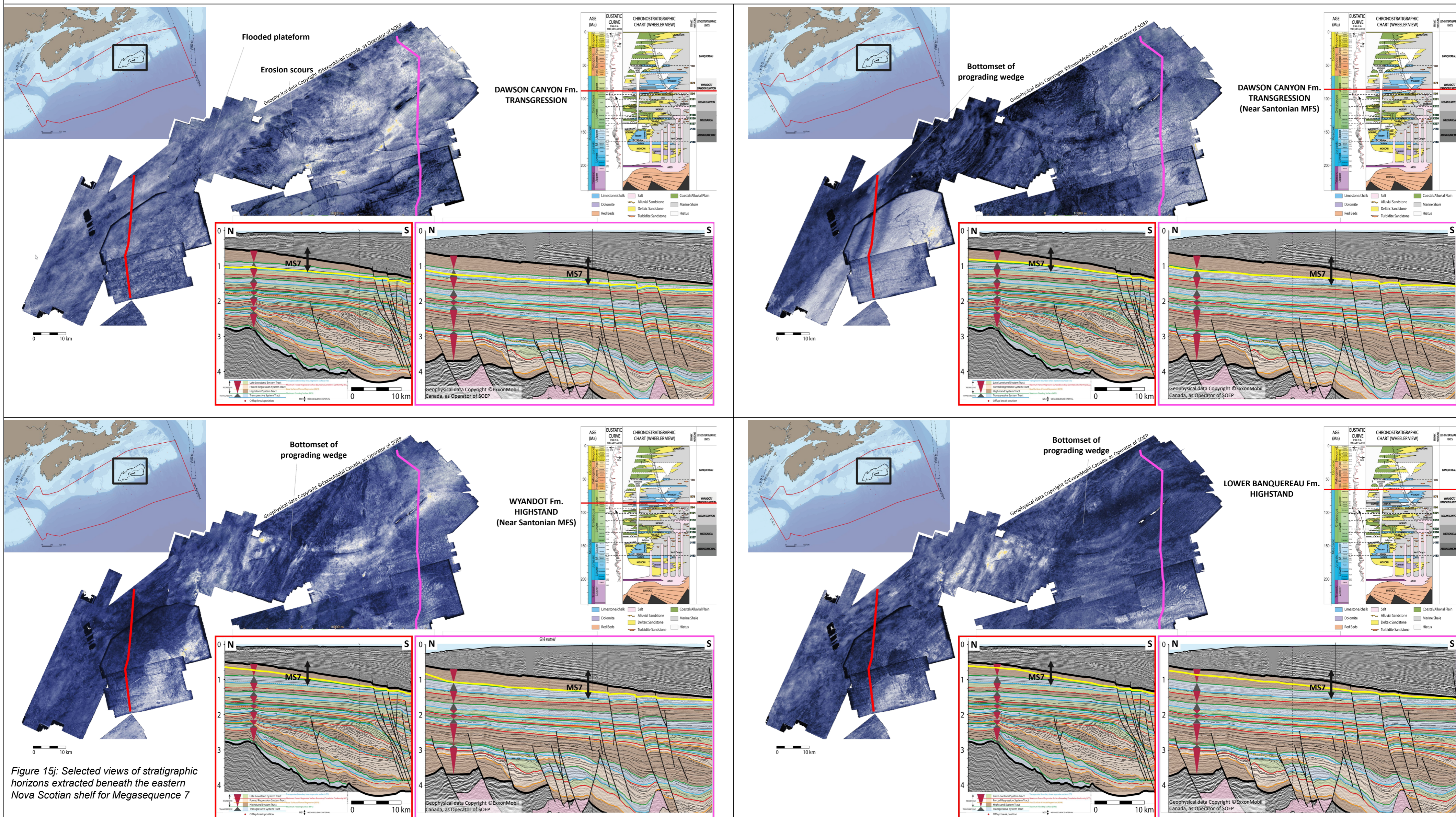
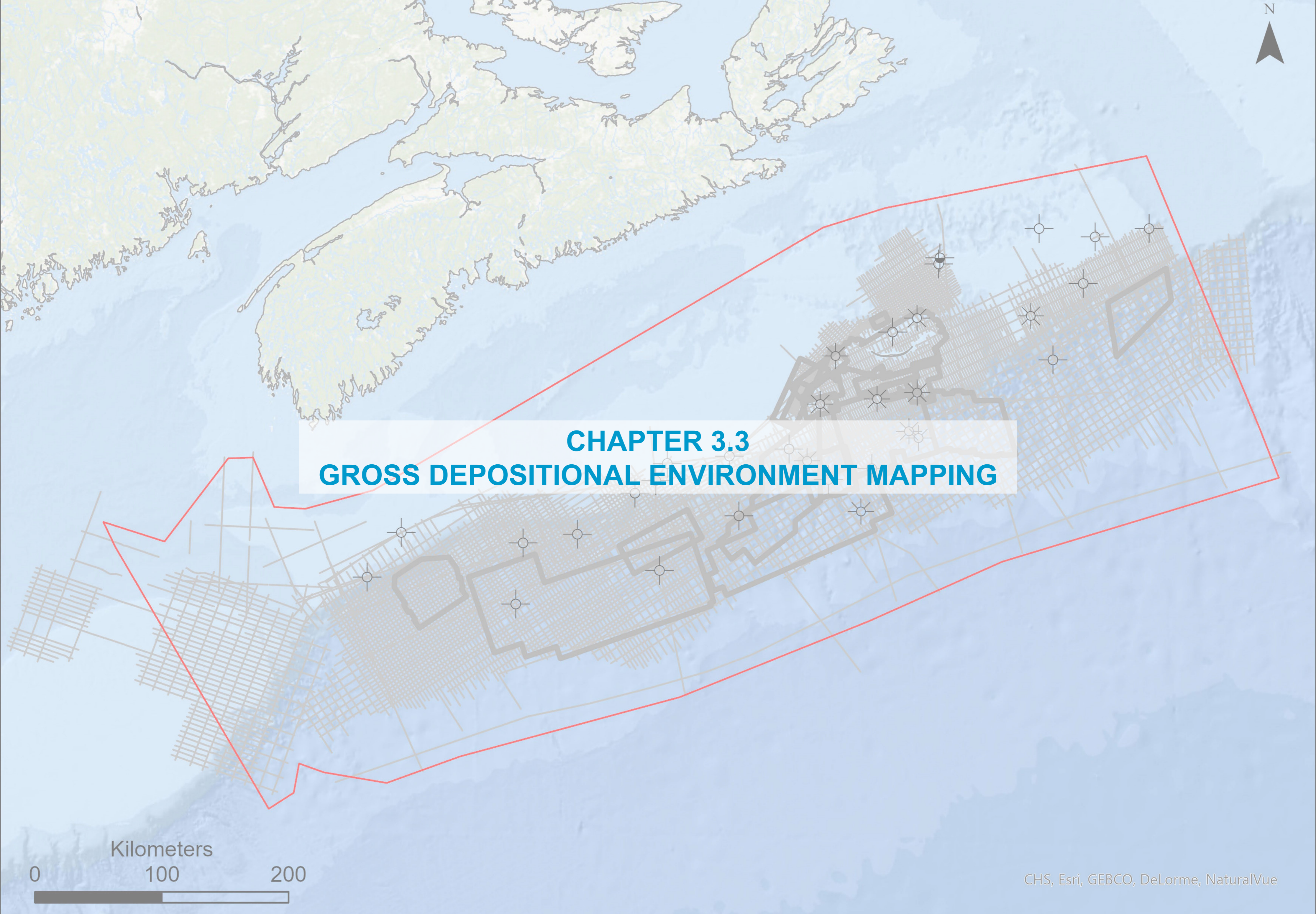


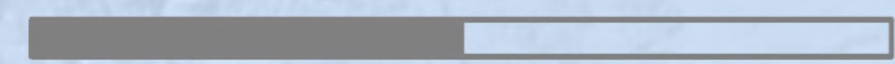
Figure 15j: Selected views of stratigraphic horizons extracted beneath the eastern Nova Scotian shelf for Megasequence 7



**CHAPTER 3.3**  
**GROSS DEPOSITIONAL ENVIRONMENT MAPPING**

Kilometers

0 100 200



## Geobody facies assignment for the Gross Depositional Environment mapping

The relevant geobodies acting as key play elements for the petroleum system (ie. reservoirs, seals and carrier beds) were exhaustively described in each megasequence. Those geobodies are the building blocks that fill the GDE maps. Depending on their seismic signature and nearby well control, a given facies is assigned to them. For example, we distinguish the turbiditic channel pathways with no significant infill, related to either bypass or ravinement by contour current, and channels with preserved turbiditic infill material.

The stratigraphic context of deposition of such geobodies is also crucial to assign their reservoir potential. Thus, a large turbiditic system with observed infill that is deposited during a period of relative sea-level fall (ie. forced regressive/falling stage system tract) is more likely to be sand prone than a narrow turbiditic funnel-shaped system deposited during a highstand system tract.

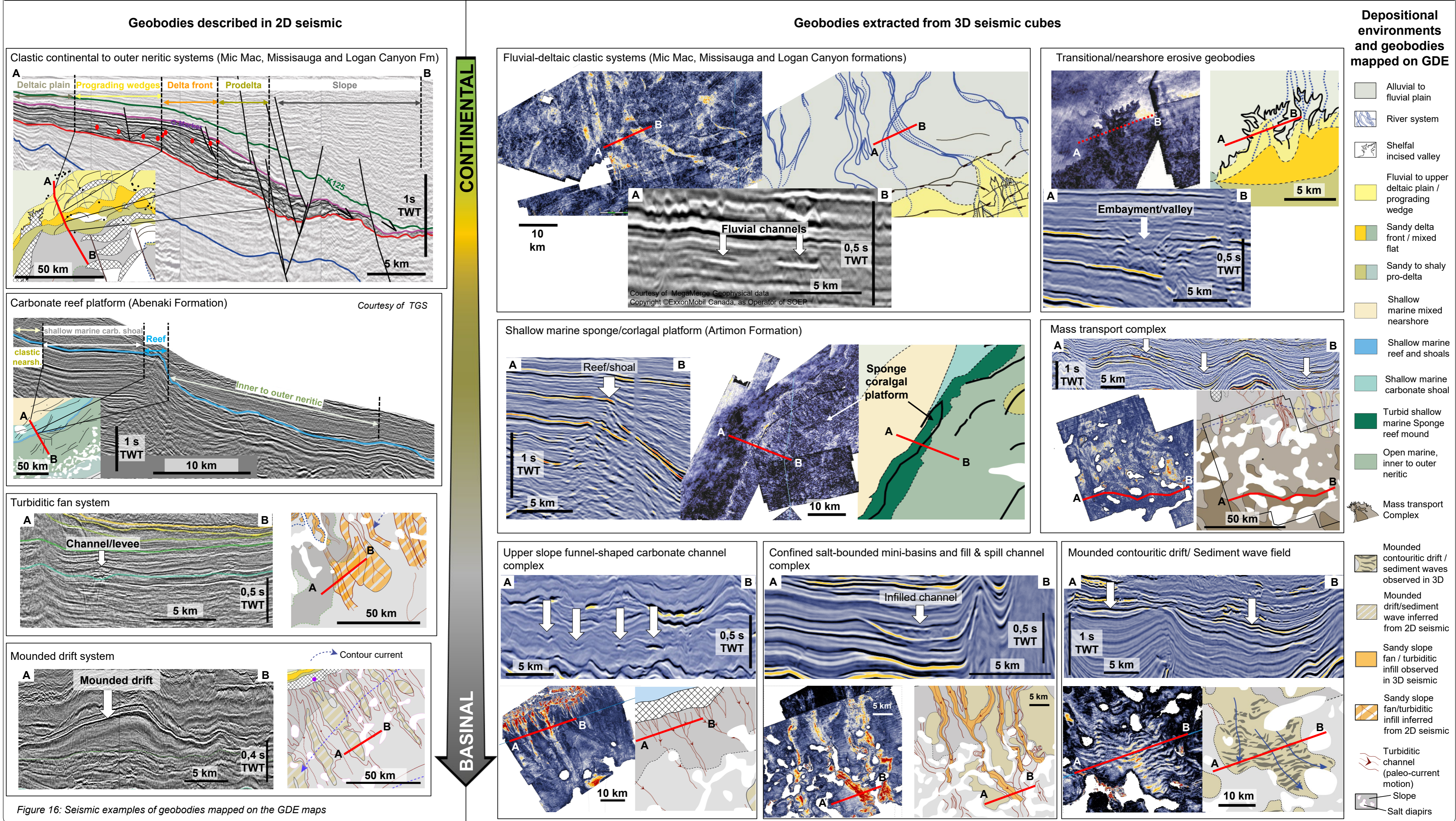
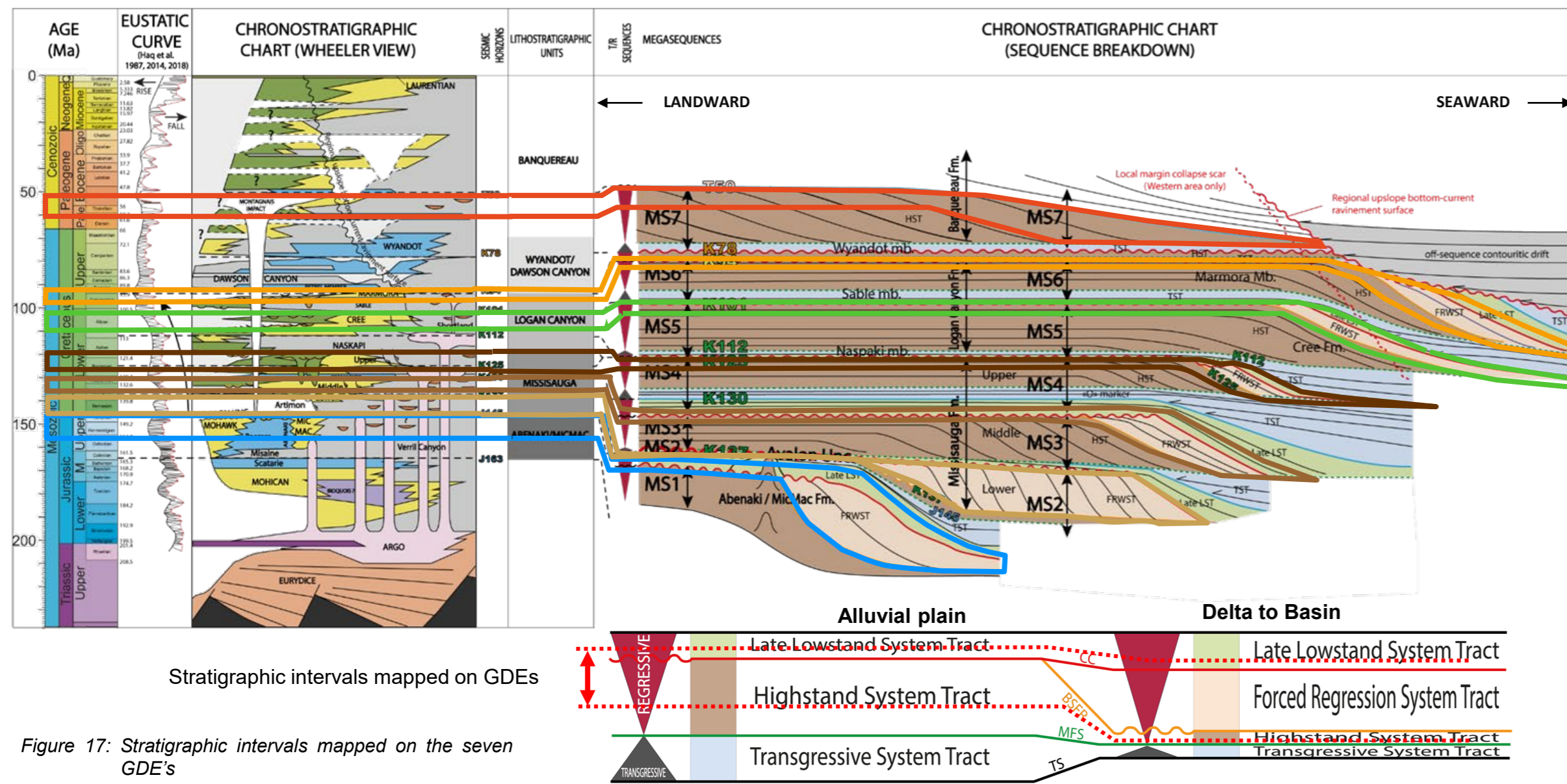


Figure 16: Seismic examples of geobodies mapped on the GDE maps

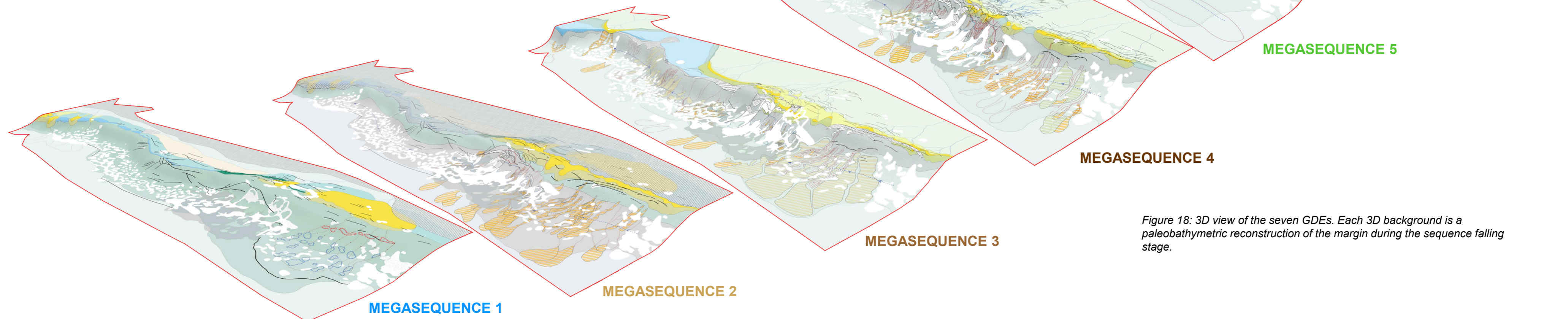
## Gross Depositional Environment Mapping: highlight deposition environment and associated geobodies

Seismic-scale depositional elements were mapped for each forced regressive systems tract documented in megasequences MS1 to MS7. The objective was to capture the spatial distribution of the sediments along the Scotian Basin and the connection between alluvial/coastal to shallow marine and deep marine sedimentary objects.



The selection of the gross depositional intervals was directly based on the sequence stratigraphic results. The most reservoir prone system tracts included in each one of the seven megasequences were highlighted on each GDE, corresponding to a sequence stratigraphic standpoint, and from source to sink, to:

- the late Highstand System Tracts, mostly preserved in the proximal/alluvial plain domain
- the Forced Regressive Systems Tracts (falling SL stage), mostly preserved in the deltaic plain, the slope and the deep basin.
- the early Late Lowstand System Tracts, present both in the proximal and distal domains.



# Gross Depositional Environment Mapping

Scotian Basin Integration Atlas 2023 – CANADA – June 2023

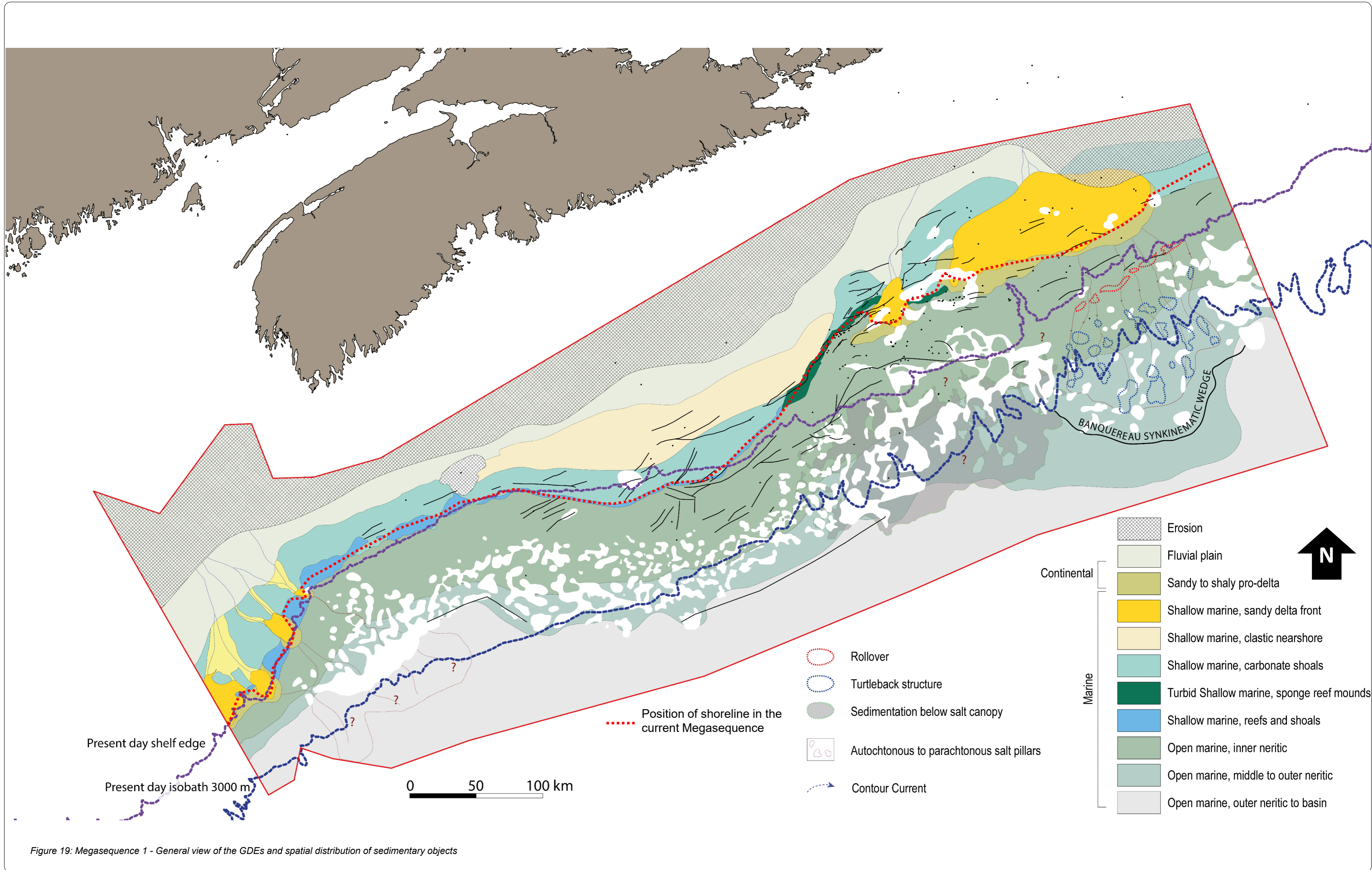


Figure 19: Megasequence 1 - General view of the GDEs and spatial distribution of sedimentary objects

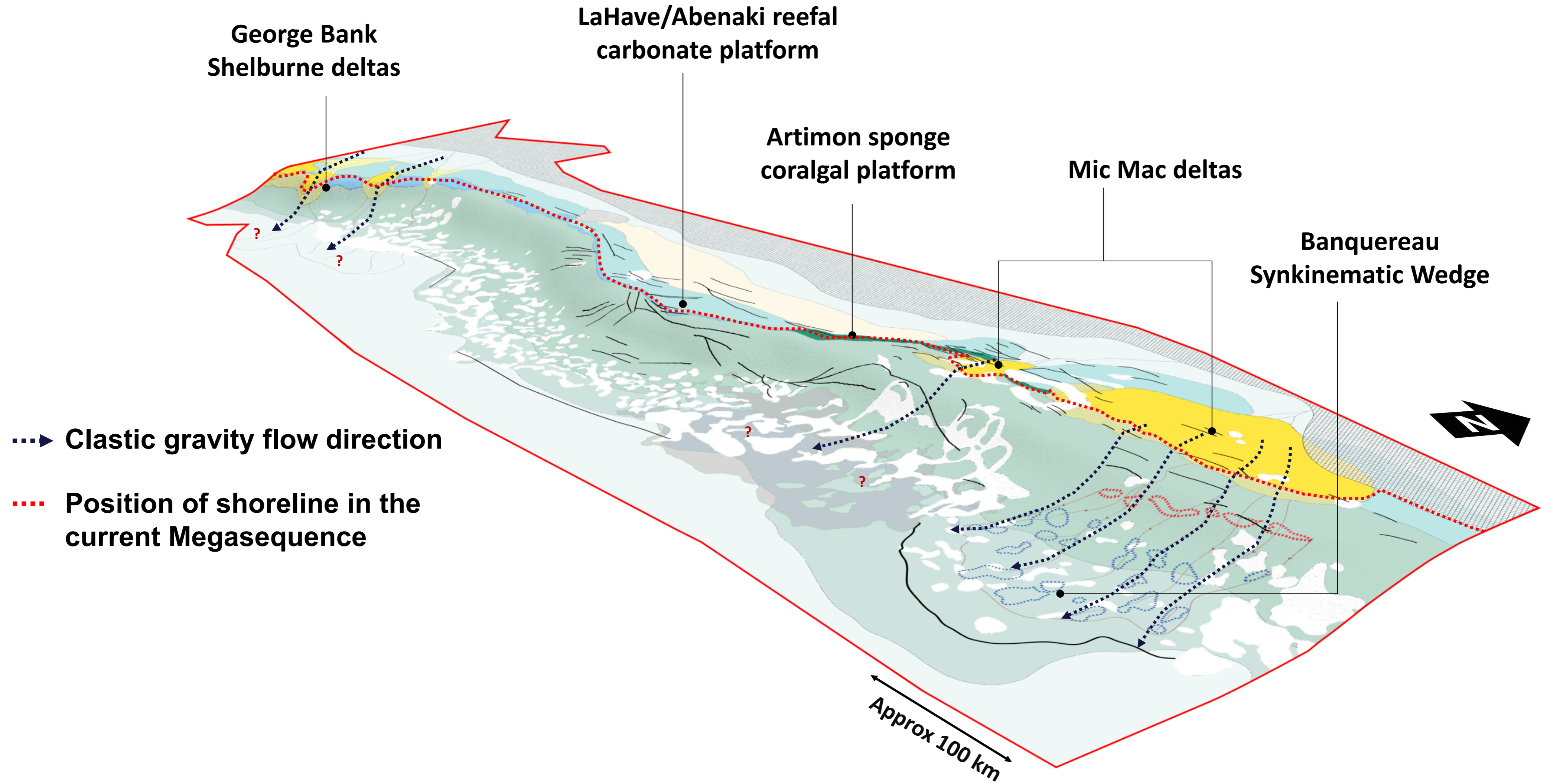
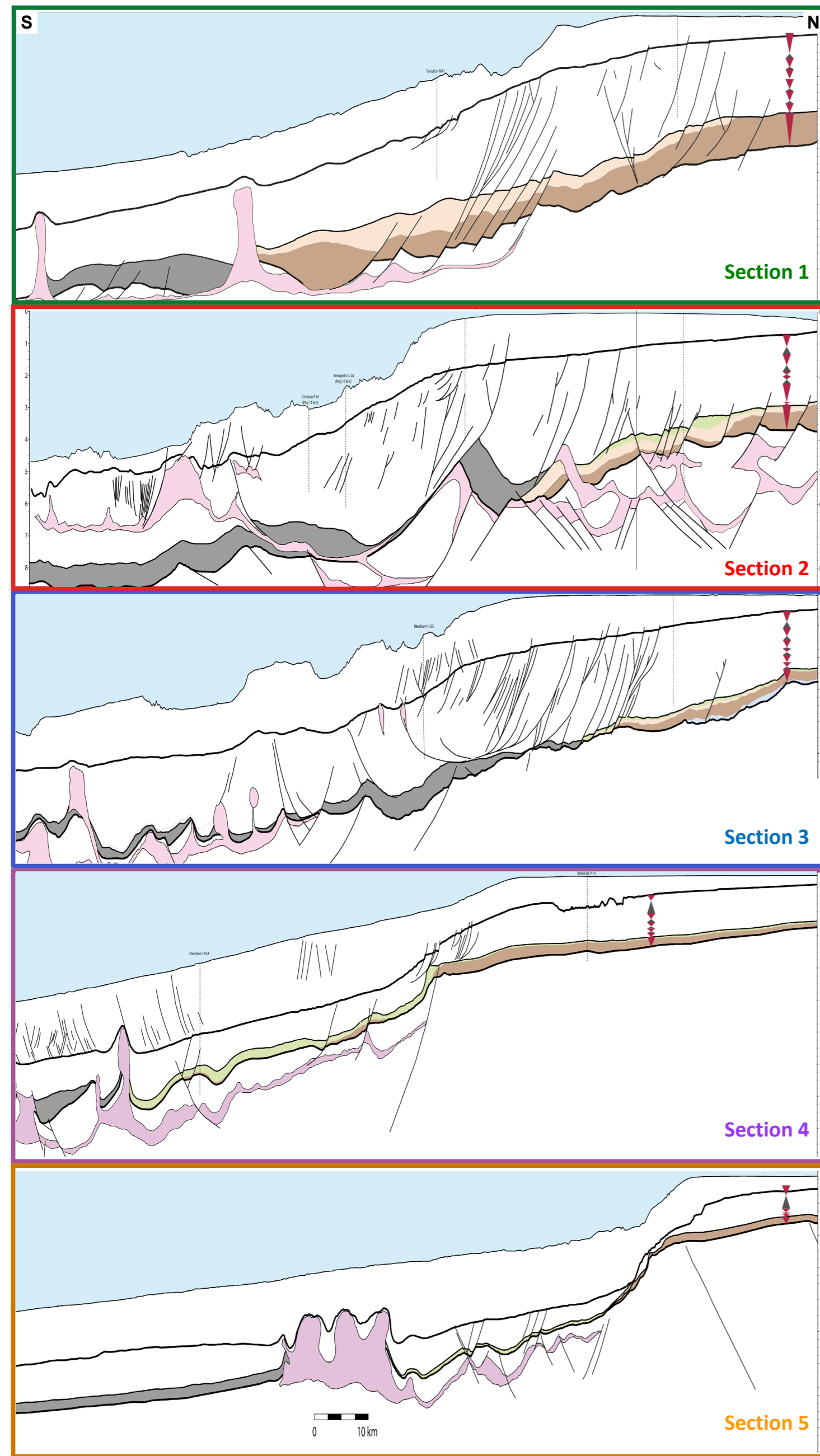


Figure 20: Megasequence 1 - General 3D view of the GDEs and direction of the main sedimentary fairways (see previous plate for GDE legend)

## Megasequence 1 – Tithonian – Top Abenaki/Mic Mac Formation – Sediment distribution



The stratigraphic interval corresponding to the first megasequence described in the Upper Jurassic is displayed on the regional sections to the left. It shows a clear change of sediment thickness and spatial distribution from east to west, with large volumes of sediment delivered to the shelf and slope on the eastern end of the margin, and that evolved rapidly to the west to a starved slope and basin, coeval with aggrading tabular sedimentation on the shelf.

This resulted from an eastern active river system (the proto Saint Lawrence River), that delivered clastic sediments toward the Upper Jurassic shelf, hence creating the Mic Mac delta. Remnant prominent forced regressive wedge visible on the red section is in line with a probable western extension of the Mic Mac delta, along the eastern end of the Abenaki platform.

Further west the slope apron tabular and aggrading shape of the shelf edge is linked with the onset of a significant carbonate reefal to shoaling platform, known as the Abenaki Formation.

In the westernmost portion of the study area, the Upper Jurassic sedimentation thickening, with the development of an early Shelburne deltaic system, alternating with carbonate deposits during transgressive trends (see Figure 9 on Plate 3.8).

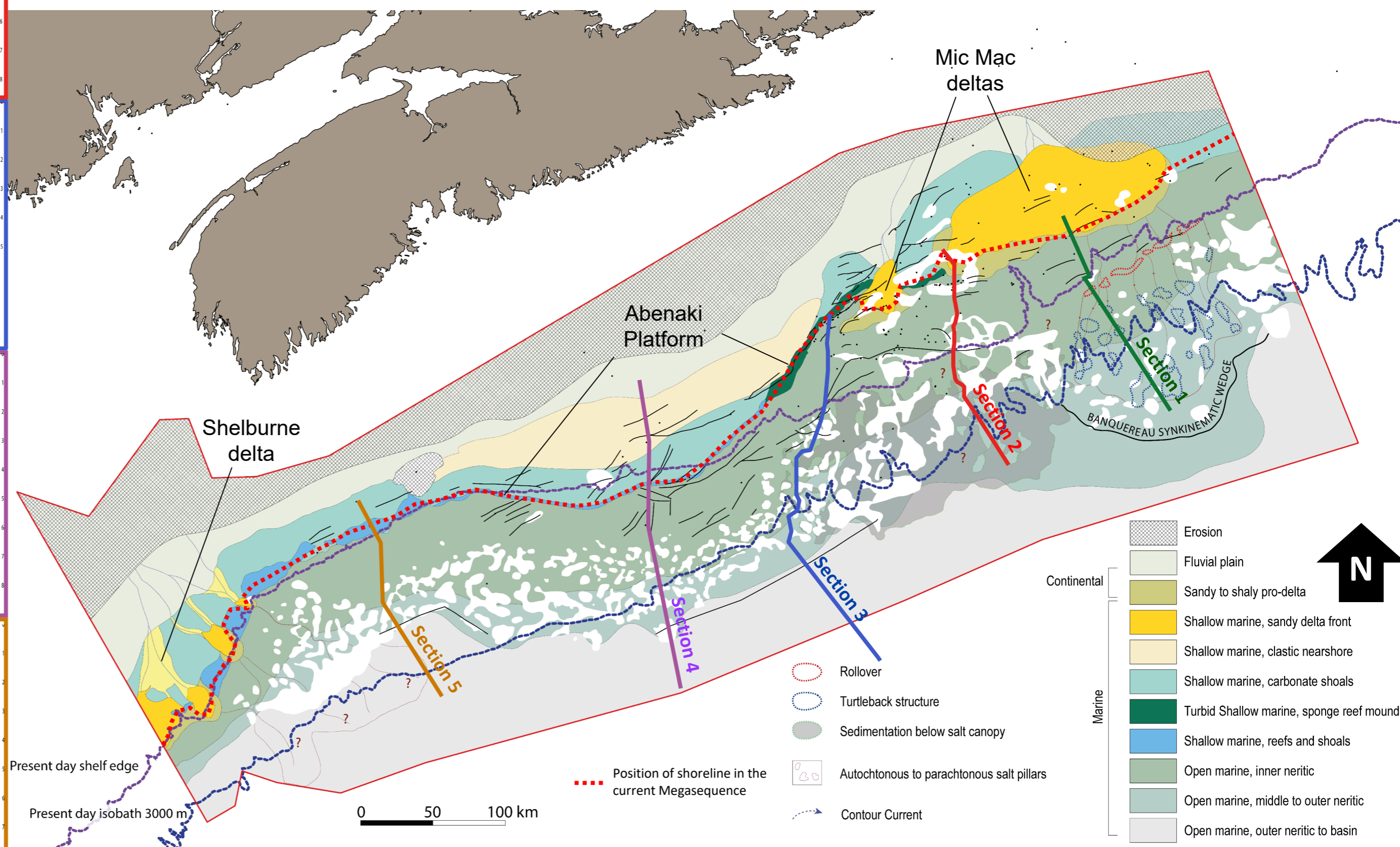
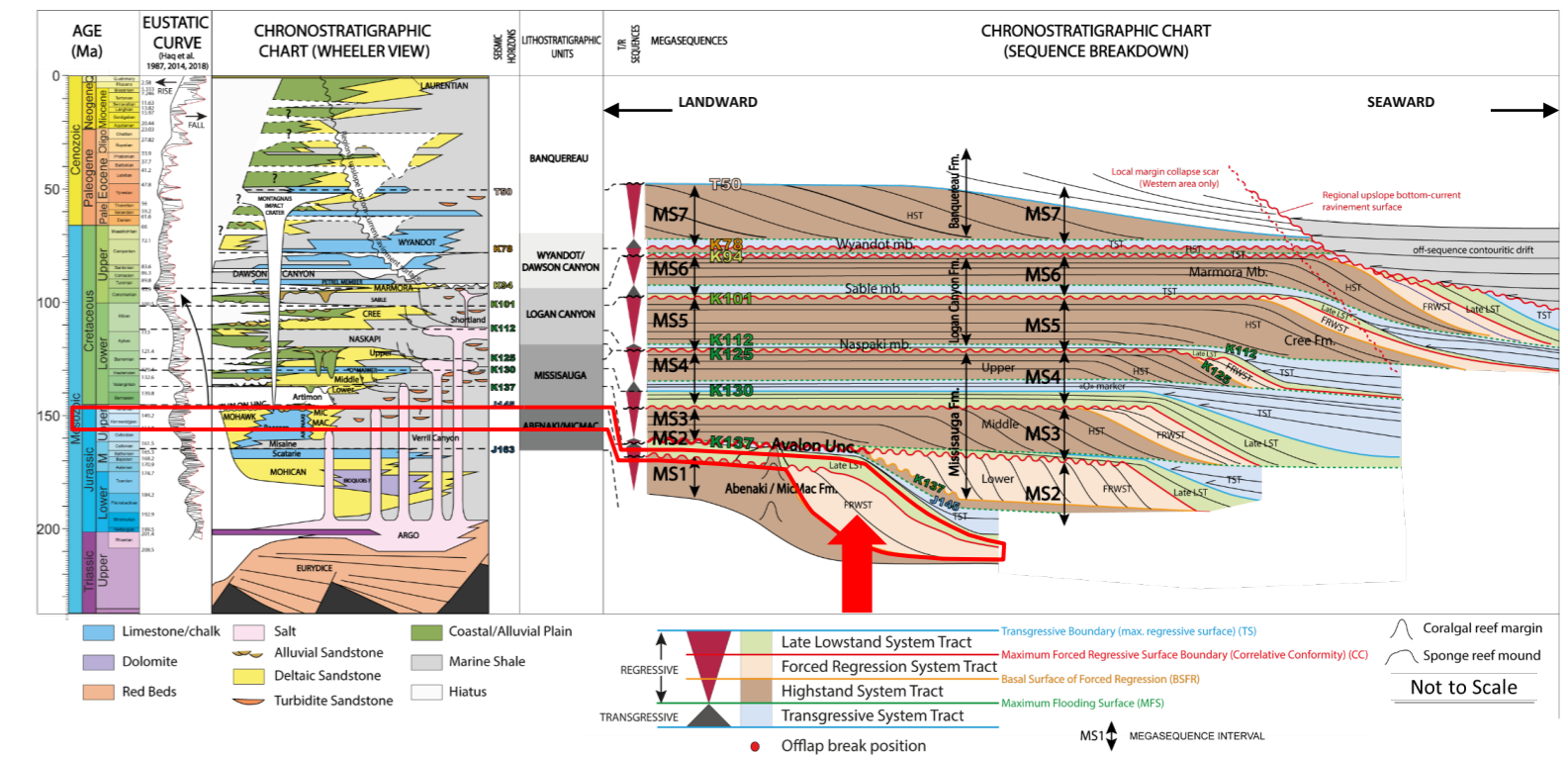


Figure 21: Megasequence 1 - Spatial sediment distribution along the Nova Scotian margin

## Megasequence 1 –Tithonian –Top Abenaki/Mic Mac Formation – Seismic and Well Information

During the uppermost Jurassic, three main domains are described along the Nova Scotia margin: two mixed carbonate/clastic deltaic systems to the East (Mic Mac deltas, Section 3) and to the west (Georges Bank/Shelburne deltas, see plate 3.8), and a carbonate platform (Abenaki Formation) in the central domain (Section 1). The nature of the carbonate factory varies along strike with respect to terrigenous input influence. We observe more carbonate reefal barrier with tidally influenced oolitic shoals in the central part, whilst to the east and west more clastic influence with foramal biological assemblages (spiculite, echinoderms, sponge, Section 2 and Panuke M-79 log).

To the east, the Mic Mac deltaic system displays a prominent forced regressive wedge as shown on Section 3. A lateral tributary of the Mic Mac delta is probably present to the west beneath the present day Sable Island, as already described in the 2016 Central Scotian Slope Atlas (correlation panel 1 and east of Section 2).

Finally, the Banquereau detachment wedge zone to the east created large growth faults at the shelf edge that were tectonically balanced basinward by compressive salt diapirs (Section 4).

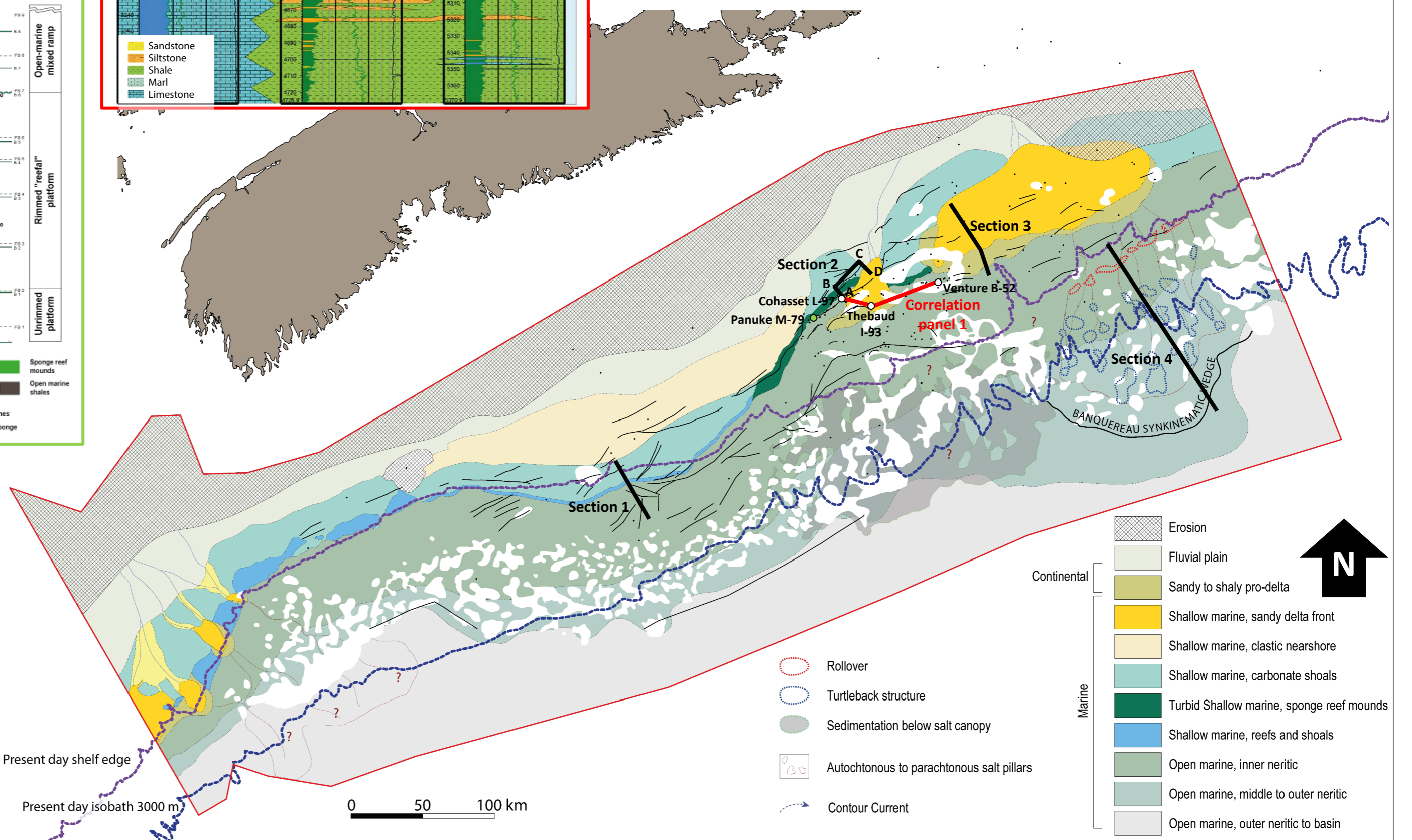
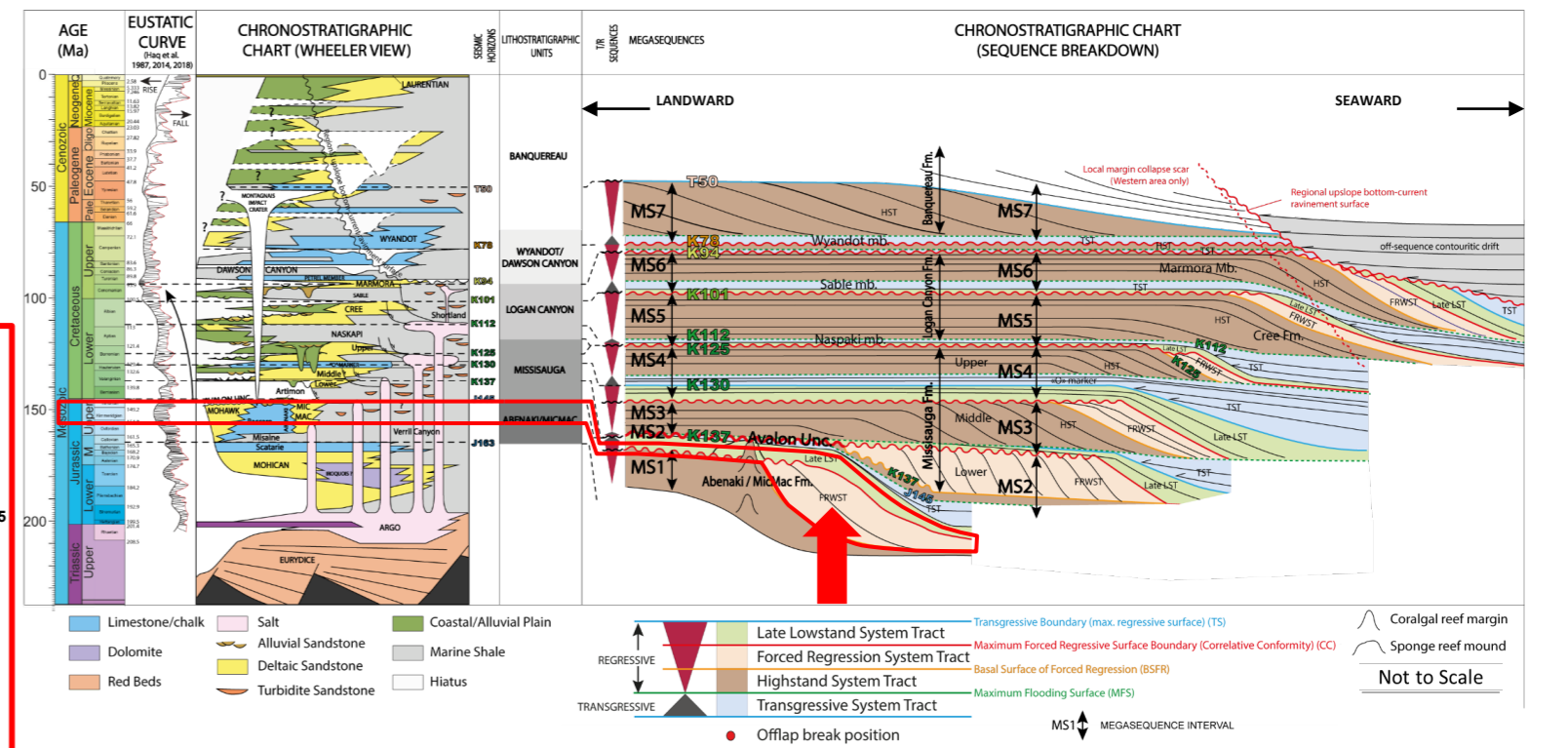
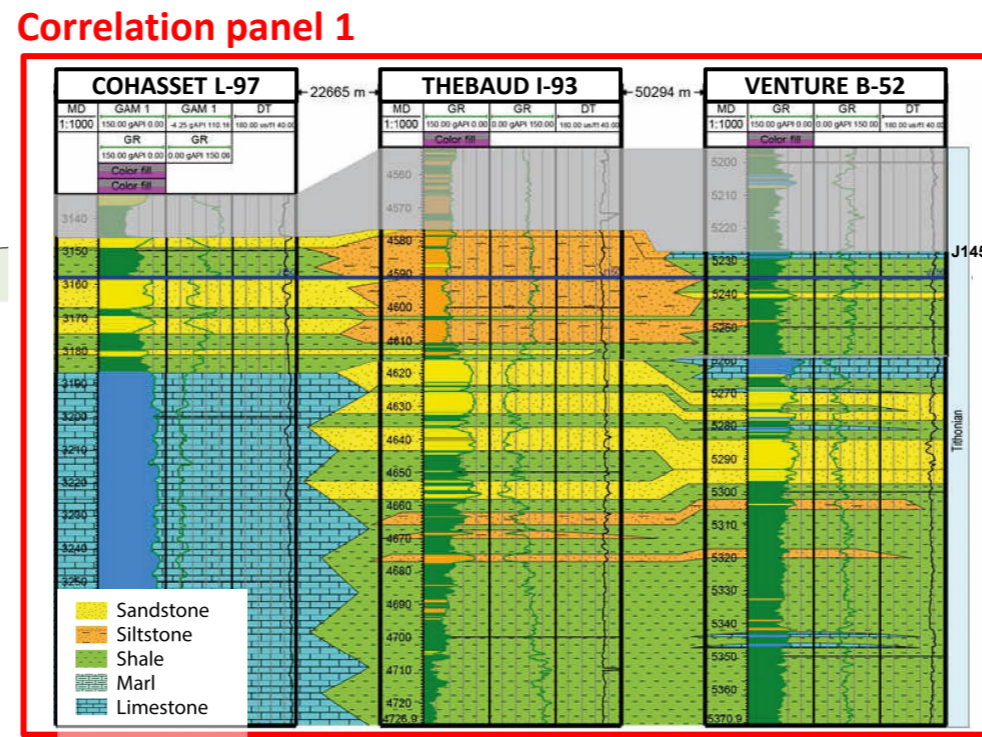
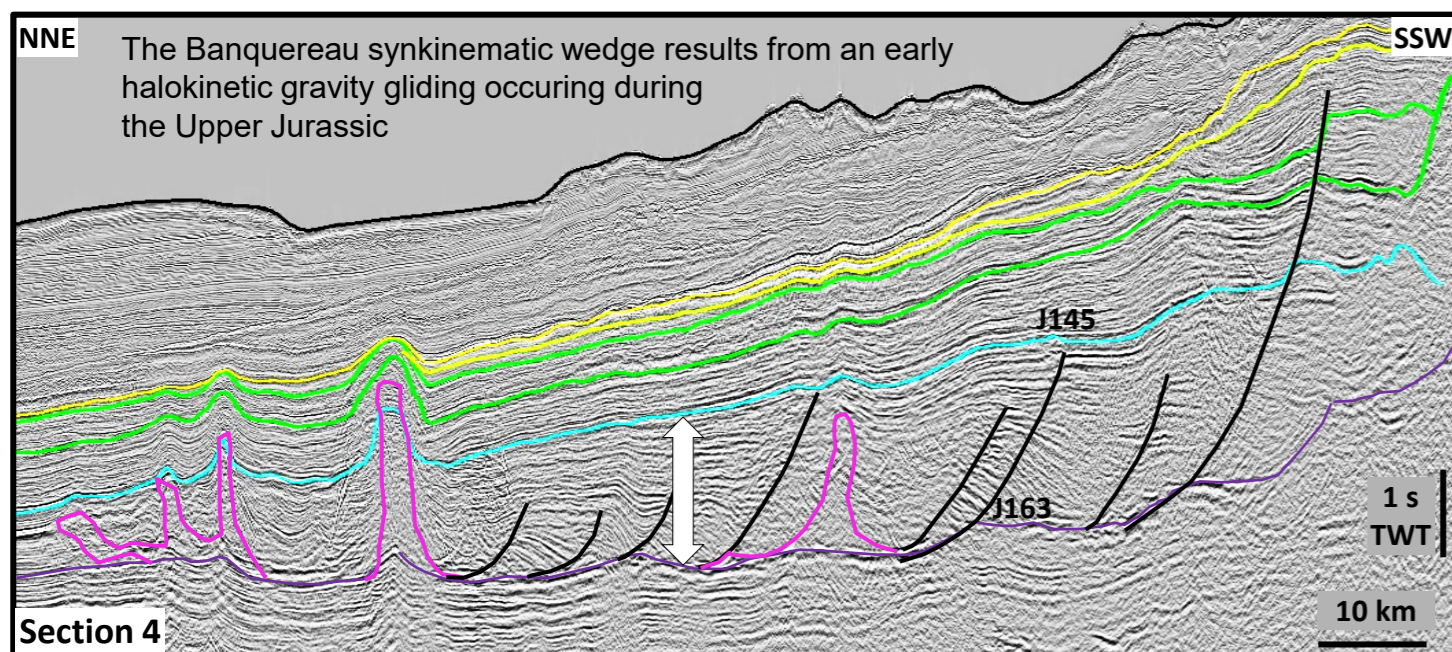
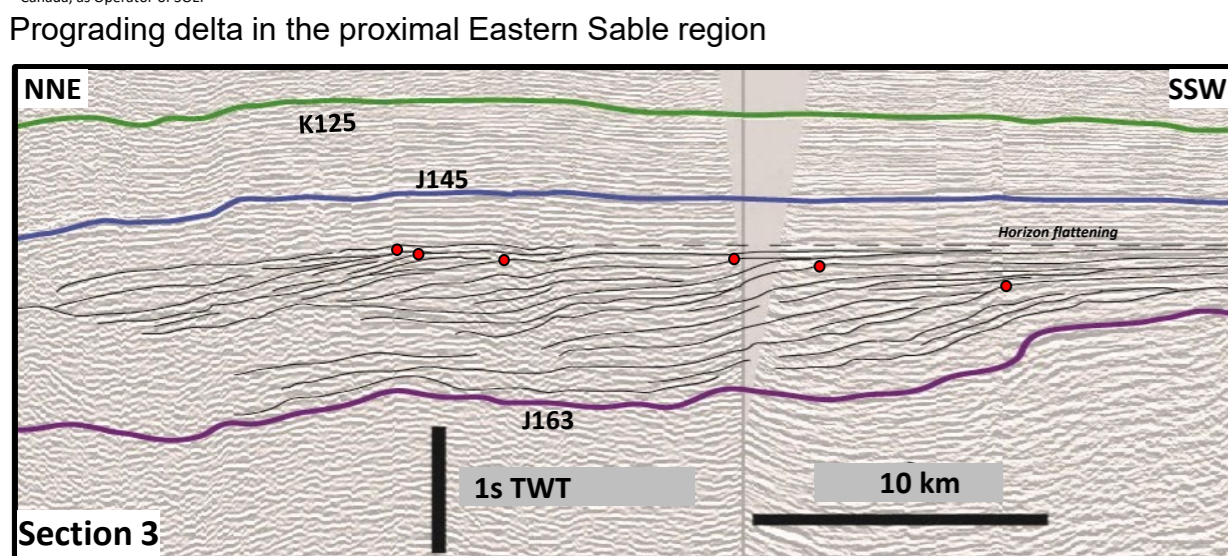
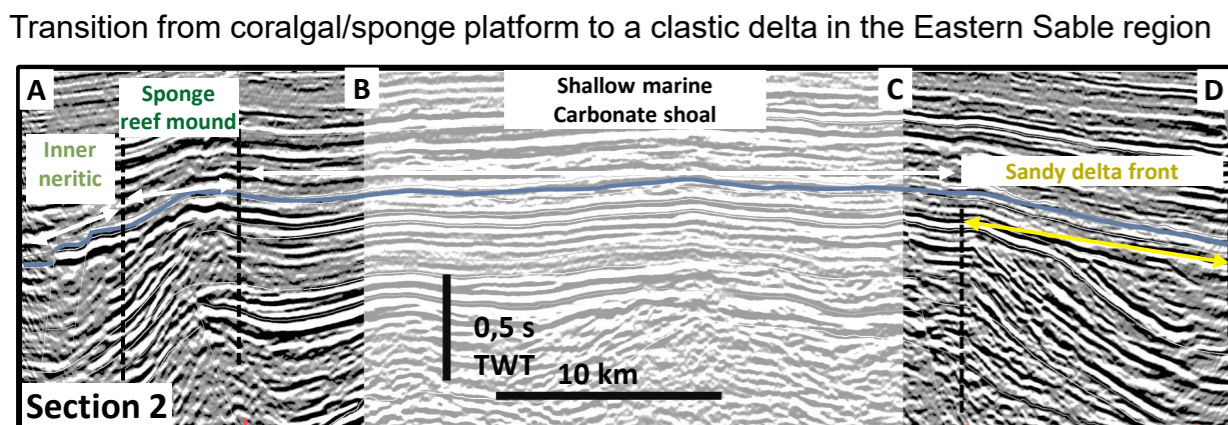
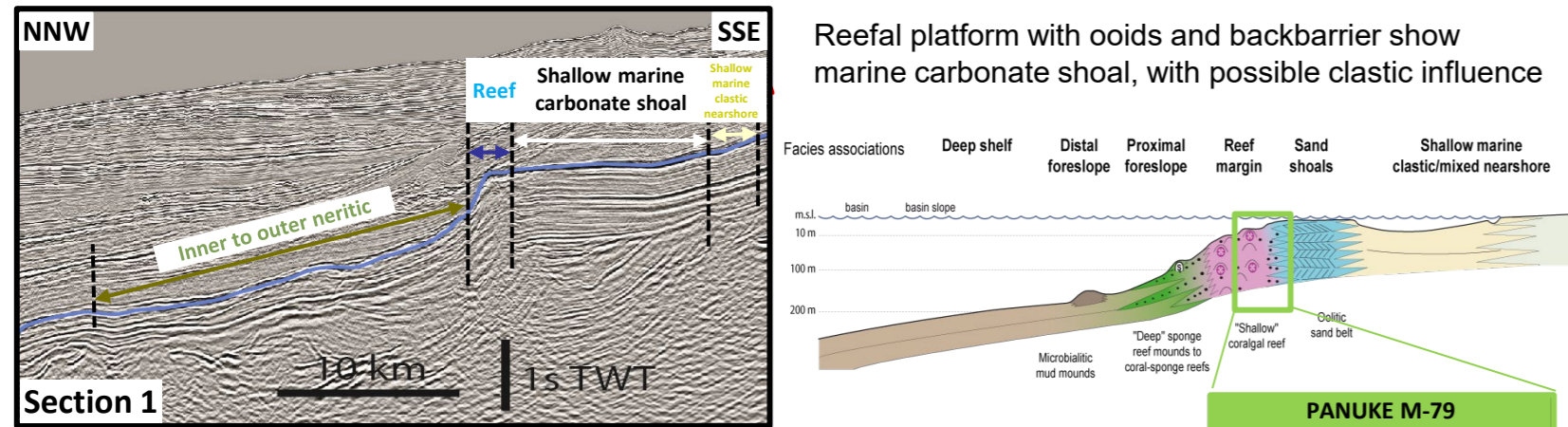


Figure 22: Megasequence 1 – Seismic examples of sedimentary objects and well lithofacies correlation panel

# Gross Depositional Environment Mapping

Scotian Basin Integration Atlas 2023 - CANADA - June 2023

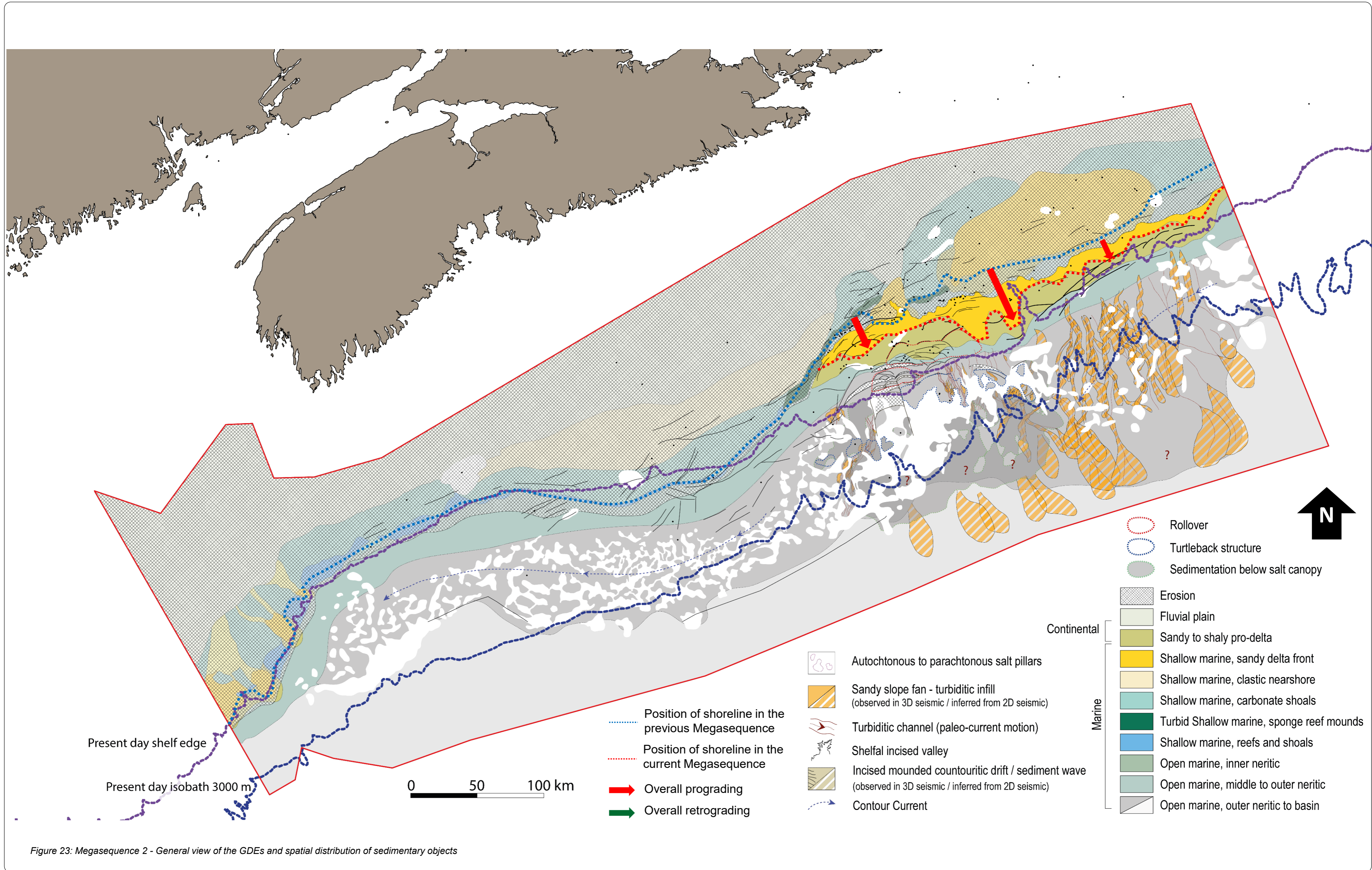


Figure 23: Megasequence 2 - General view of the GDEs and spatial distribution of sedimentary objects

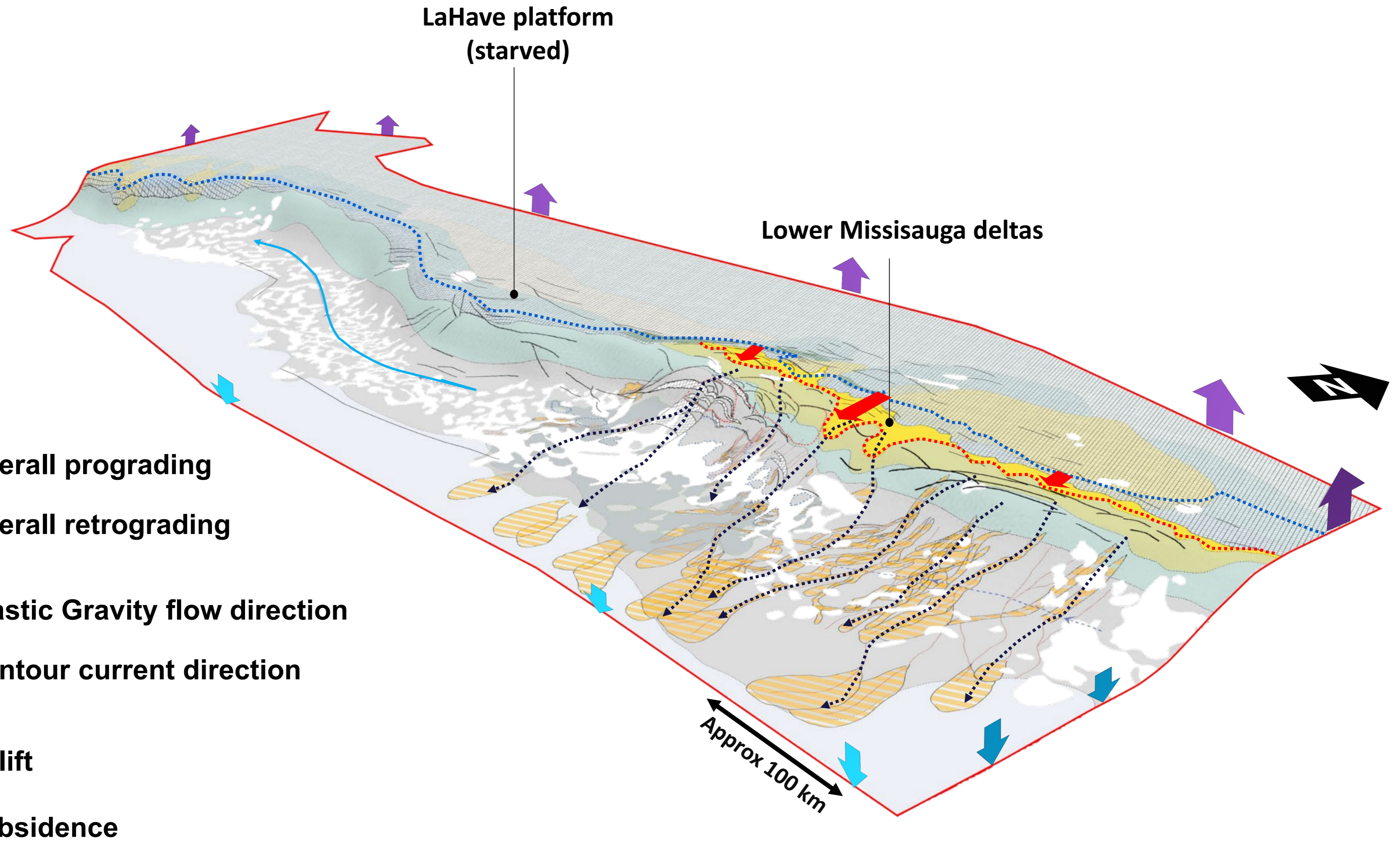
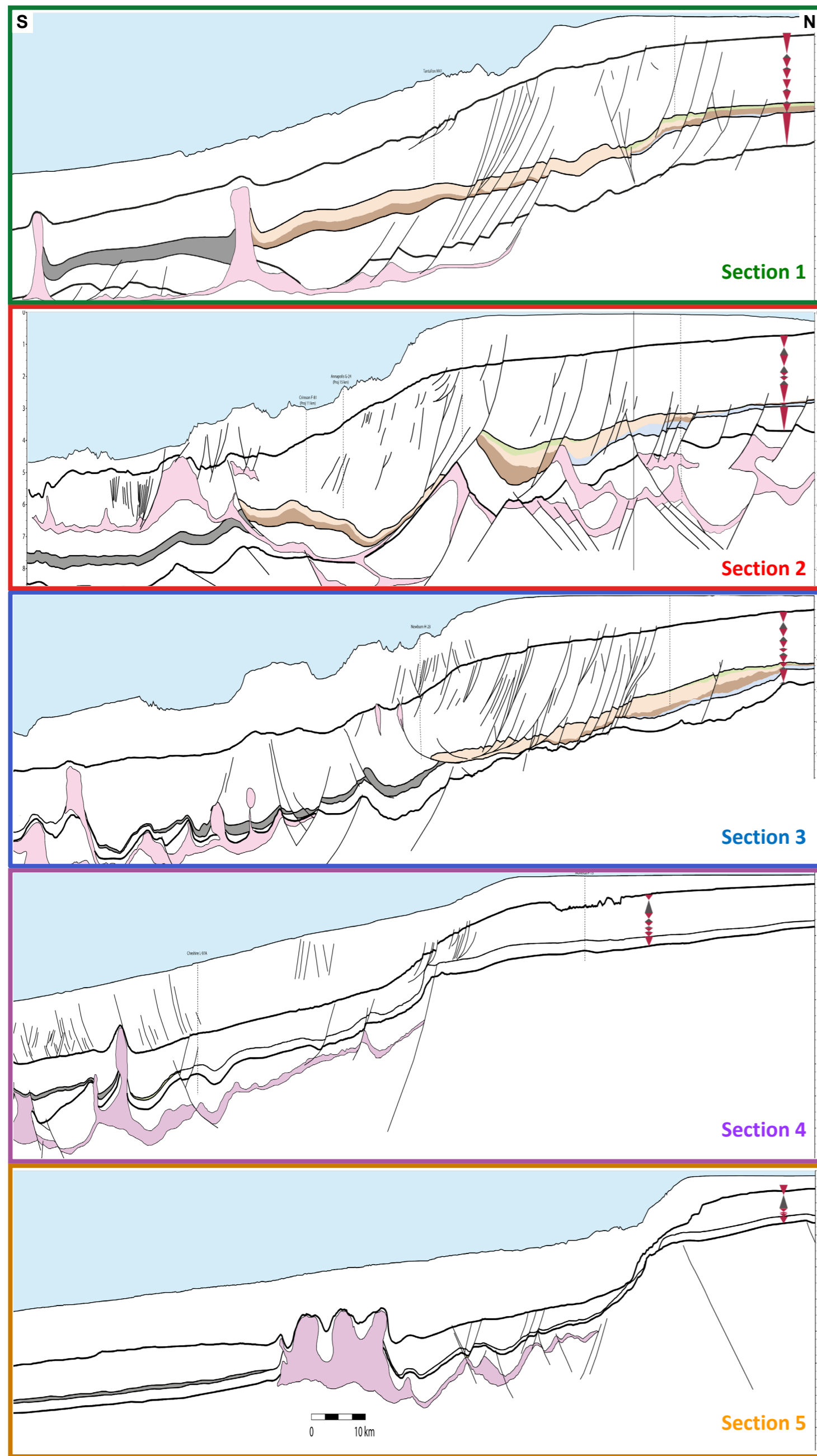


Figure 24: Megasequence 2 - General 3D view of the GDEs and direction of the main sedimentary fairways (see previous plate for GDE legend)

## Megasequence 2 – Berriasian – Near Base Cretaceous Unconformity/Lower Missisauga Formation – Sediment distribution



This stratigraphic interval corresponds to the 2<sup>nd</sup> megasequence. The sediment distribution and thickness is displayed on the regional sections to the left and displays a clear thinning of the sequence to the west, which demonstrates the westward progressive decreasing of clastic supply from the eastern proto-Saint Lawrence river.

Such lateral variation of the sediment thickness could also be explained by the Avalon uplift on the margin that occurred during the Berriasian. The uplift partially eroded the Upper Jurassic Mic Mac delta to the east, remobilizing large amount of clastics further south.

However, further west, the effect of the uplift differs considerably. The exhumation of the underlying carbonate platform in the LaHave region led to the dissolution of carbonates, hence leading to sediment starvation in the deep-water environment.

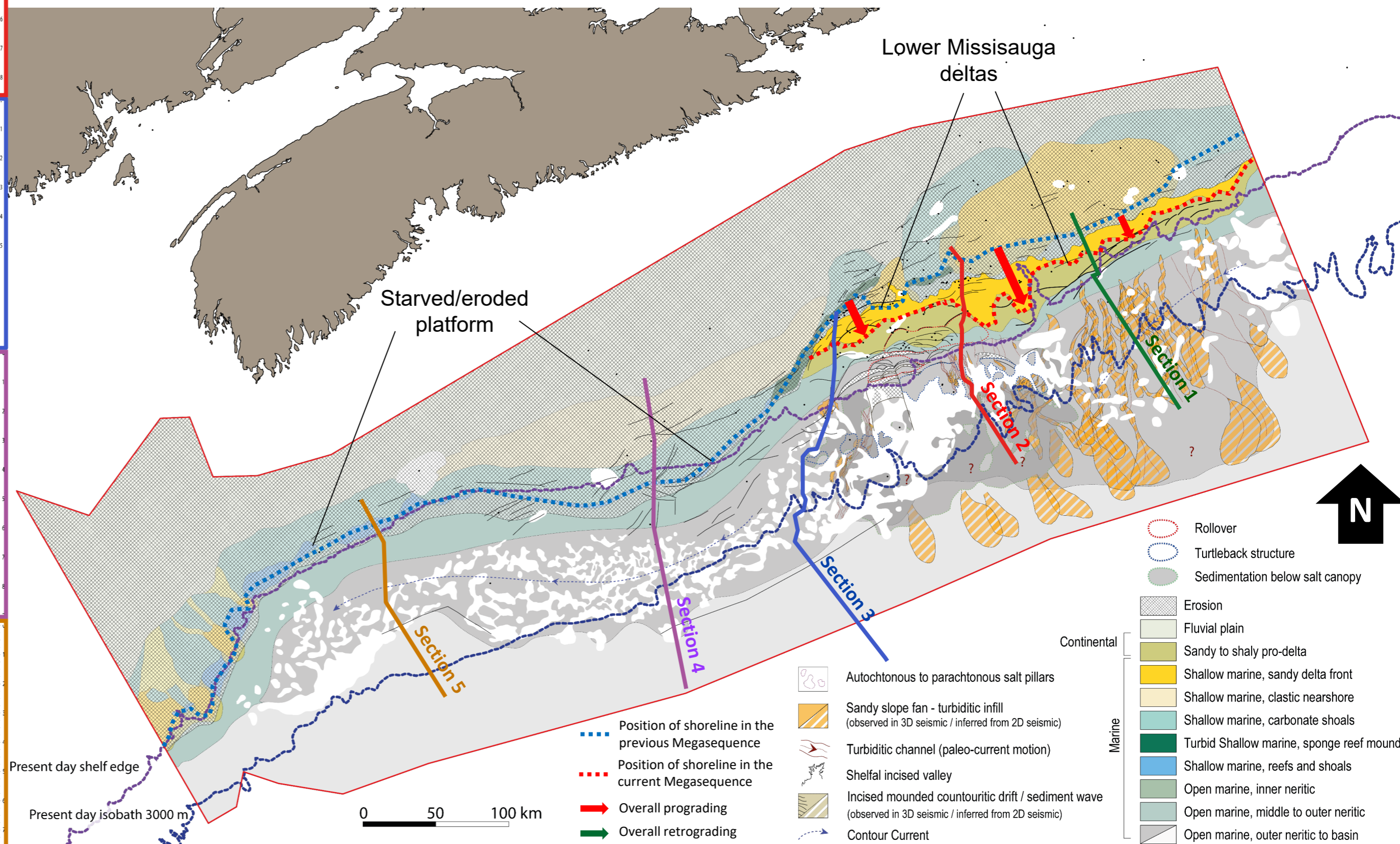
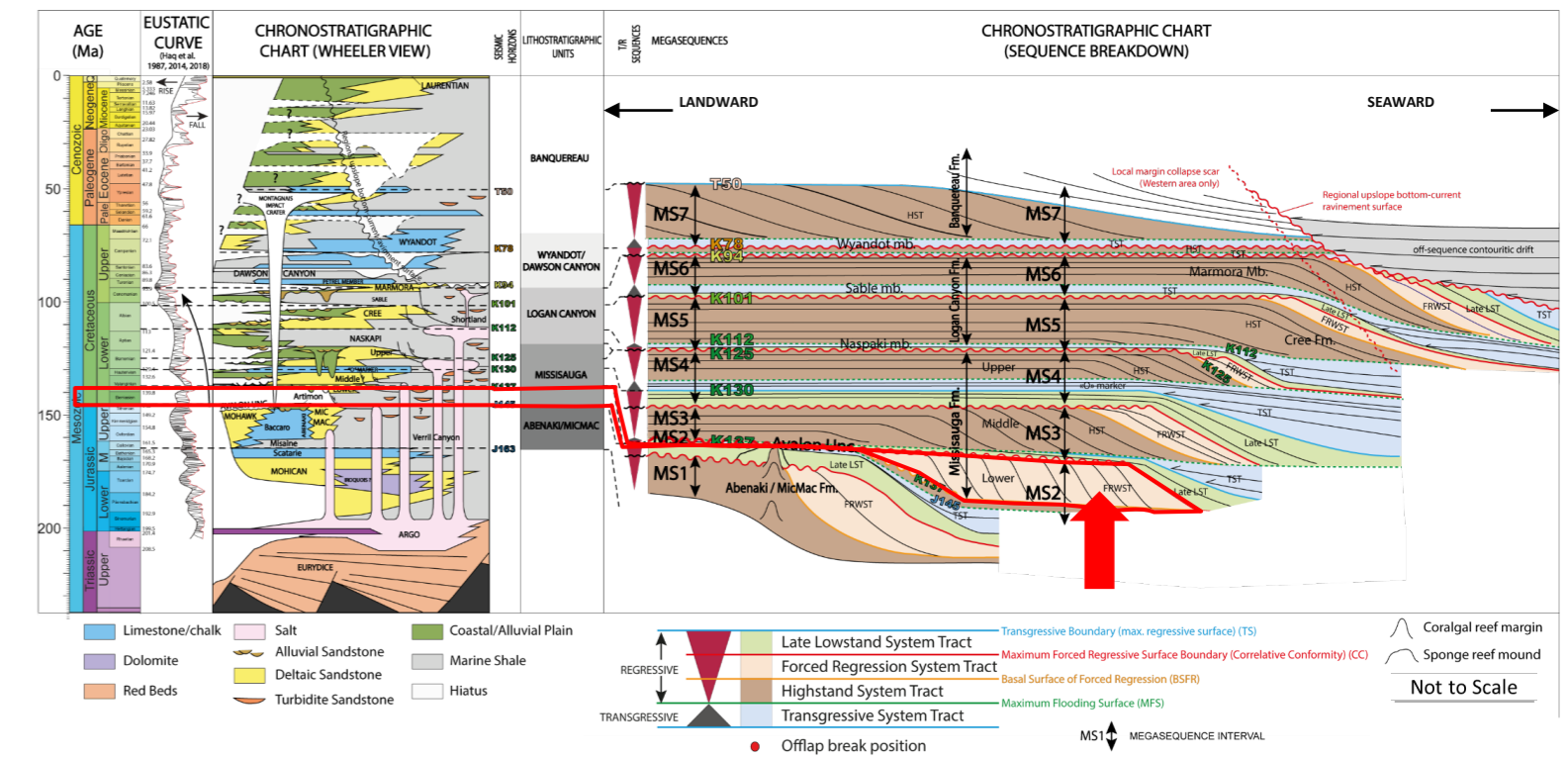
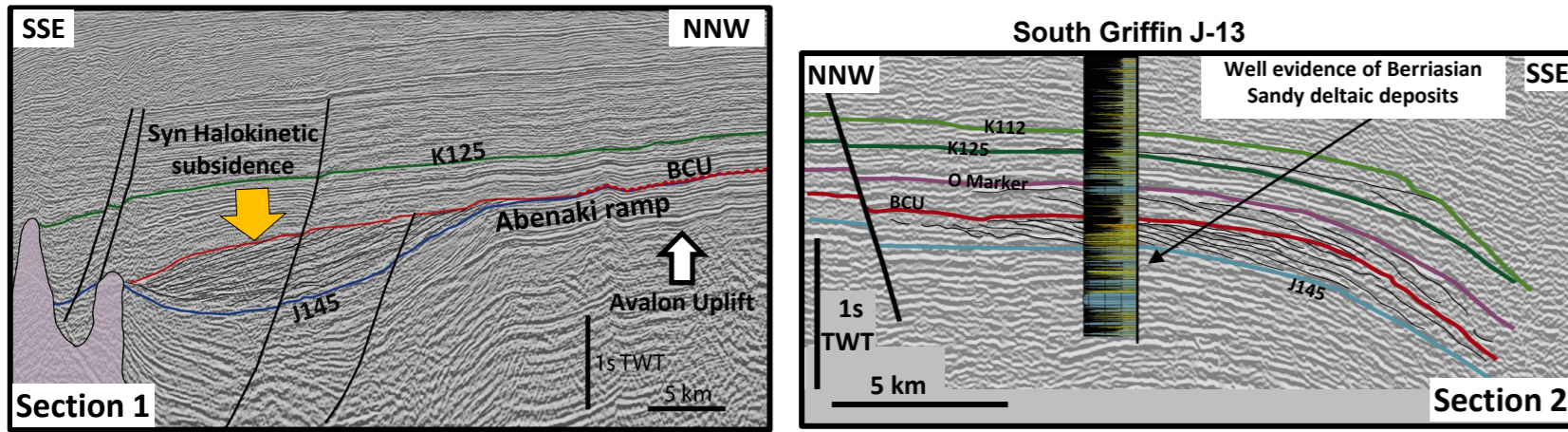


Figure 25: Megasequence 2 - Spatial sediment distribution along the Nova Scotian margin

## Megasequence 2 – Berriasian – Near Base Cretaceous Unconformity/Lower Missisauga Formation – Seismic and Well Information

The Berriasian interval is characterized by a major tectonic event, regionally known as the Avalon uplift, that induced tilting and erosion of the shallow margin with concurrent drowning of the outer margin domain, leading to the formation of significant syn-halokinesis grabens in the central Sable Subbasin. This tectonic event mainly affected the shelf with significant erosion of the underlying Jurassic sediments ("Near Base Cretaceous Unconformity", also known as BCU, Section 3).

At the border of the margin, such events were previously considered as coeval with a time of low sedimentation rate and condensed sequences. The new sequence stratigraphic approach used in this study allowed connection to the shelfal BCU with a prominent forced regressive delta (Section 1) that is spreading along the eastern part of the study area, and that is filling the remnant accommodation space within some grabens induced by salt gravity spreading. Further south on the eastern basin slope, the sedimentary thickness is high and a dense network of amalgamated to channelized turbiditic fans is observed, in particular in the less confined easternmost Banquereau Basin (Section 5). Turbiditic objects connectivity is less obvious in the central Scotian Slope, due to the complex salt deformation, which lead to the segmentation of numerous minibasins (Section 4).



Seismic examples and well correlation of the Berriasian forced regressive wedge, coeval with the proximal BCU. The formation/member equivalent is the lower part of the Missisauga.

### Correlation panel 2

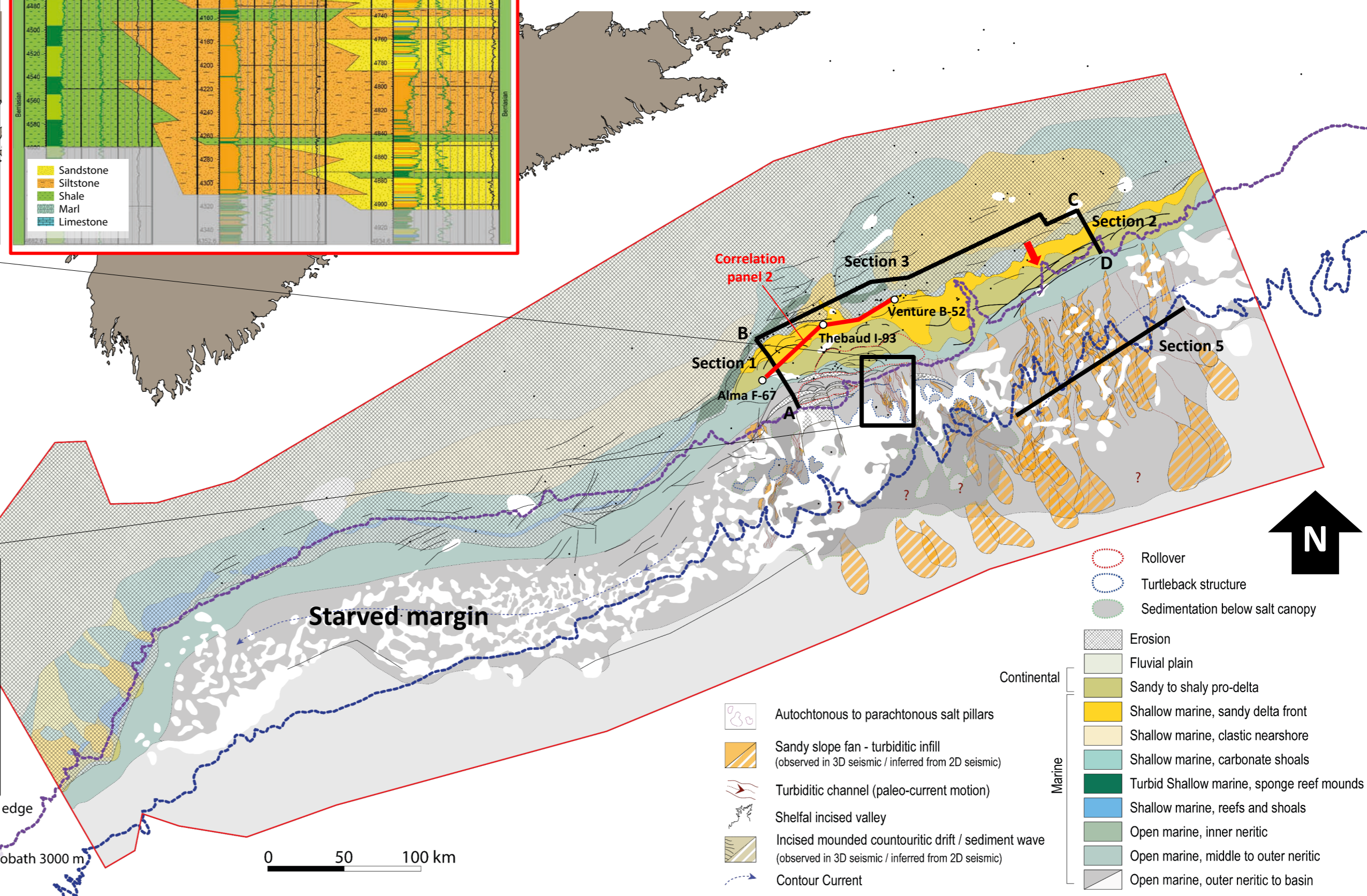
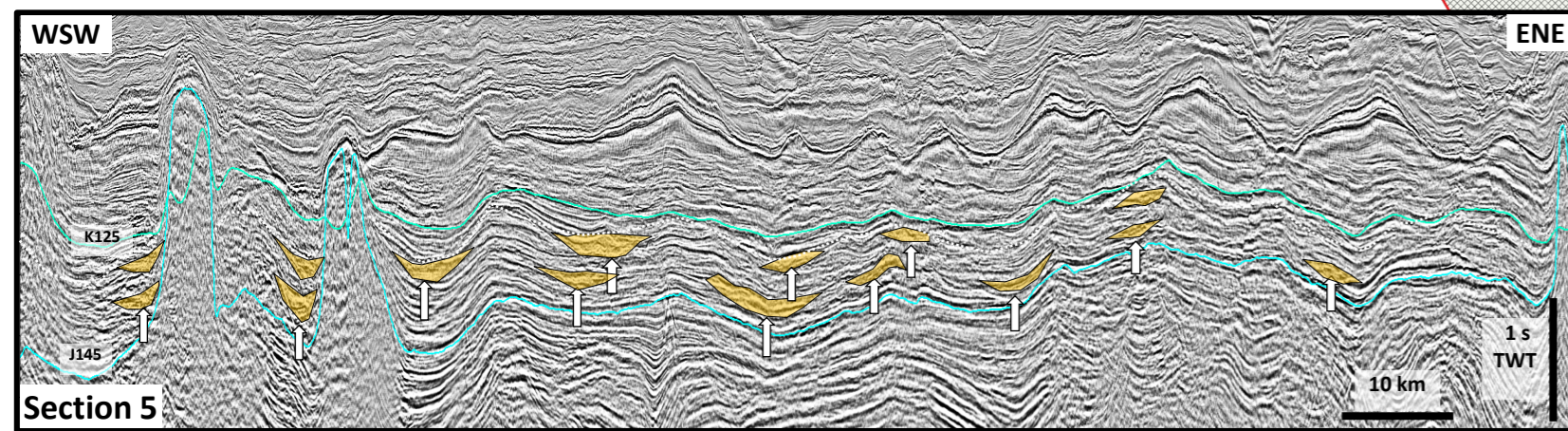
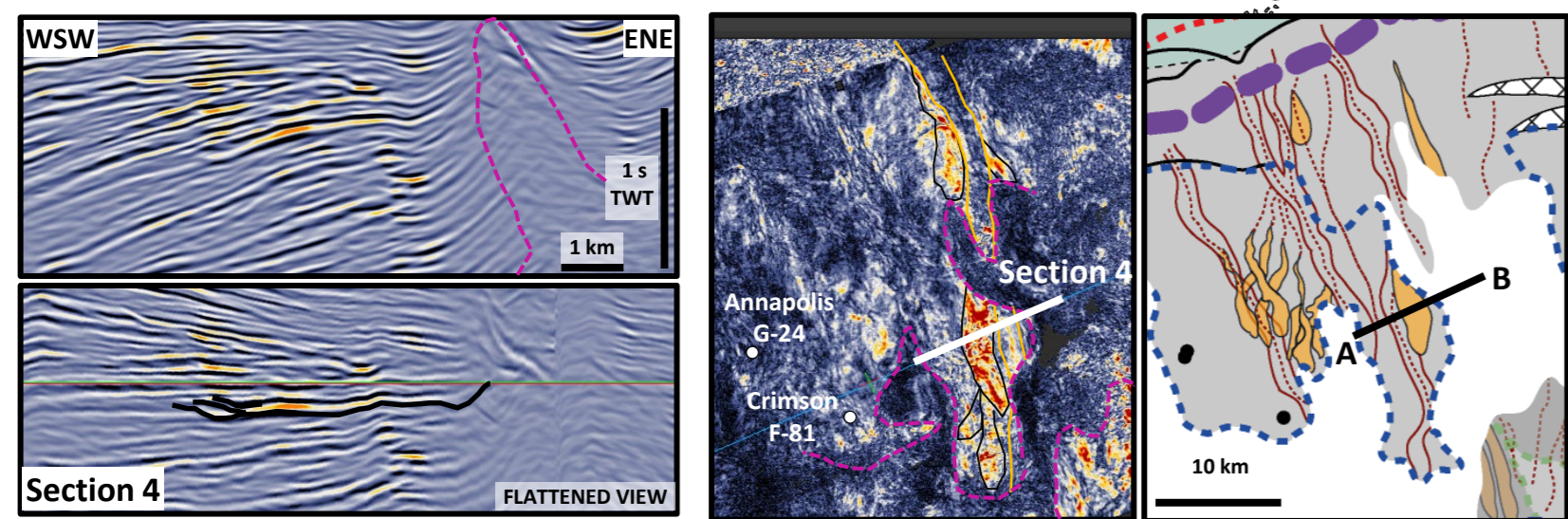
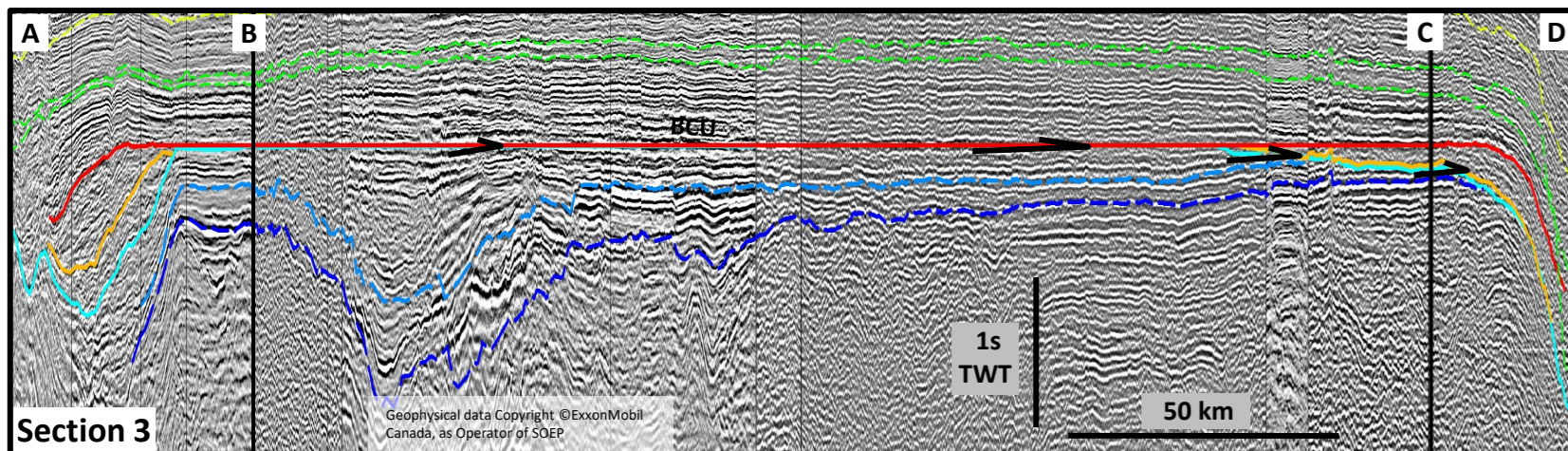
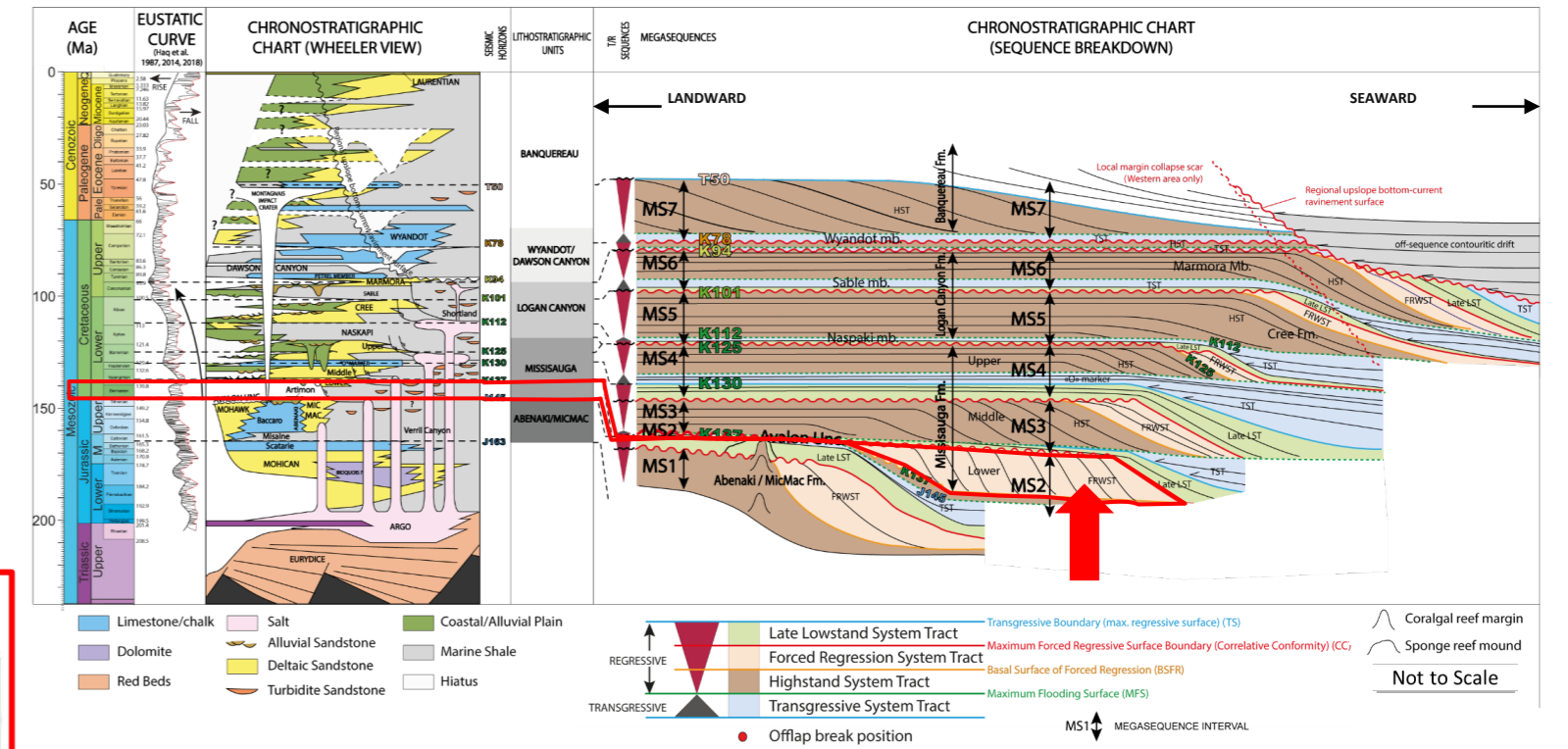
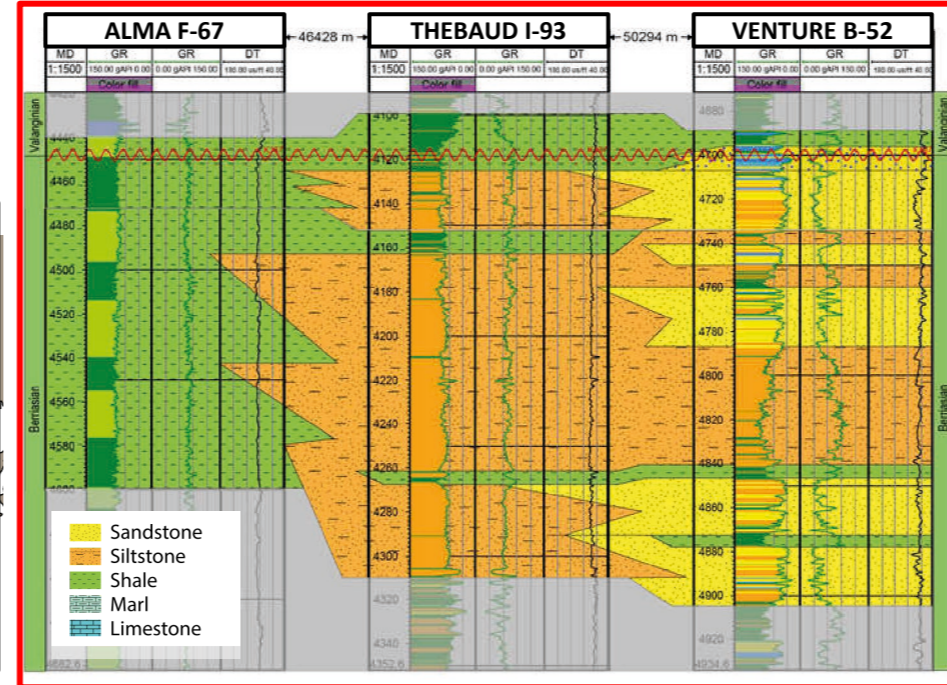


Figure 26: Megasequence 2 – Seismic examples of sedimentary objects and well lithofacies correlation panel

# Gross Depositional Environment Mapping

Scotian Basin Integration Atlas 2023 - CANADA - June 2023

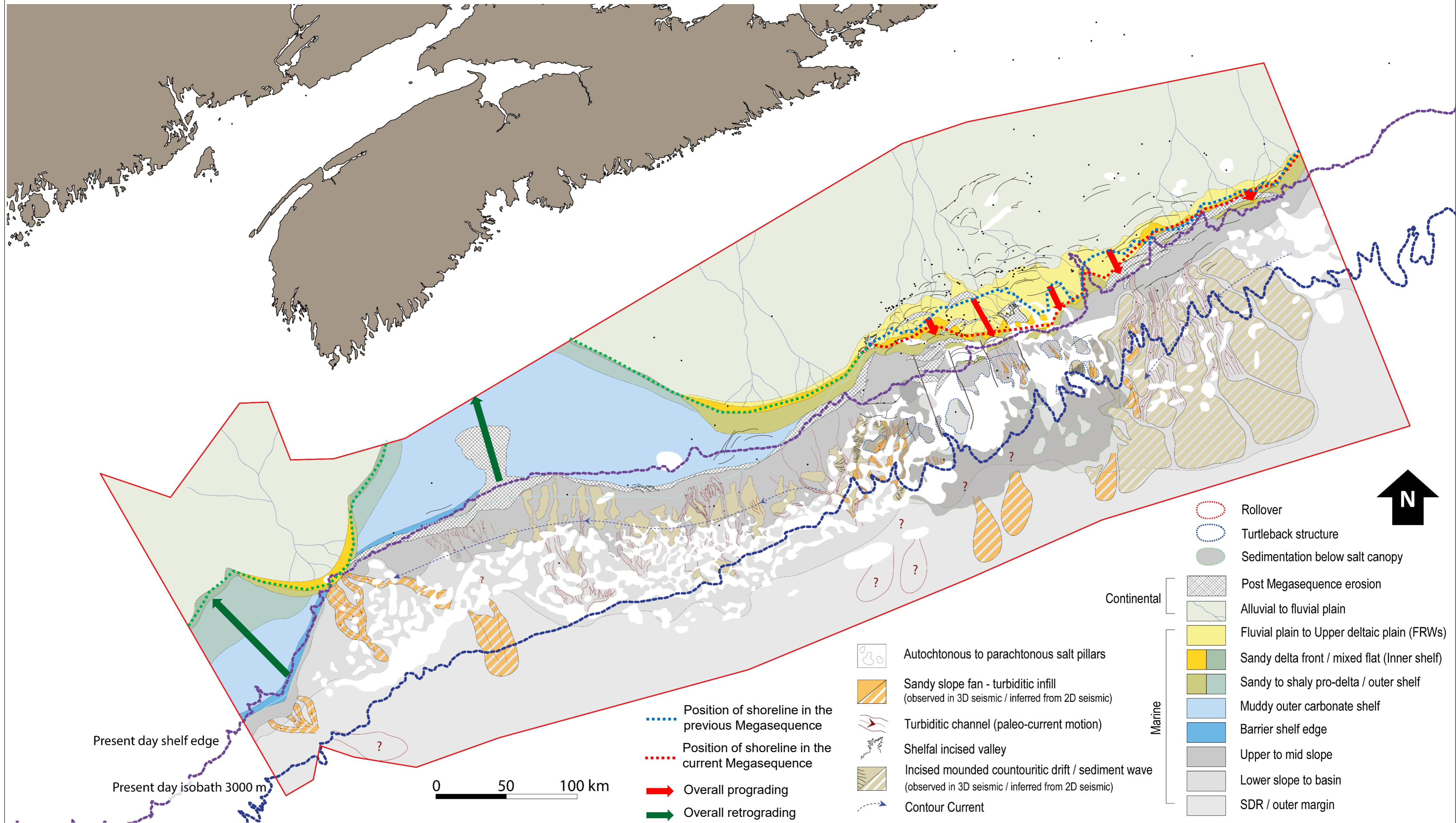


Figure 27: Megasequence 3 - General view of the GDEs and spatial distribution of sedimentary objects

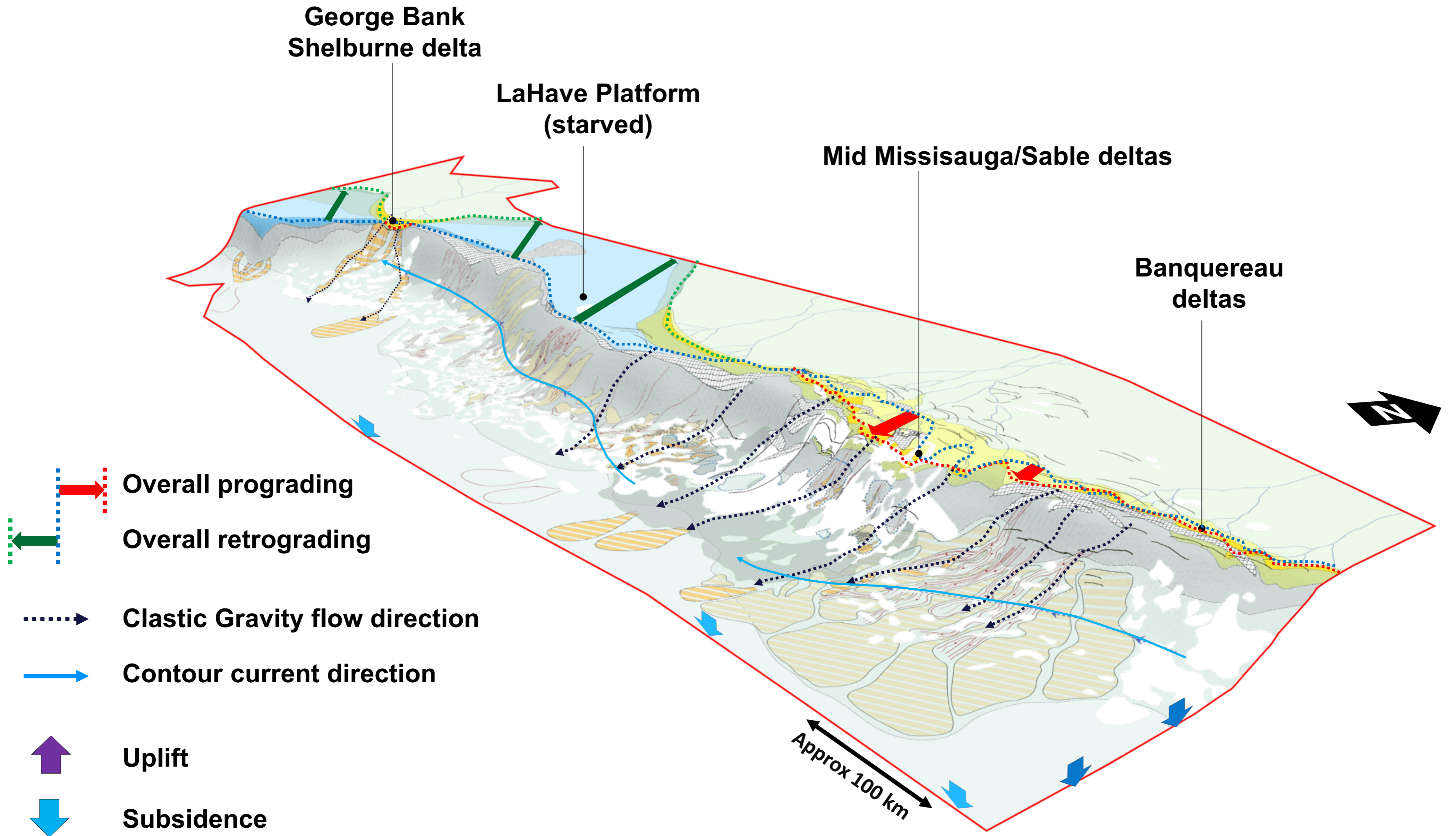


Figure 28: Megasequence 3 - General 3D view of the GDEs and direction of the main sedimentary fairways (see previous plate for GDE legend)

## Megasequence 3 – Hauterivian – Middle Missisauga Formation – Sediment distribution

The end of Valanginian and Hauterivian interval marked the continuation of the Missisauga deltaic progradation to the east and a coastal retrogradation onto the the pre-existing LaHave carbonate platform to the west.

This induced a strong variation of the sediment thickness from a thick eastern margin clastic sediment succession, to a starved margin on central/western LaHave platform, as observed in sections 4 and 5, and an easternmost moderately thick intra-shelf delta on Georges Bank (see Figure 9 on plate 3.8).

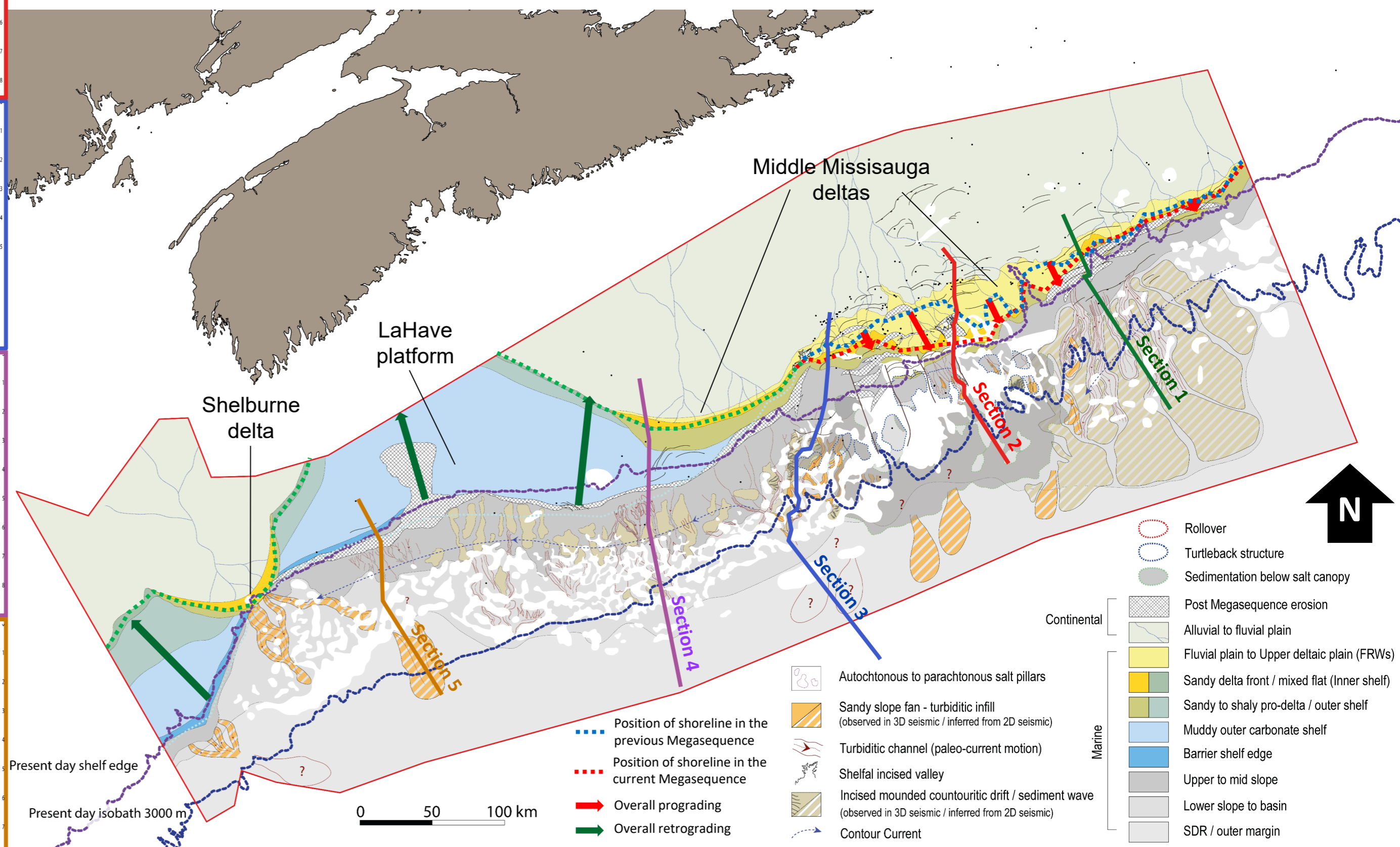
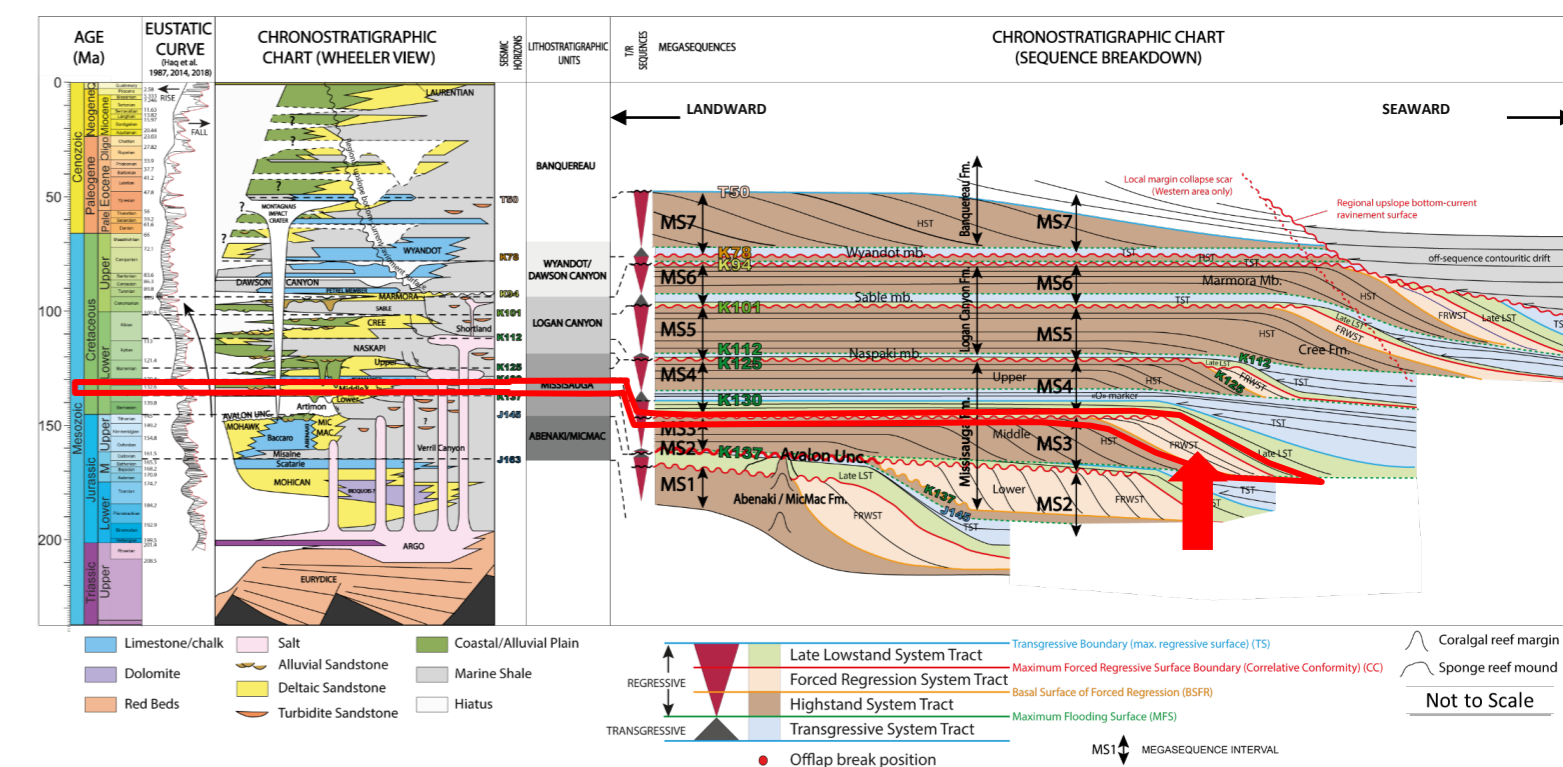
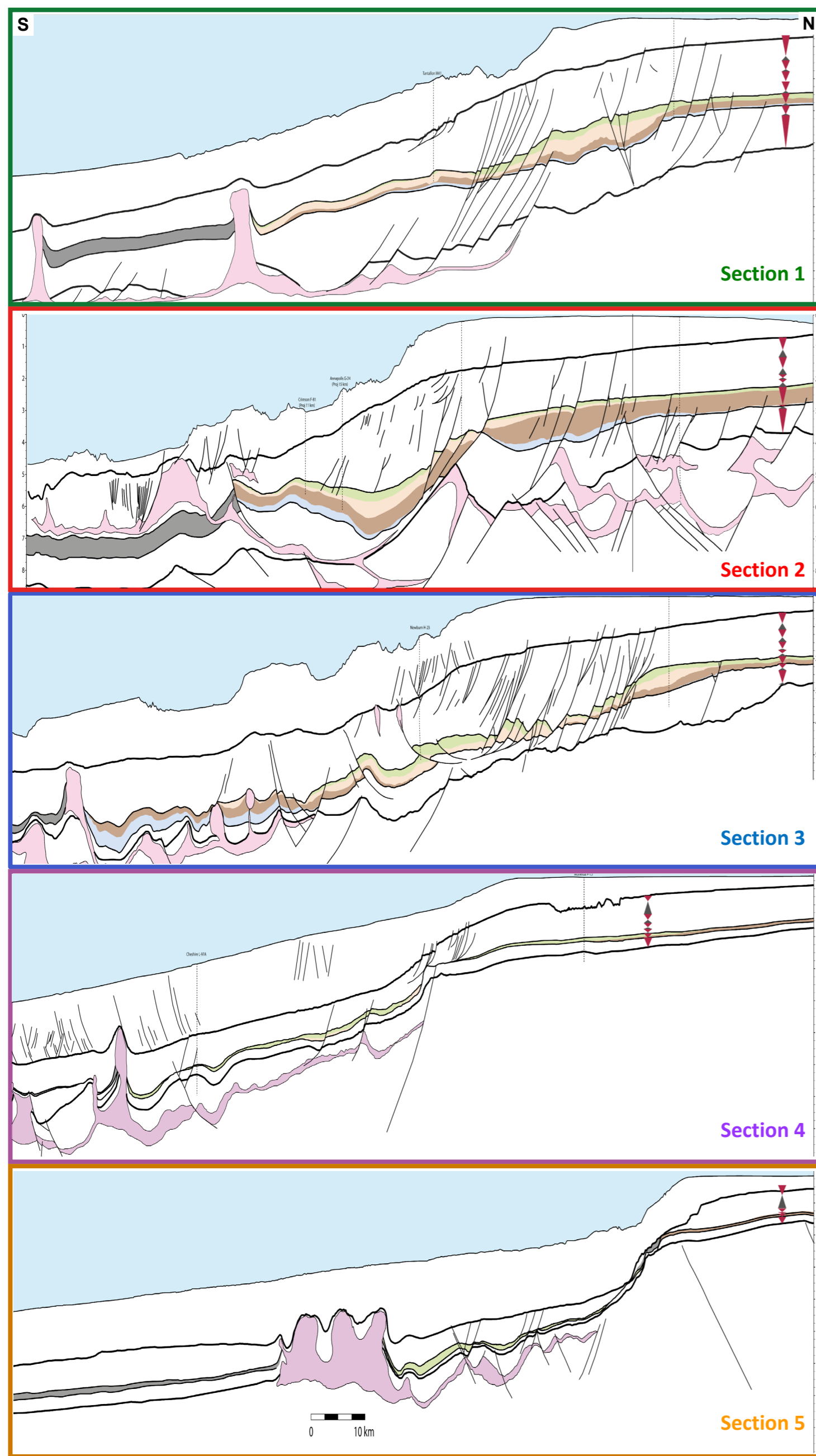


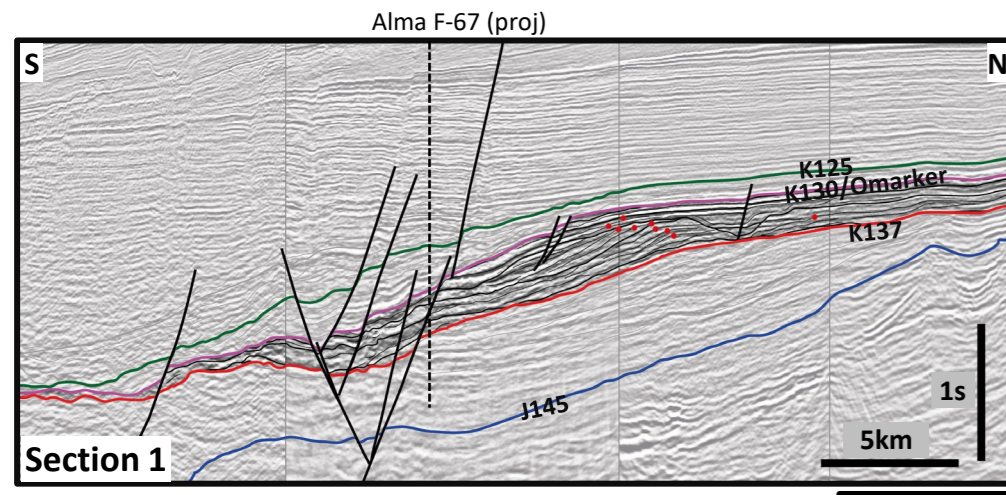
Figure 29: Megasequence 3 - Spatial sediment distribution along the Nova Scotian margin

## Megasequence 3 – Hauterivian – Middle Missisauga Formation – Seismic and Well Information

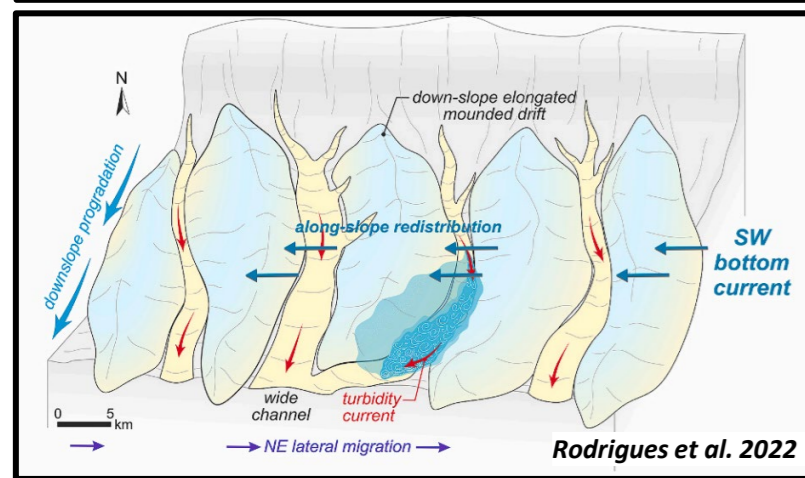
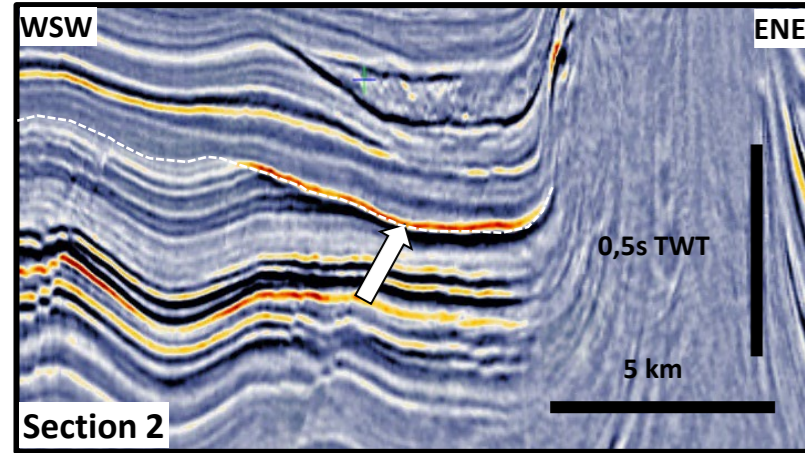
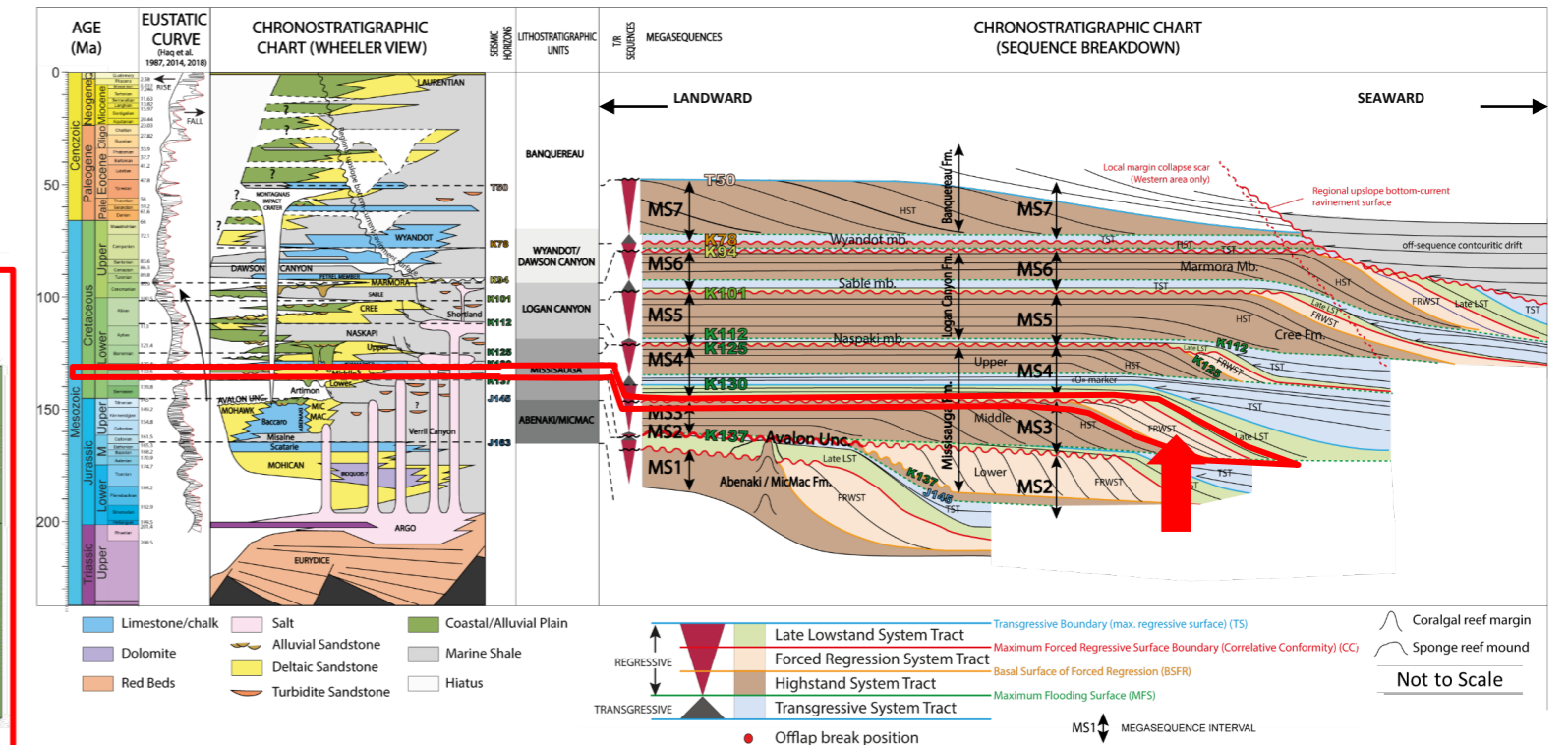
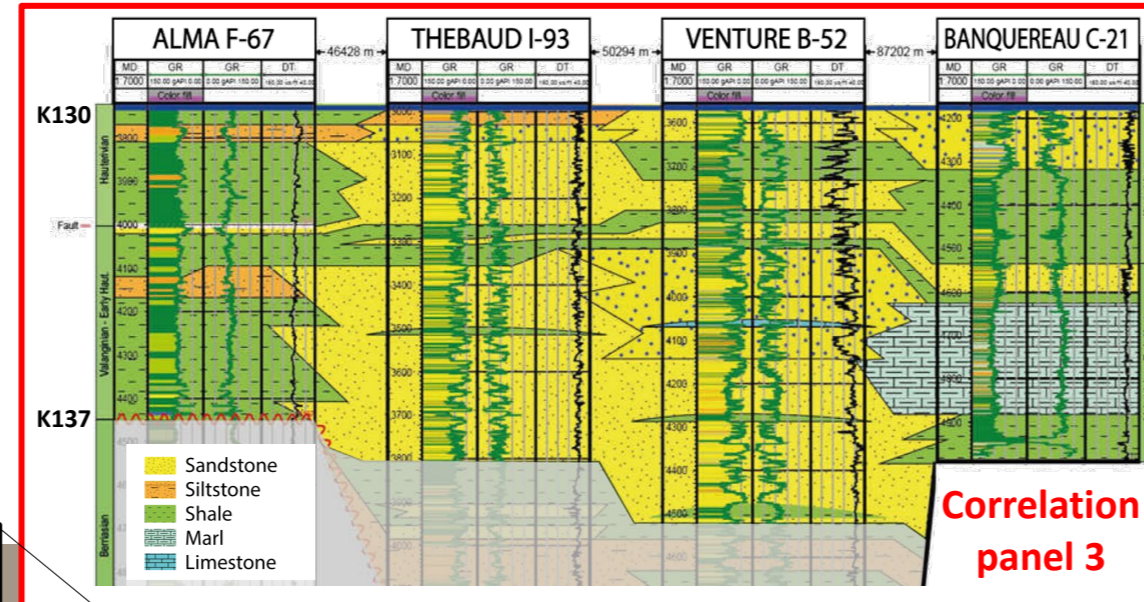
The Valanginian/Hauterivian deltaic progradations (Middle Missisauga Formation) are clearly visible in the Sable and Banquereau regions (Section 1), while the Shelburne delta further west remained active with a slope apron deltaic lobe developing on Georges Bank (see Figure 9 on plate 3.8).

The active salt tectonics induce unconfined fairways along the uppermost part of the slope and at the Banquereau detachment domain, but also confined minibasins that spread along the outer domain (Section 2).

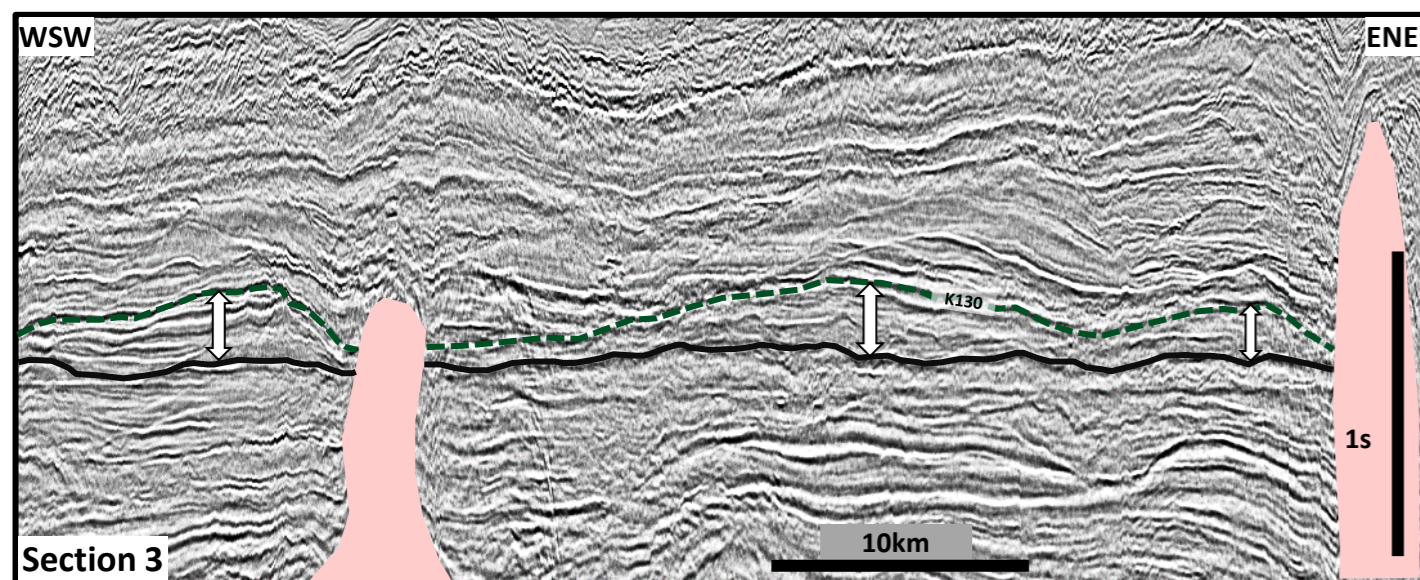
Bottom currents are documented at this age along upper slope with imbrication between channelized gravity flow deposits and contouritic drift (Section 3). This observation is in line with the model proposed by Rodriguez et al. (2022), explaining the reworking of the gravity flow material, and subsequent overbank feeding, by strong counterclockwise-oriented bottom currents. However, we also observe that turbiditic channel infills look less reworked and are consequently better preserved in the confined minibasin areas.



Seismic examples and well correlation of the Megasequence 3 forced regressive wedge. Well control of such sandy deltaic Berriasian deposits is also observed in Gloscap C-63, and Cohasset L-97.



Seismic examples of empty turbiditic channel (white arrow) with lateral contouritic mound accretion. Such organization could be explained by the reworking of turbiditic channel infill by bottom currents.



Seismic examples (flattened on base megasequence 3) of Eastern Banquereau contouritic mound below K130 horizon (top of Megasequence 3).

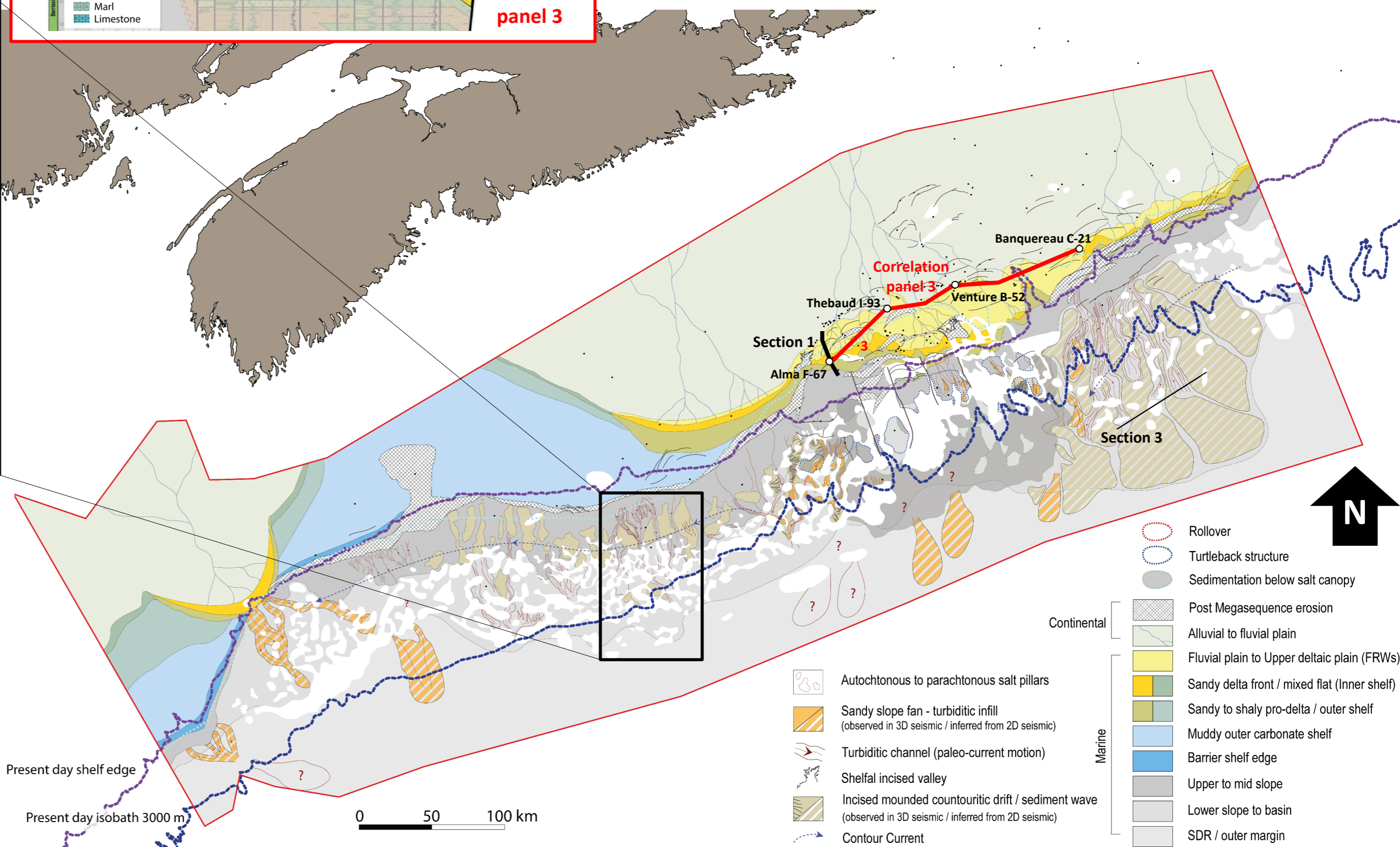


Figure 30: Megasequence 3 – Seismic examples of sedimentary objects and well lithofacies correlation panel

# Gross Depositional Environment Mapping

Scotian Basin Integration Atlas 2023 - CANADA - June 2023

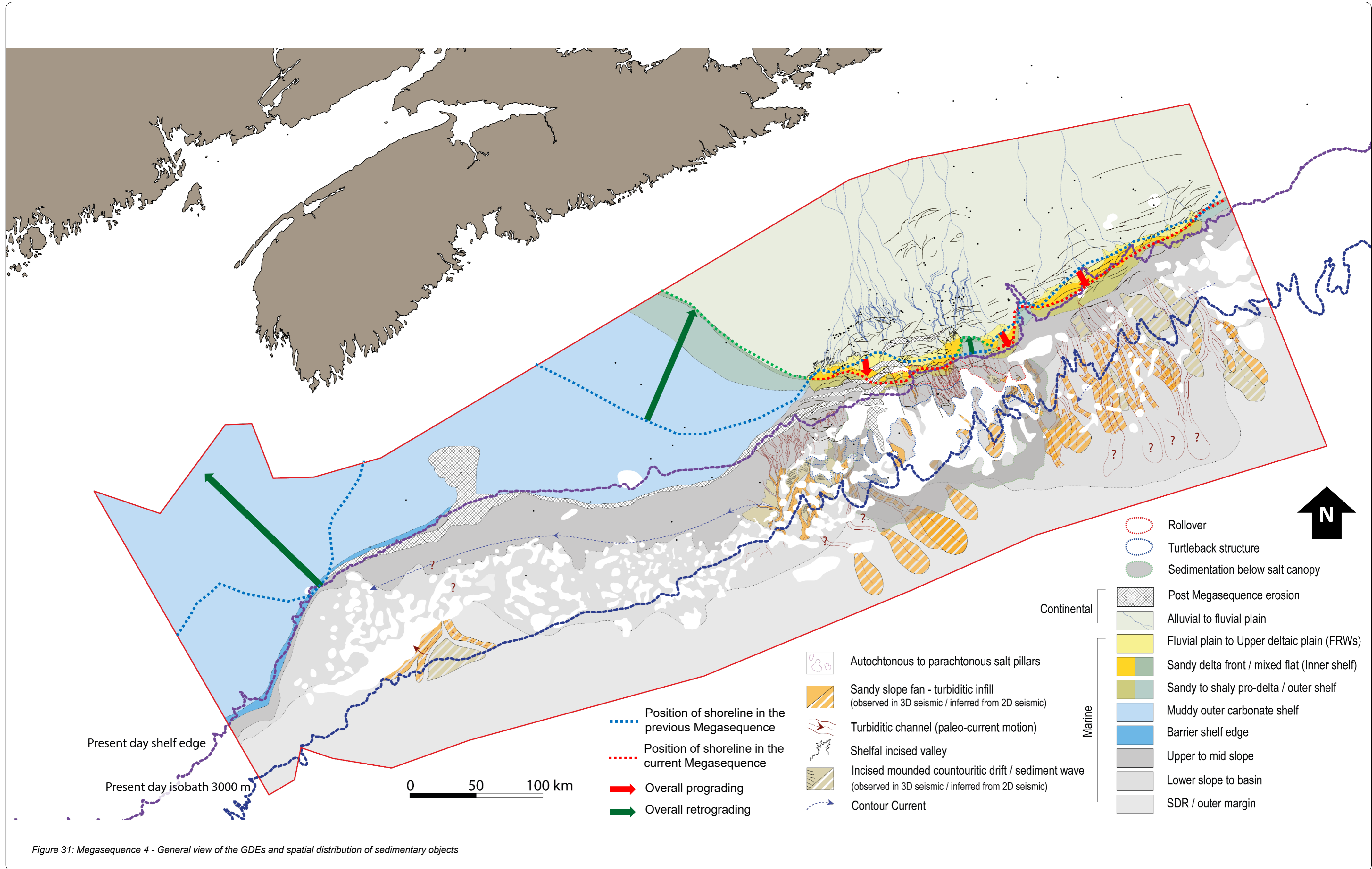


Figure 31: Megasequence 4 - General view of the GDEs and spatial distribution of sedimentary objects

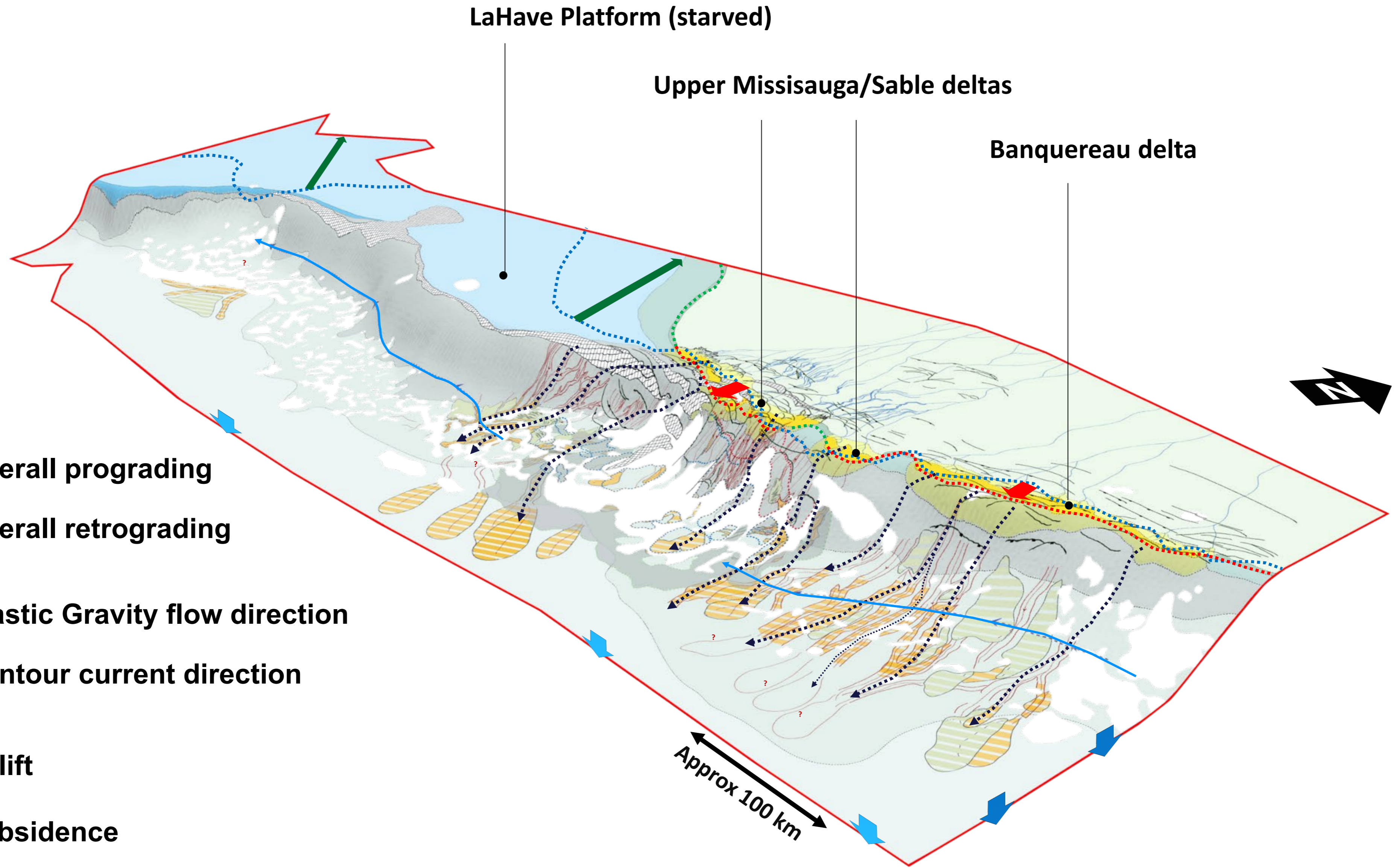
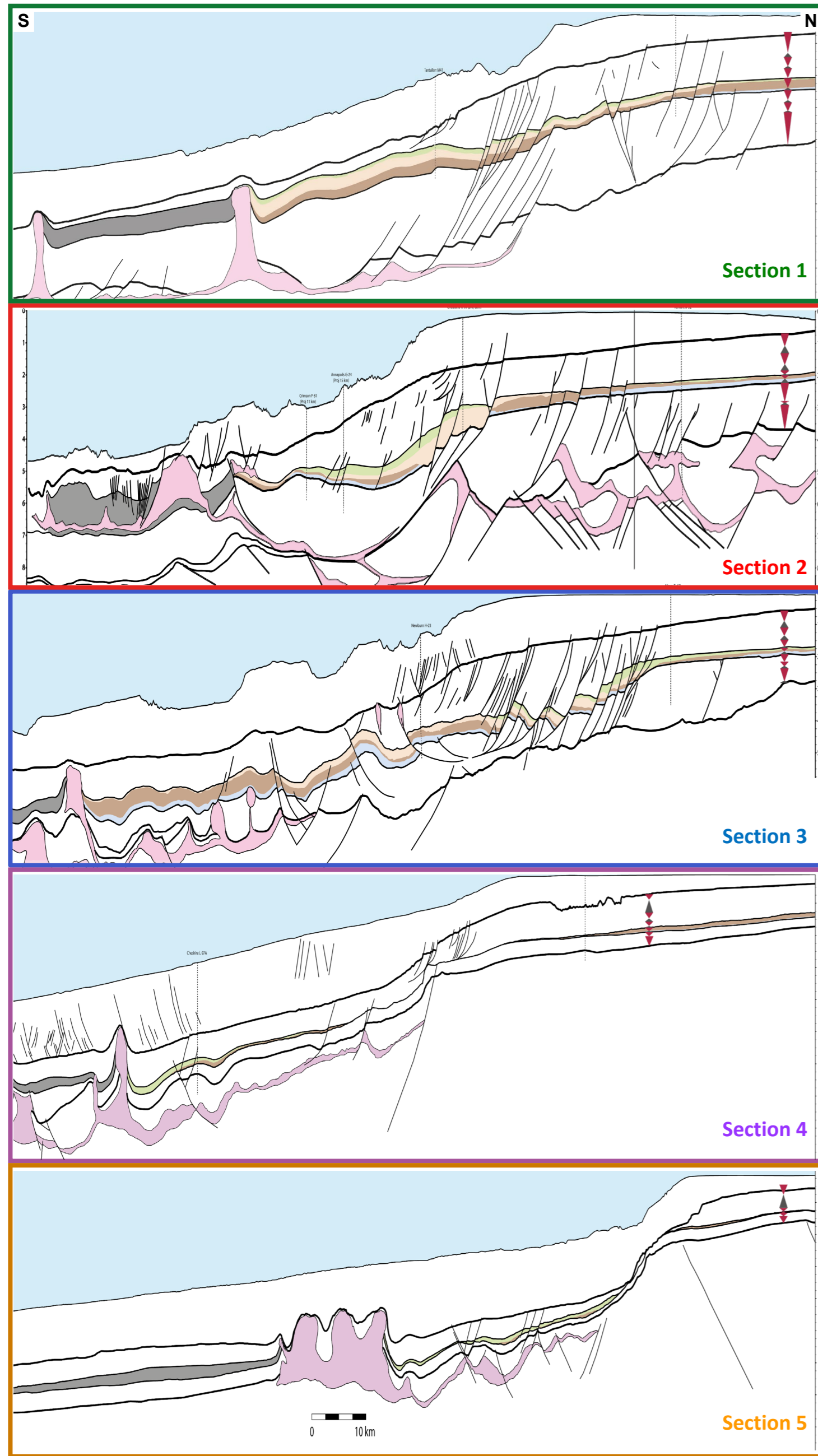


Figure 32: Megasequence 4 - General 3D view of the GDEs and direction of the main sedimentary fairways (see previous plate for GDE legend)

## Megasequence 4 – Upper Barremian/Lower Aptian – Upper Missisauga Formation – Sediment distribution



In this stratigraphic interval, there is only one deltaic system developing to the east (Missisauga deltas). During the Barremian and the Lower Aptian, the eastern deltaic system progressively spread to the central of the margin and continued prograding basinward.

The western Georges Bank delta was probably inactive during this megasequence, with starved sedimentation from the shelf down to the slope.

The LaHave platform remained starved, with condensed sedimentation on the platform and bottom current reworking on the adjacent slope.

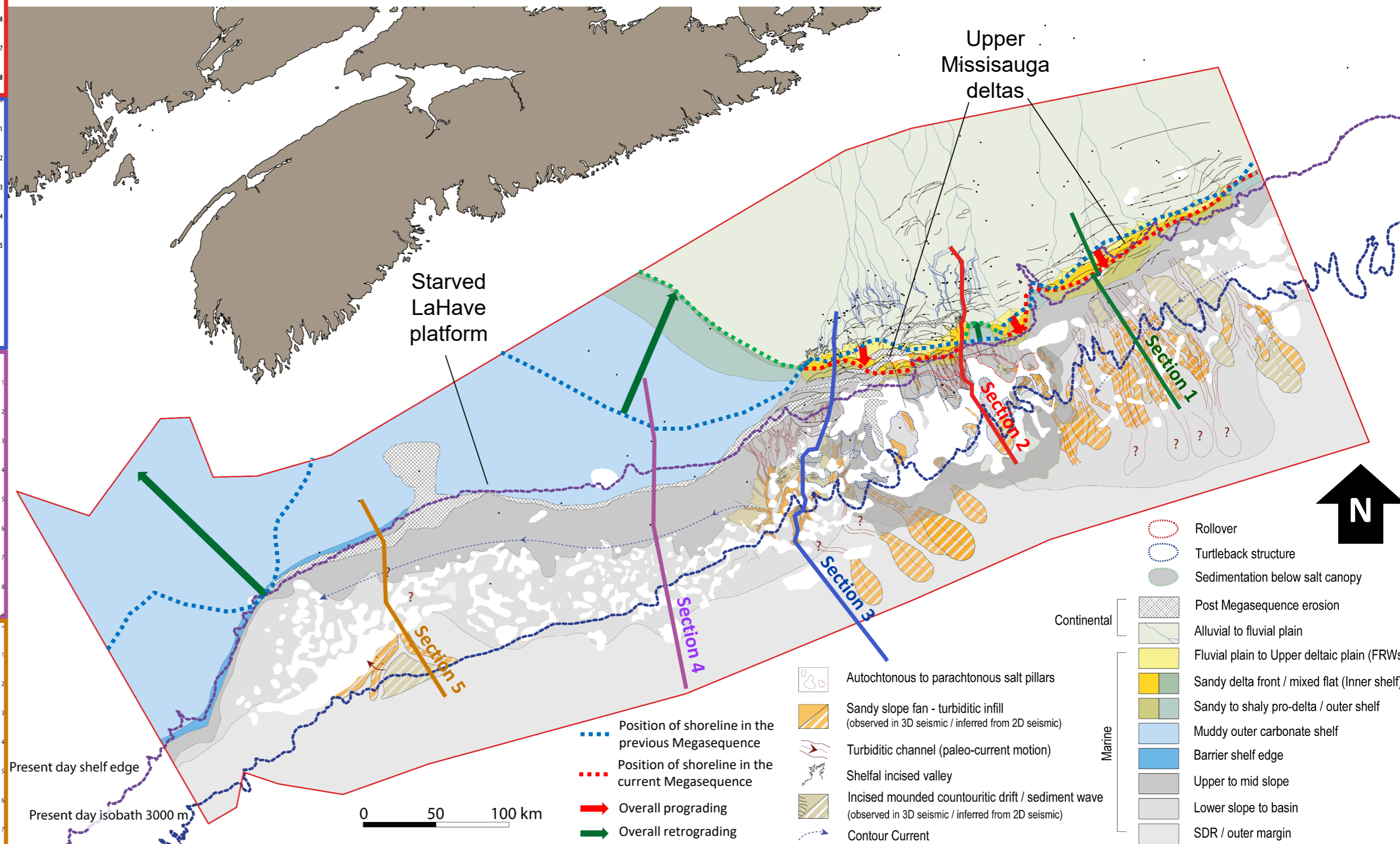
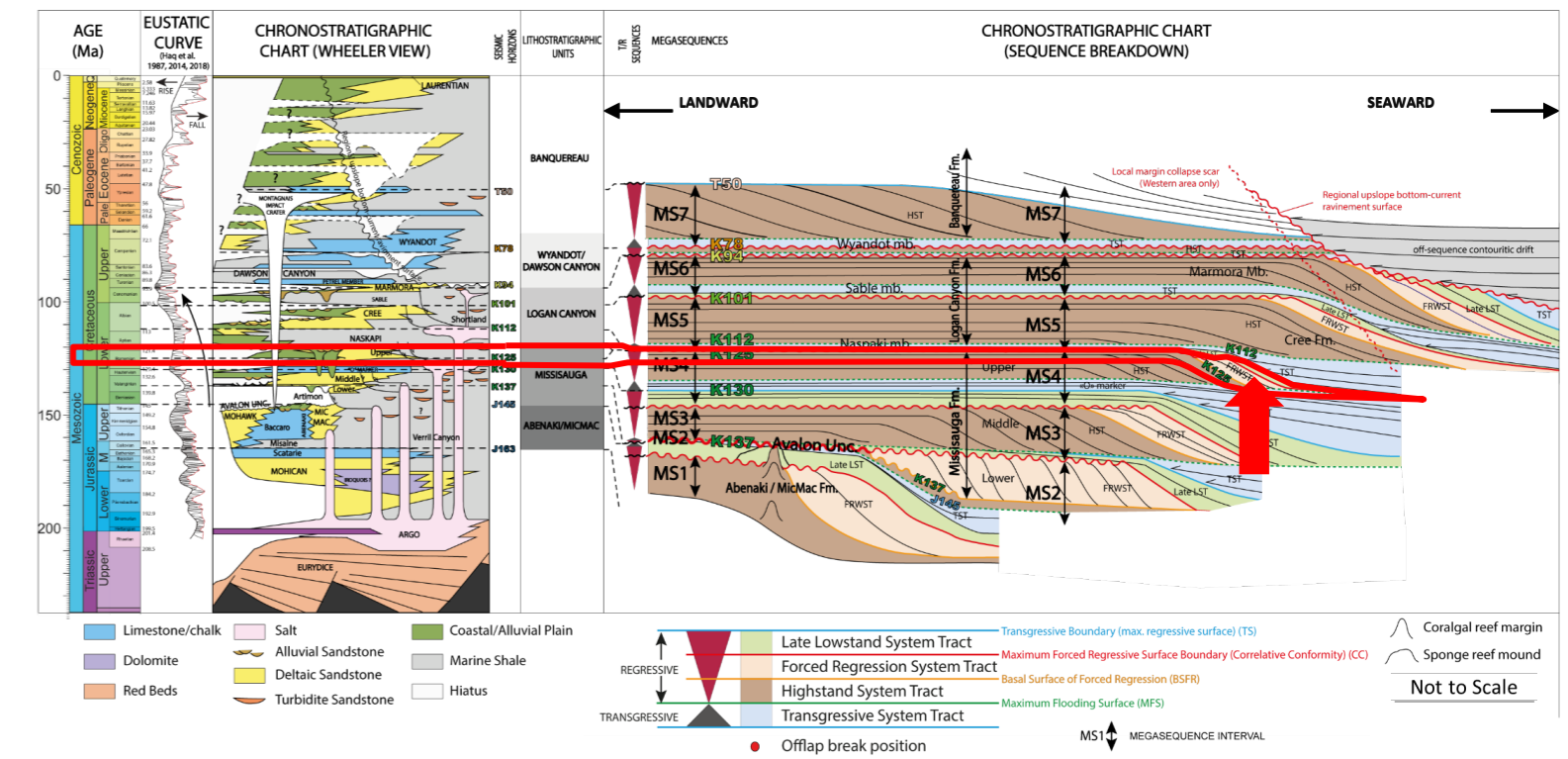
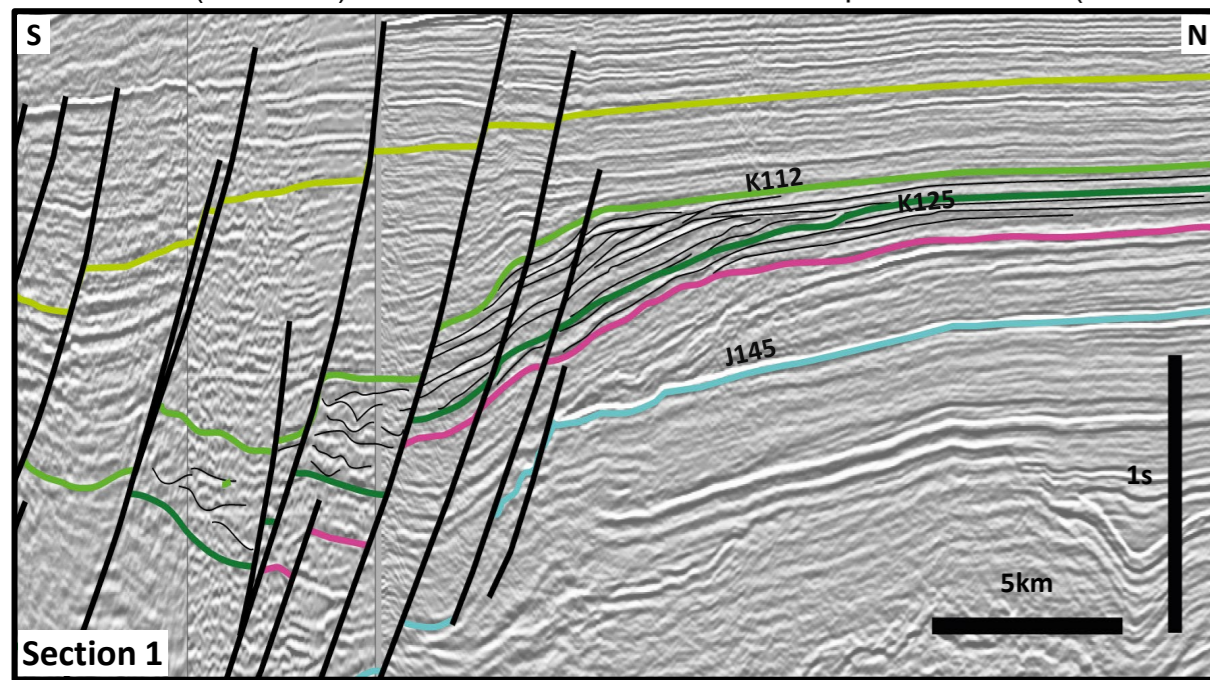


Figure 33: Megasequence 4 - Spatial sediment distribution along the Nova Scotian margin

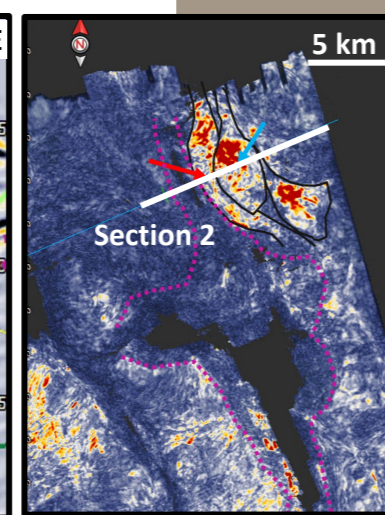
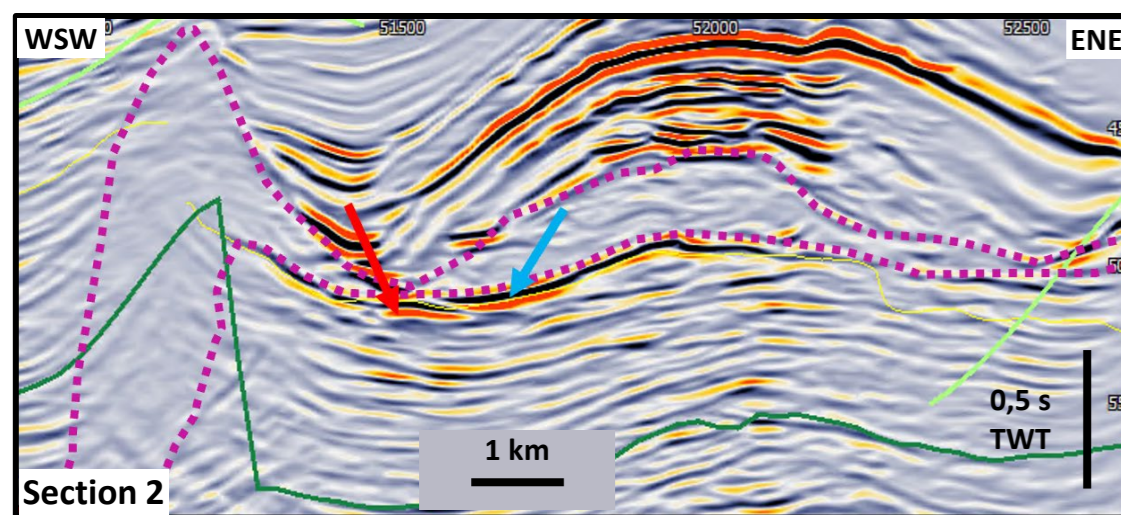
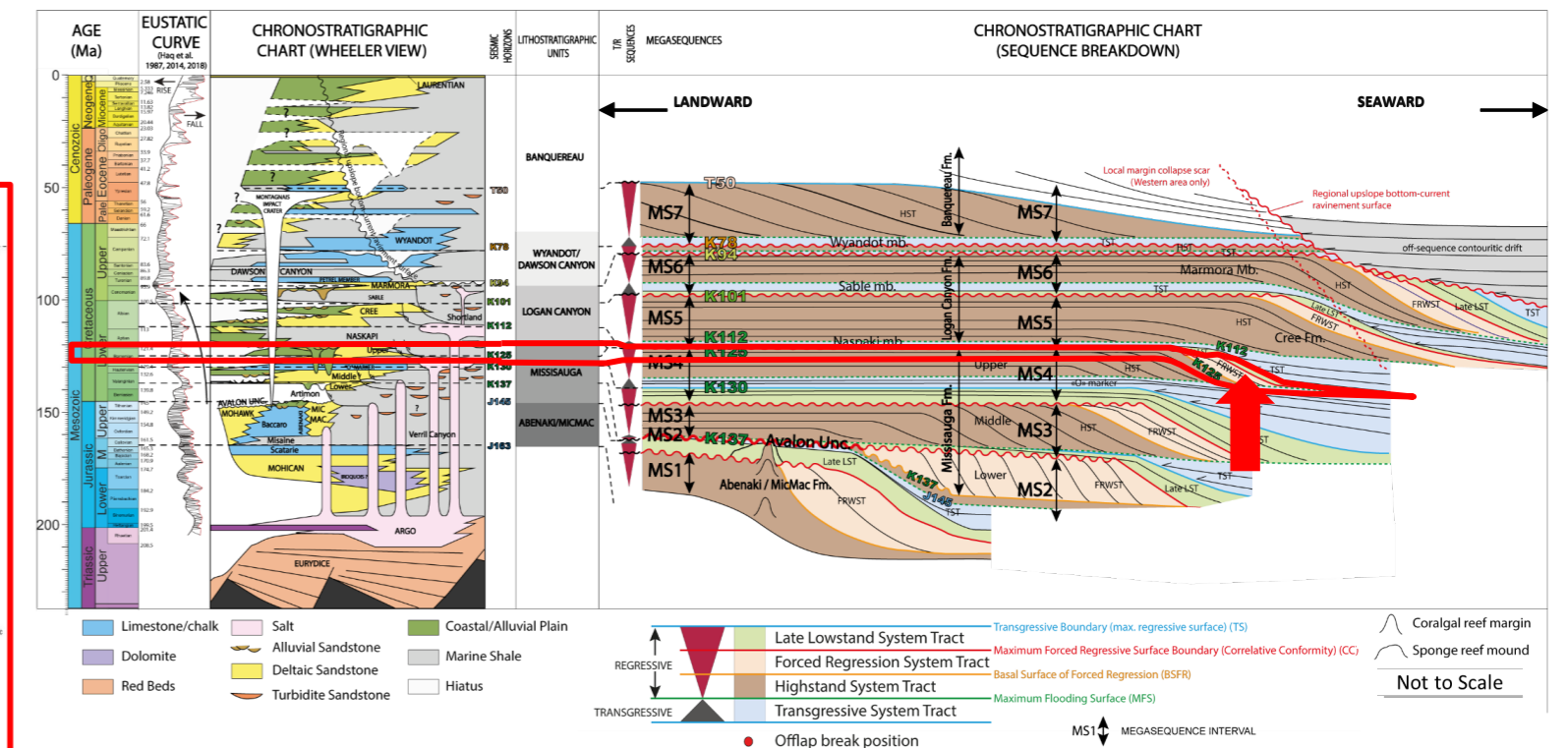
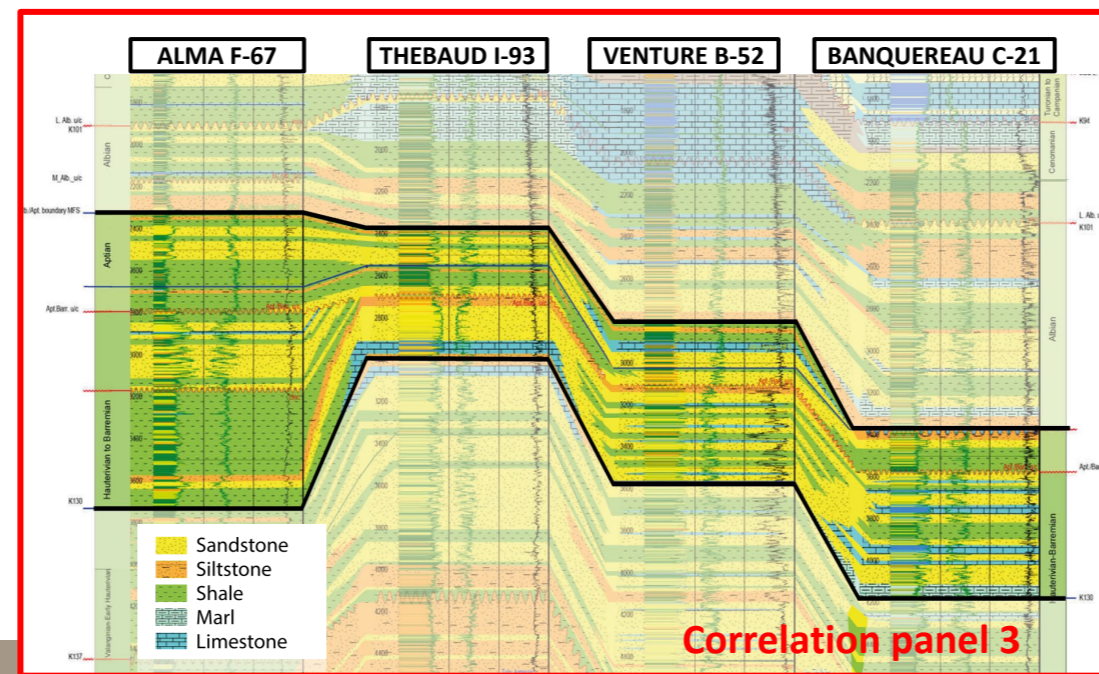
## Megasequence 4 – Upper Barremian/Lower Aptian – Upper Missisauga Formation – Seismic and Well Information

The eastern Missisauga Delta fronts can be geometrically followed along the eastern 3D surveys (Section 1). However, the sand content of the forced regressive delta is only partially described in one well (Chebucto K-98). Most of the well information is more proximal, and thus record the sandy fluvial/alluvial systems coeval with the highstand system tract of the megasequence.

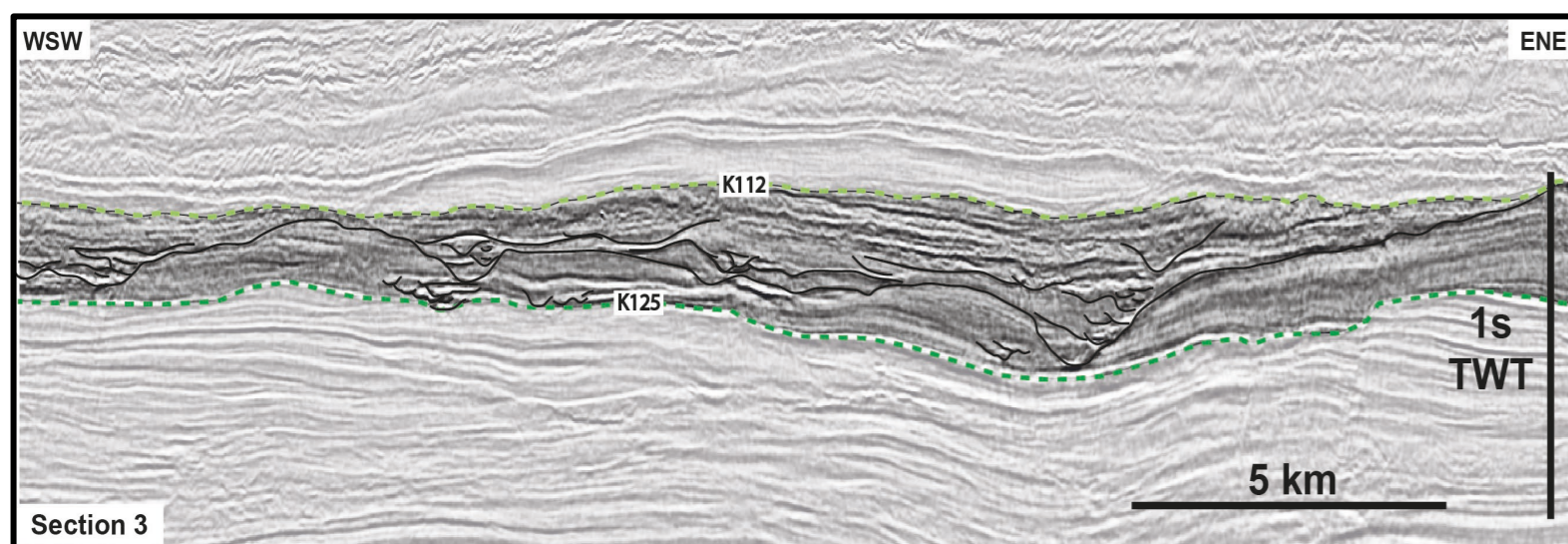
The forced regressive system tract is well expressed on the slope and in the basin, with several turbiditic geobodies (channels, lobes, etc.) described in the complex Sable minibasins (Section 2) and in the undeformed South Banquereau domain (Section 3).



Seismic examples of the forced regressive wedge, coeval with the Megasequence 4 in the western Sable region. Well control of such sandy deltaic Barremian/Lower Aptian deposits is partly observed in Chebucto K-98



Seismic examples of successive avulsion turbiditic lobes on stepped Sable paleoslope



Seismic examples of mixed erosive/constructive turbiditic channels on Banquereau paleoslope. Channel sedimentary package is genetically connected to the upslope Banquereau forced regressive wedge and subsequent late lowstand wedge

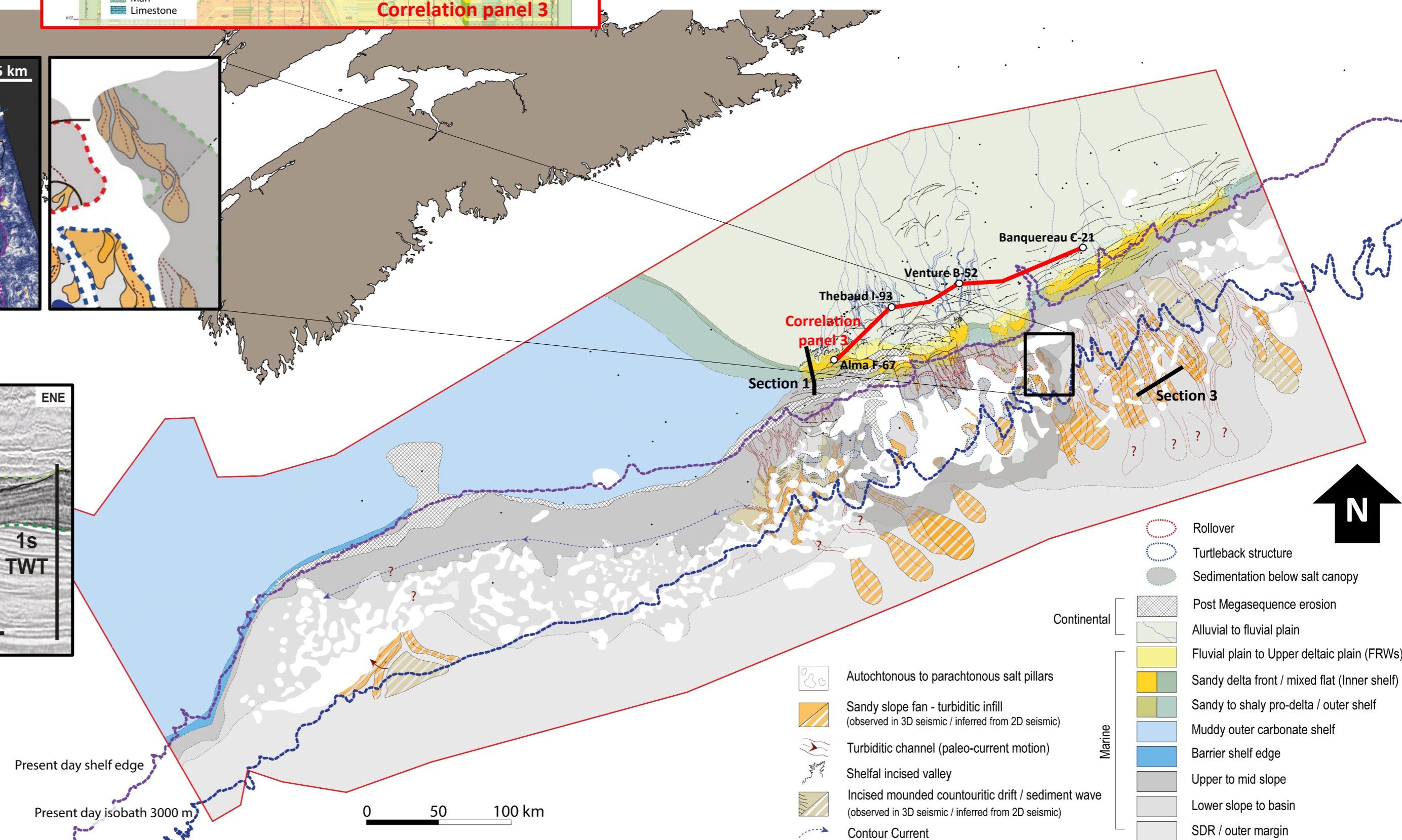


Figure 34: Megasequence 4 – Seismic examples of sedimentary objects and well lithofacies correlation panel

# Gross Depositional Environment Mapping

Scotian Basin Integration Atlas 2023 – CANADA – June 2023

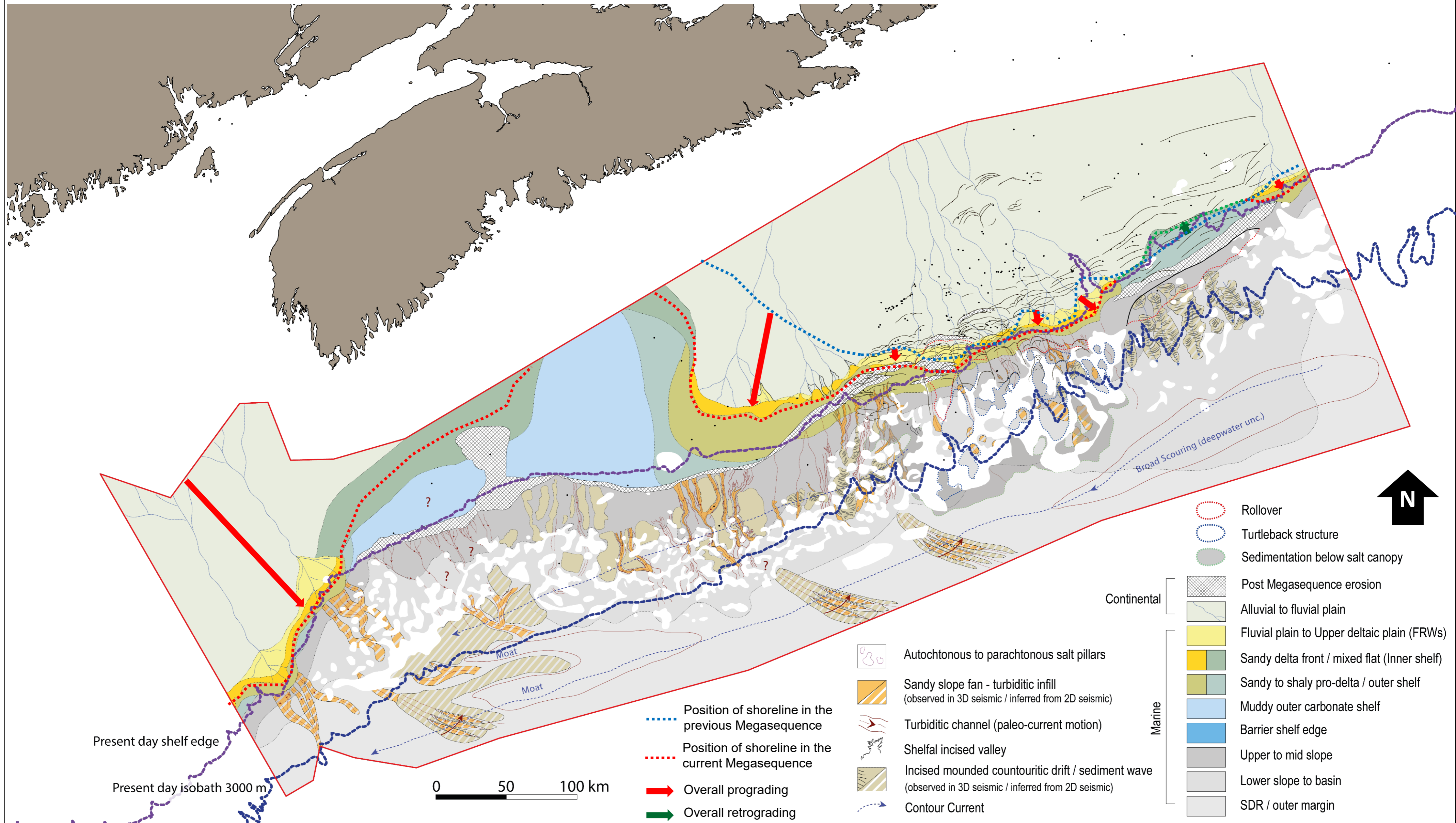


Figure 35: Megasequence 5 - General view of the Gross Depositional Environments and spatial distribution of sedimentary objects

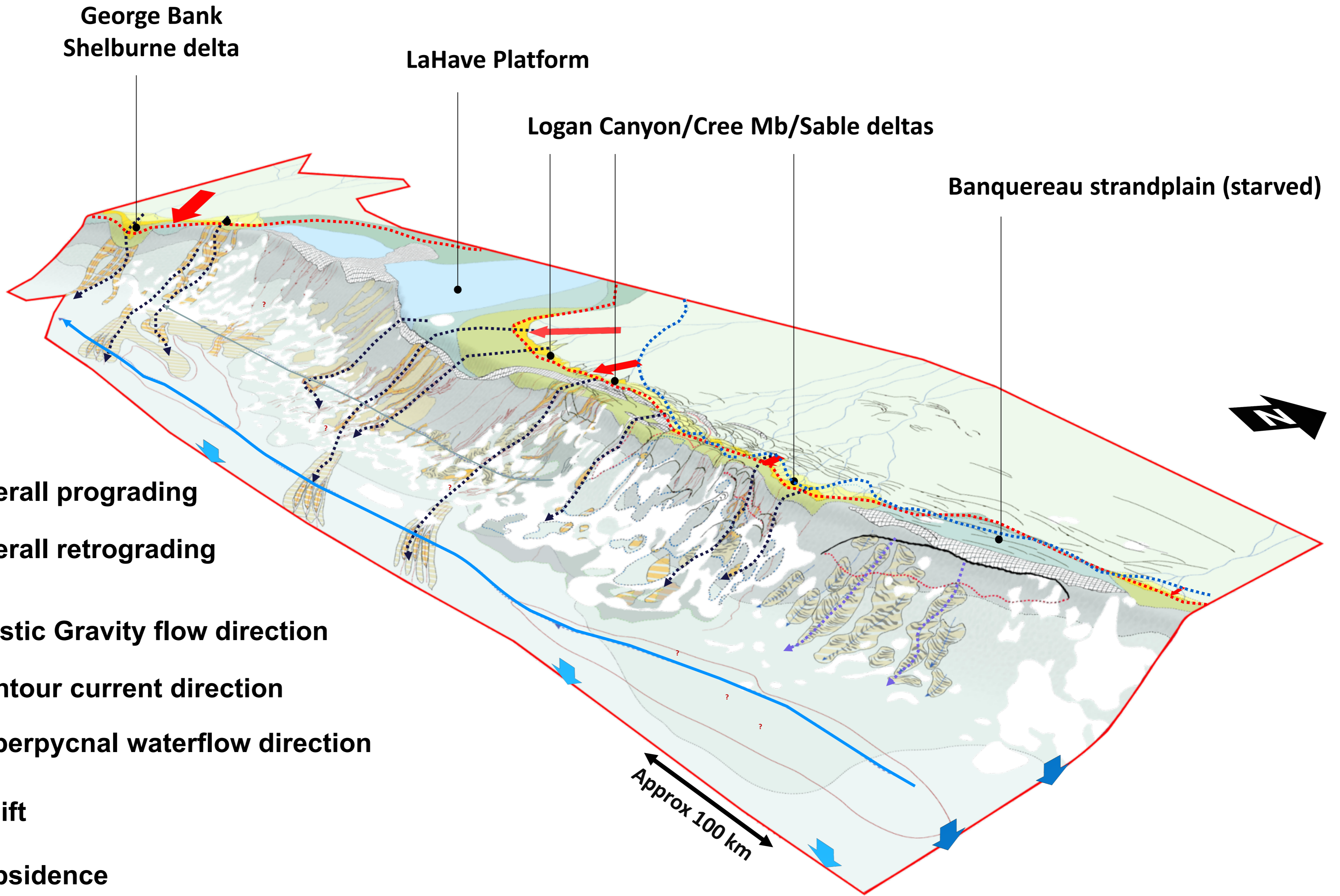


Figure 36: Megasequence 5 - General 3D view of the GDEs and direction of the main sedimentary fairways (see previous plate for GDE legend)

## Megasequence 5 – Late Aptian/Albian – Cree Member – Sediment distribution

This 20 Myr long megasequence is characterized by a relative decrease of sedimentation in the Scotian Basin.

The depocenters are localized in the eastern Sable region and on the George Bank shelf (see Figure 9 on plate 3.8). However, less sediments were transferred to the basin to the south of the Banquereau area, which suggests more highstand conditions.

The LaHave platform is still starved at this time and the adjacent slope is dominated by bypass and condensed sedimentation.

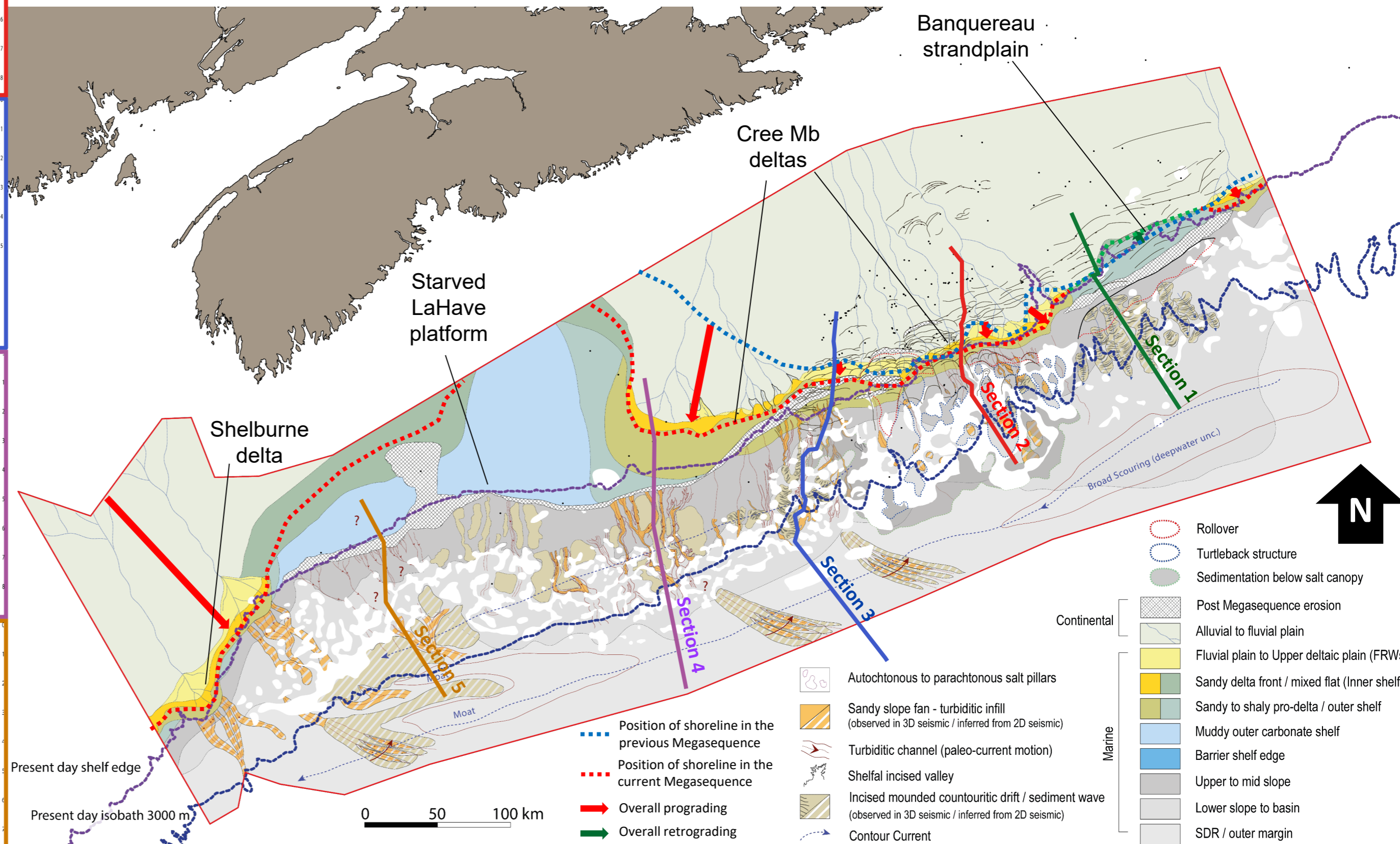
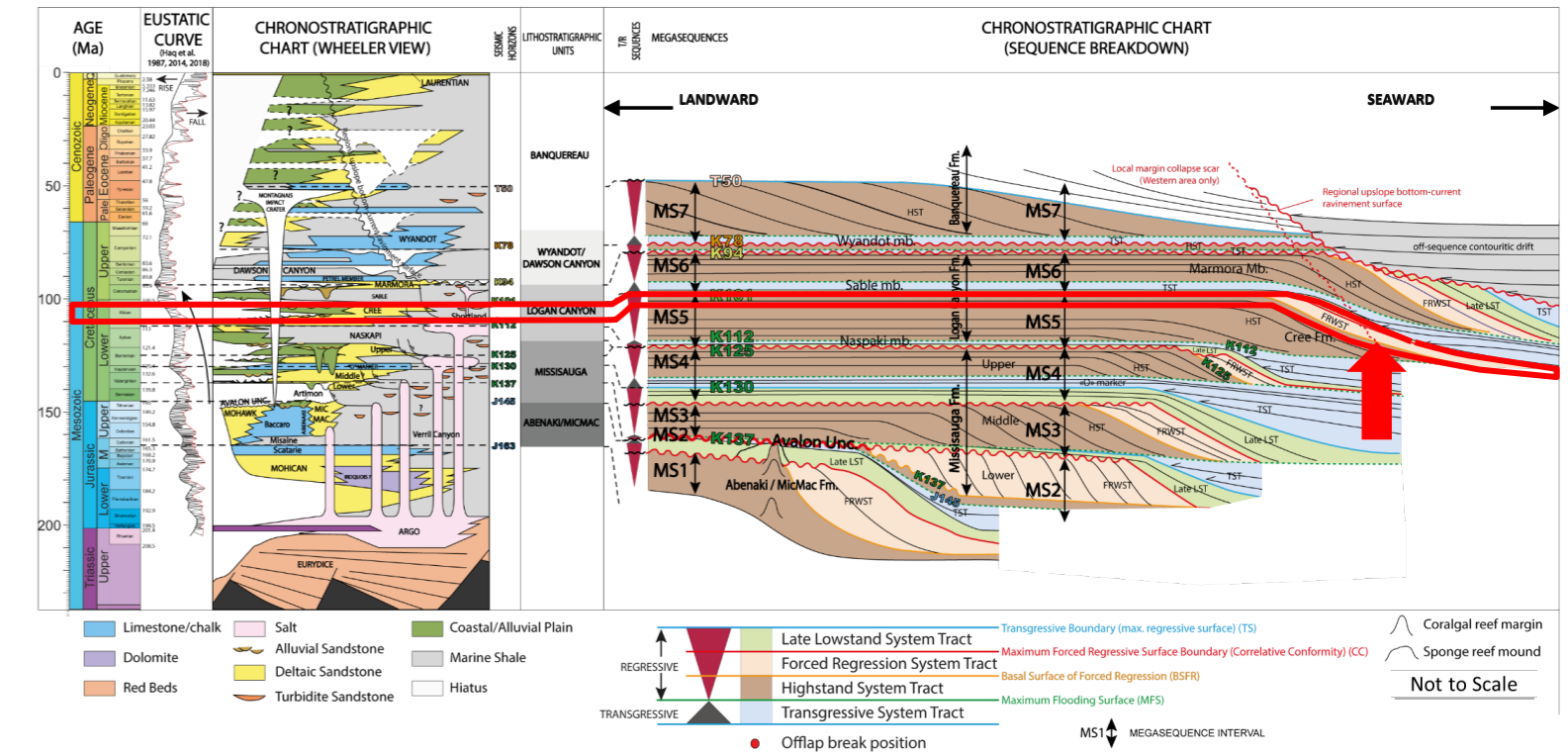
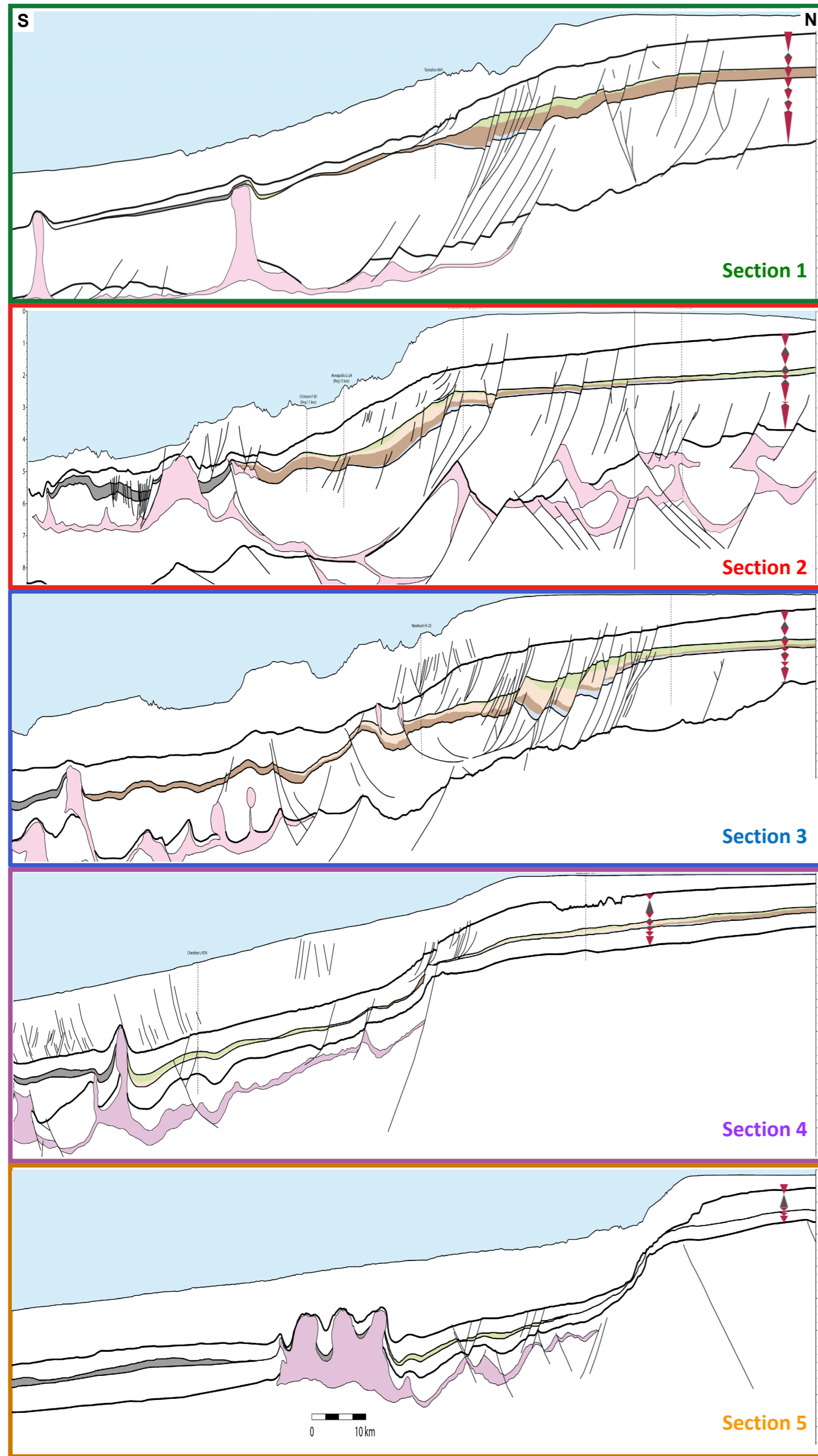
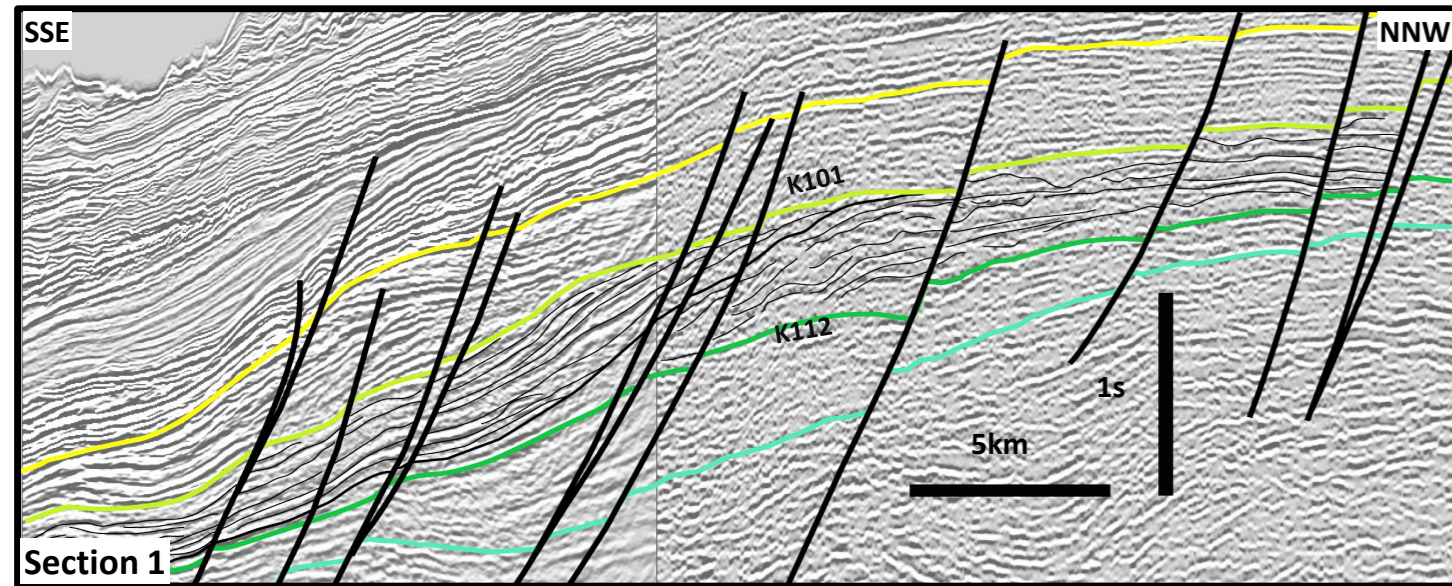


Figure 37: Megasequence 5 - Spatial sediment distribution along the Nova Scotian margin

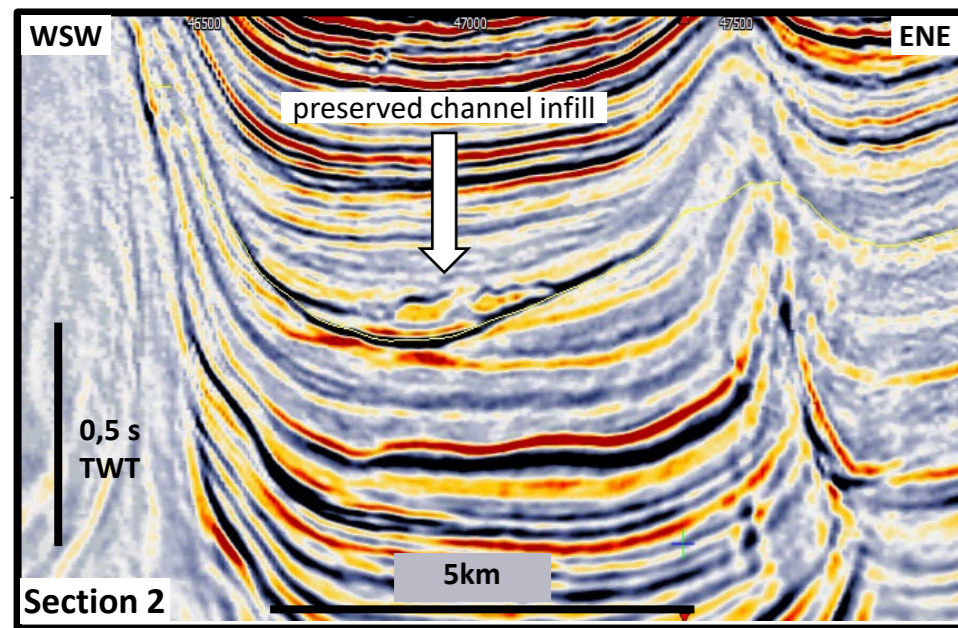
## Megasequence 5 – Late Aptian/Albian – Cree Member – Seismic and Well Information

In this stratigraphic interval, there are two distinct deltas developing to the west (Shelburne deltas) and to the east (Missisauga deltas). The eastern deltaic system progressively spread to the central part of the margin and continued prograding basinward during Albian (Section 1). The moderate clastic influx at this age formed a deltaic sandy deposits known as the Cree Member (correlation panel 3). It followed a mid to late Aptian period of low sedimentation regime and shaly deposits, known as the Naskapi Formation. This period of reduction in sediment input may have corresponded to an abrupt shift of the St Lawrence proto river to the Bay of Fundy (Strathdee, 2012; Tsikouras et al., 2012). During Albian, the western George Bank area turned to a consequent clastic sedimentation with a significant prograding clastic wedge and slope apron delta.

The LaHave platform remained starved with condensed sedimentation on the platform and bottom current reworking on the adjacent slope. The sedimentation in the easternmost Banquereau region appeared drastically reduced, with a prominent highstand/aggrading strandplain on the shelf, coeval to a starved slope with the only presence of migrating sediment wave fields/antidunes that are interpreted as downcascading current deposits (Section 3).



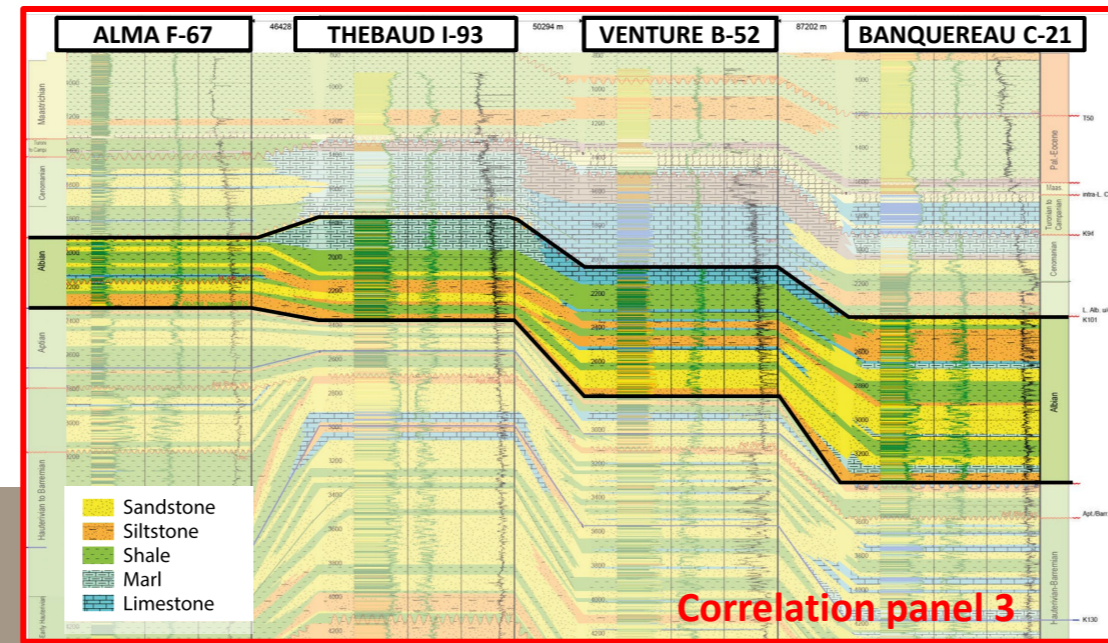
Section 1  
Seismic examples of the Megasequence 5 forced regressive wedge in the western Sable region. Well control of such sandy deltaic Barremian/lower Aptian deposits is observed in Oneida O-25, Gloopscap C-63.



Section 2  
Seismic examples of Albian preserved turbiditic channel infill in the Central domain.



Section 3  
Seismic examples of climbing-up antidunes on the Banquereau paleoslope. Such organization could be explained by the reworking of underlying strata by downcascading underwater density currents.



Correlation panel 3

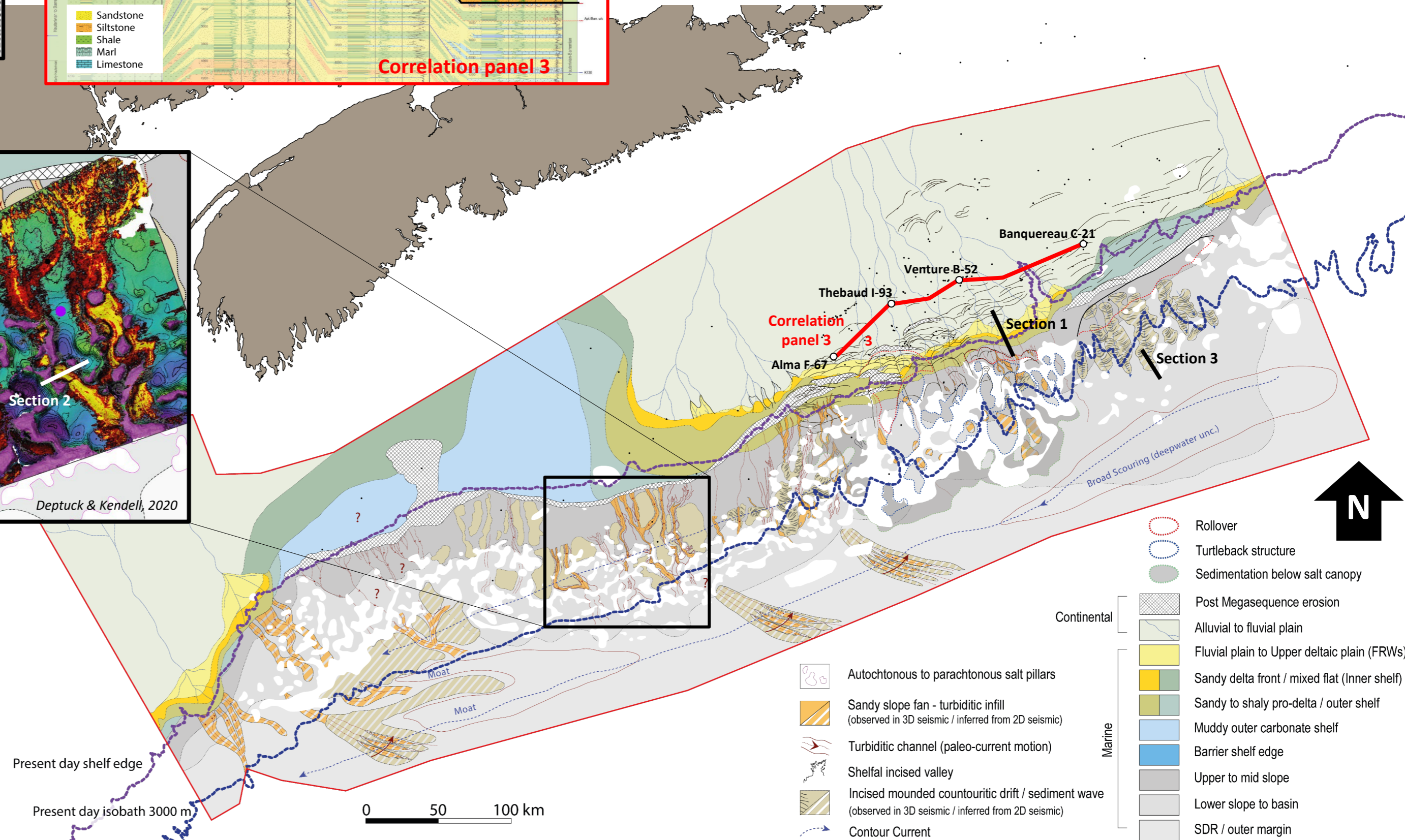
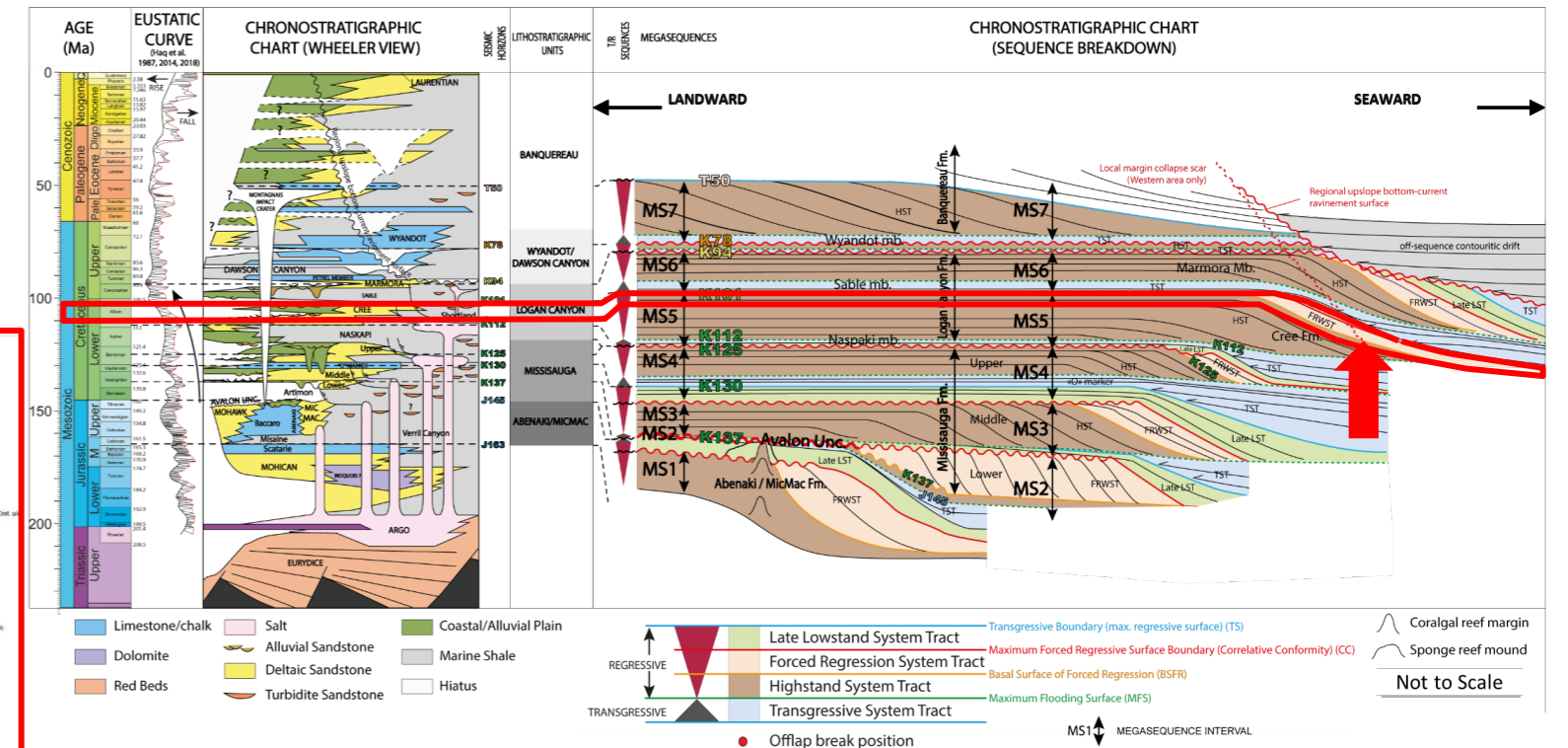


Figure 38: Megasequence 5 – Seismic examples of sedimentary objects and well lithofacies correlation panel

# Gross Depositional Environment Mapping

Scotian Basin Integration Atlas 2023 - CANADA - June 2023

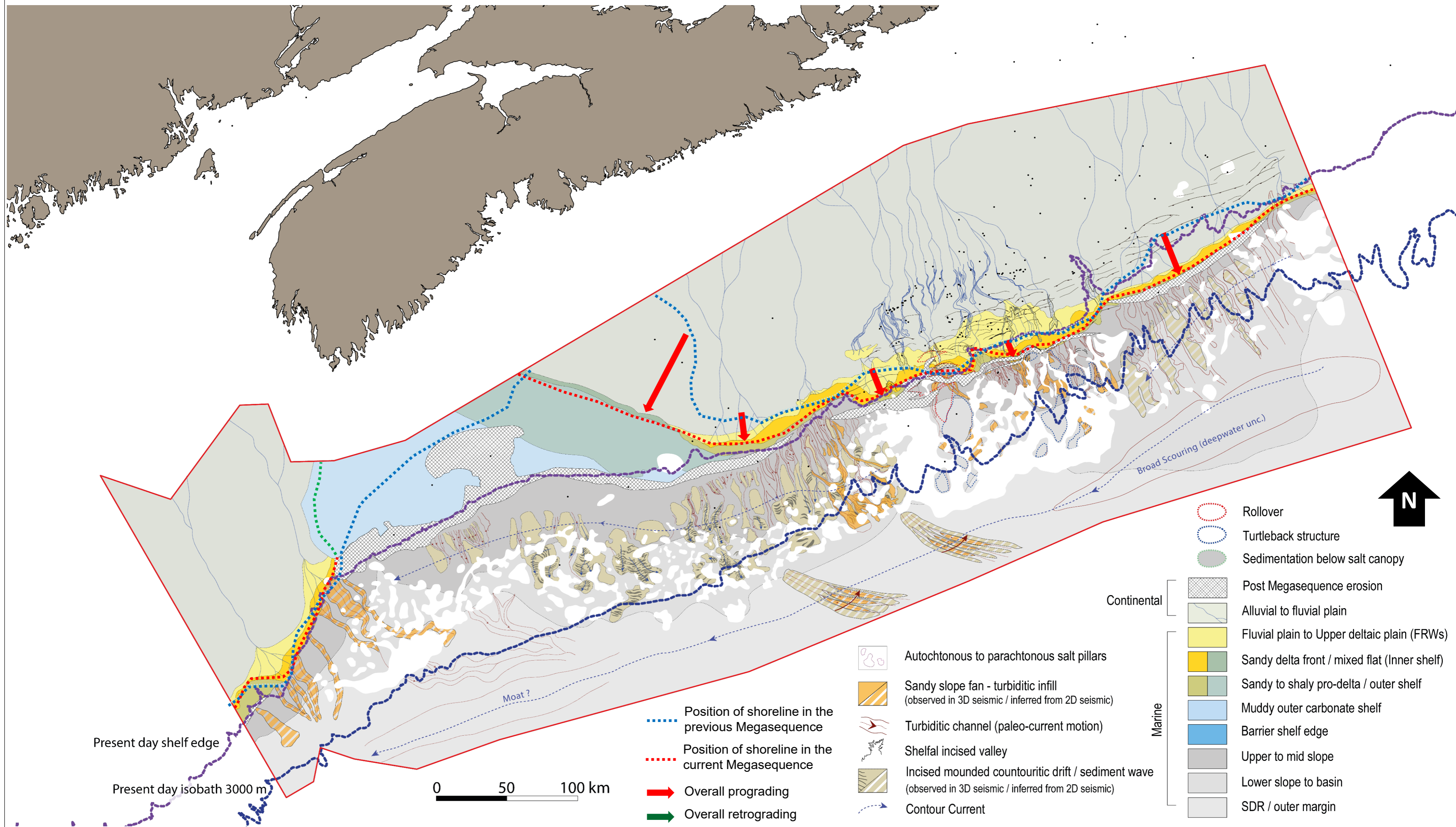
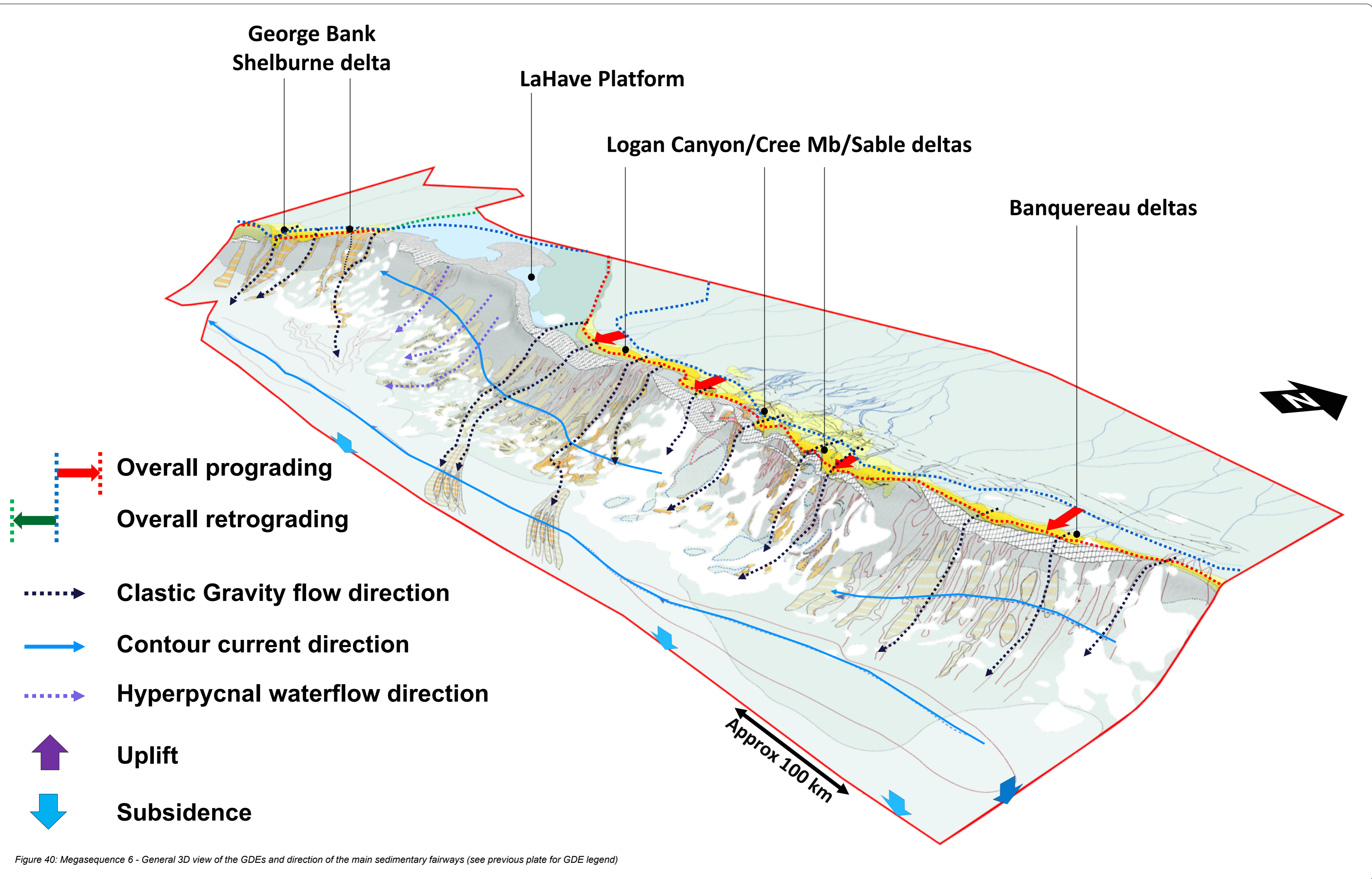
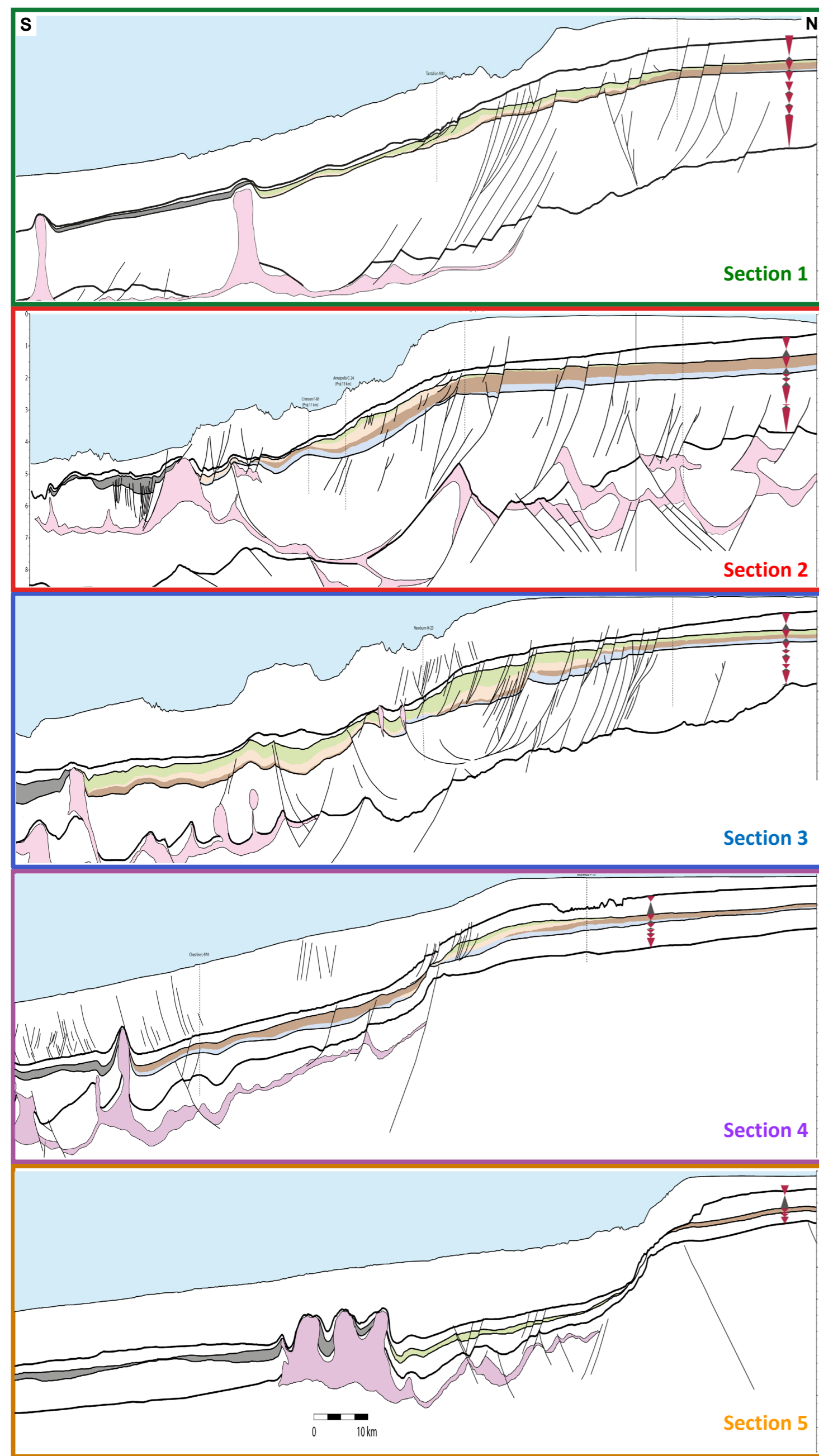


Figure 39: Megasequence 6 - General view of the GDEs and spatial distribution of sedimentary objects



## Megasequence 6 – Cenomanian – Upper part of Marmora Member – Sediment distribution



This GDE map corresponds to the maximum of progradation (maximum of basinward advance of the delta) of the whole depositional system.

The spatial distribution of sediments clearly shows a migration of the depocenters in the central part of the studied area, as shown on the purple section, onto which a prograding deltaic wedge is visible.

The western sections (4 and 5) still shows a starved platform, with condensed sedimentation on the slope, while clastic sedimentation continues on the westernmost Georges Bank with the prograding Shelburne delta (see Figure 9 on Plate 3.8).

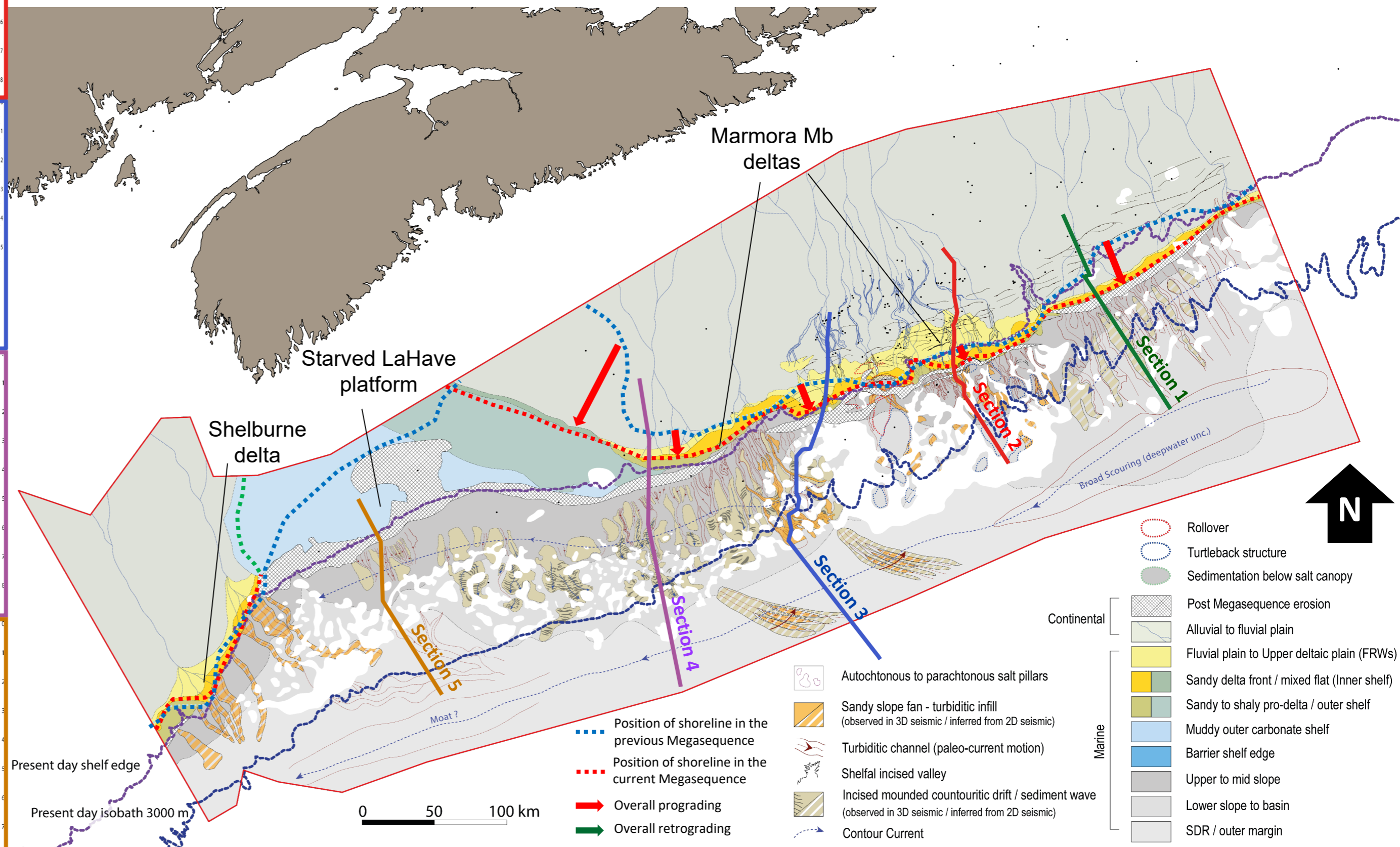
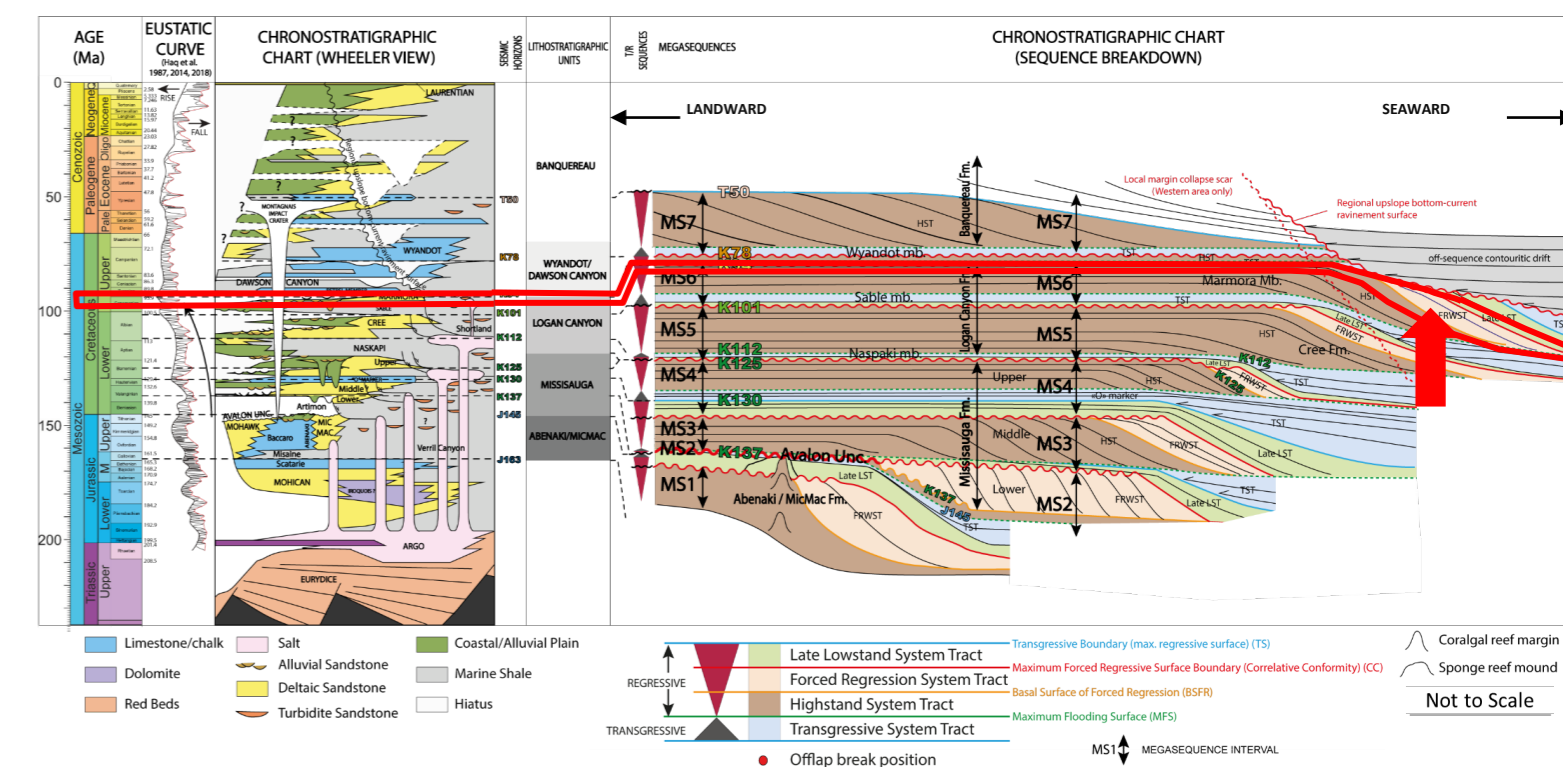
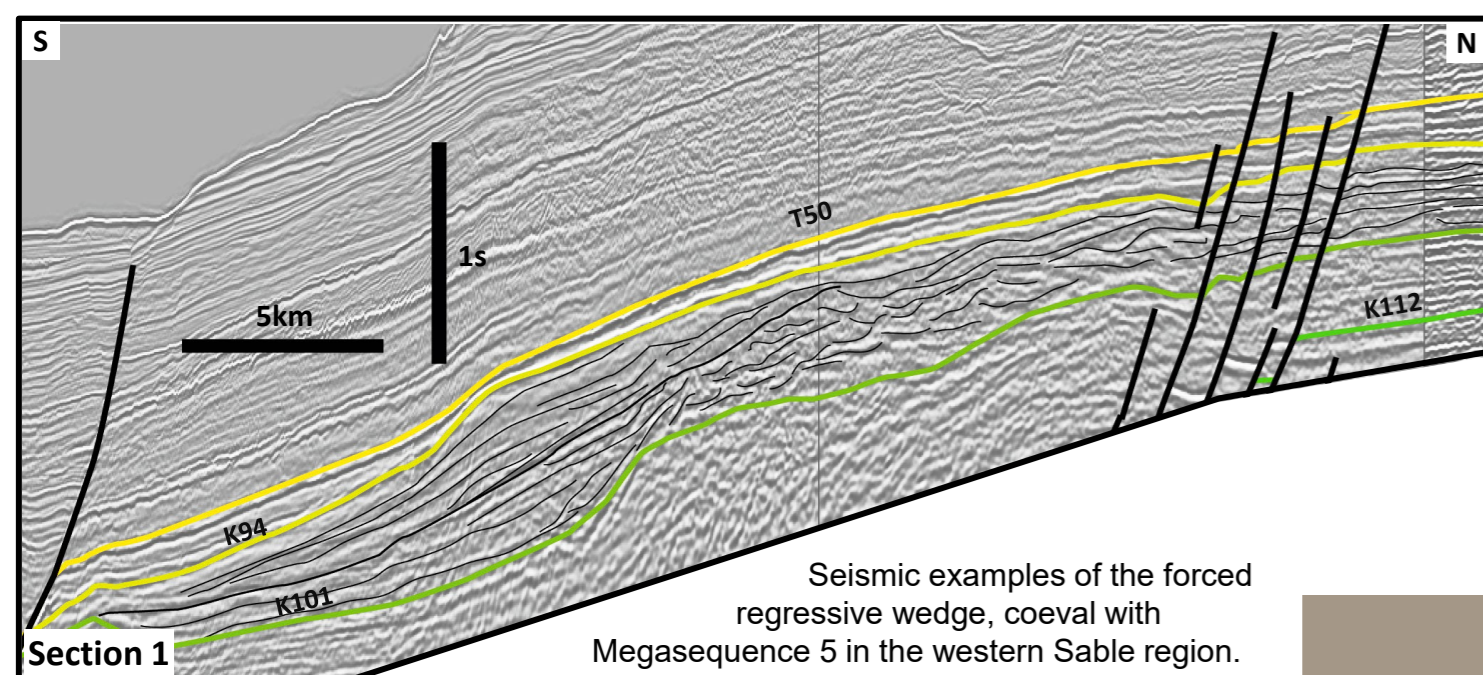


Figure 41: Megasequence 6 - Spatial sediment distribution along the Nova Scotian margin

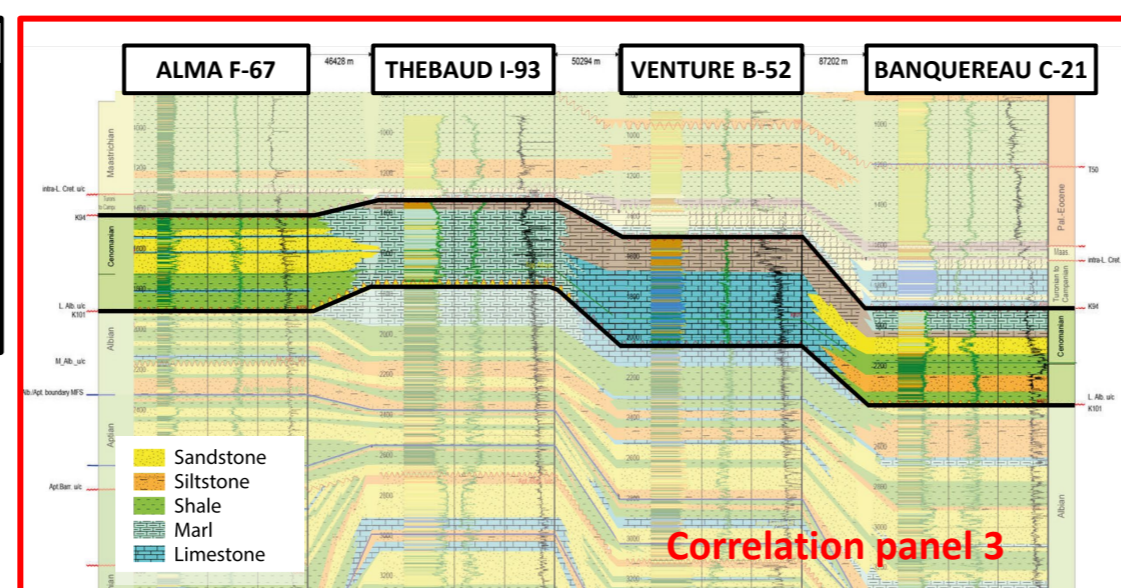
## Megasequence 6 – Cenomanian – Upper part of Marmora Member – Seismic and Well Information

During the Cenomanian, the deltaic wedges reached their maximum of progradation, with late lowstand clinofolds described beneath the present day upper slope in the western Sable region (Section 1)

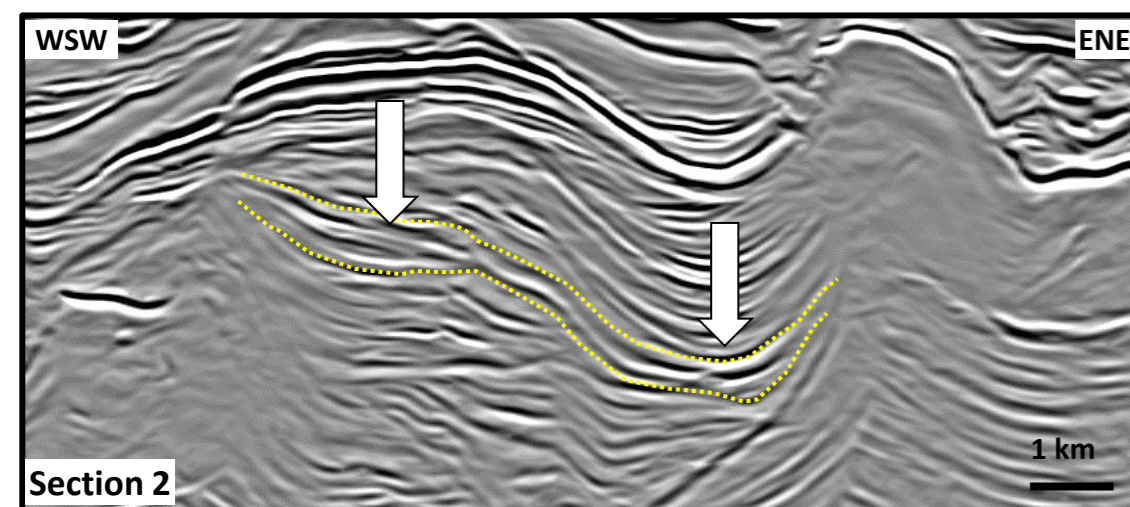
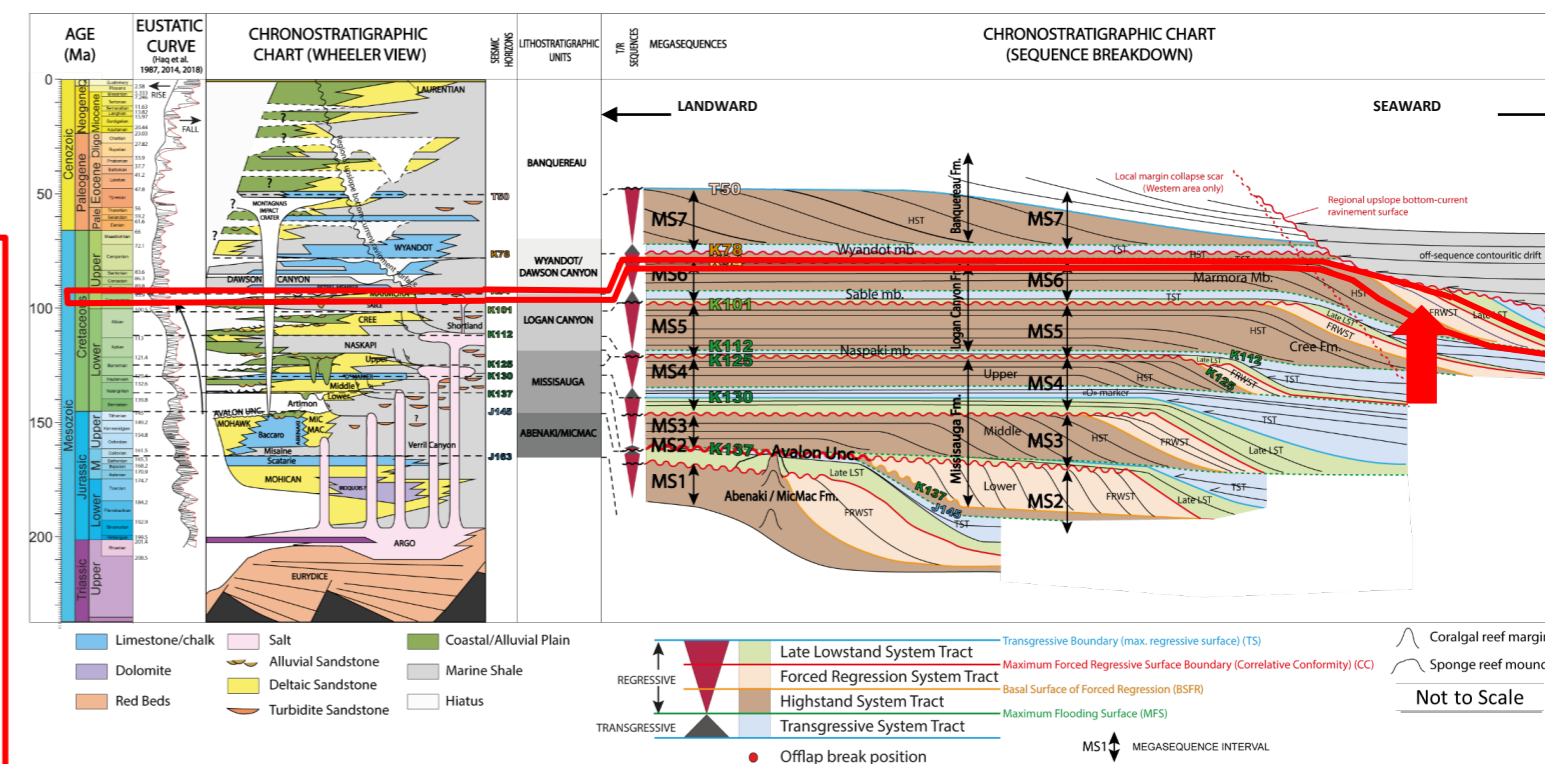
There were still two distinct deltas to the west (Shelburne deltaic system, see Figure 9 on Plate 3.8) and to the east (Upper Logan Canyon Fm./Marmora Mbr.), that significantly fed the basin. This is observed by the significant turbiditic channel network observed on the slope, with preserved turbiditic infill, mostly in the South Sable minibasins (Section 2).



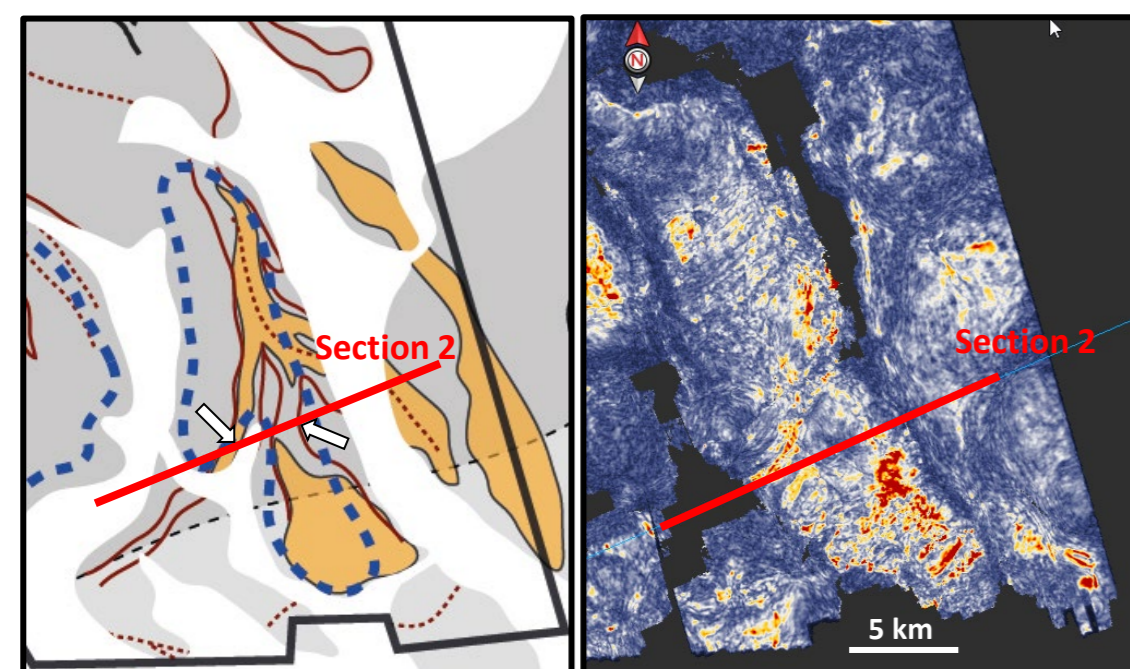
Section 1  
Seismic examples of the forced regressive wedge, coeval with Megasequence 5 in the western Sable region. Well control of such sandy deltaic Barremian/Lower Aptian deposits is not observed.



Correlation panel 3



Section 2



Seismic examples of Cenomanian turbiditic channel in the Eastern Sable slope domain

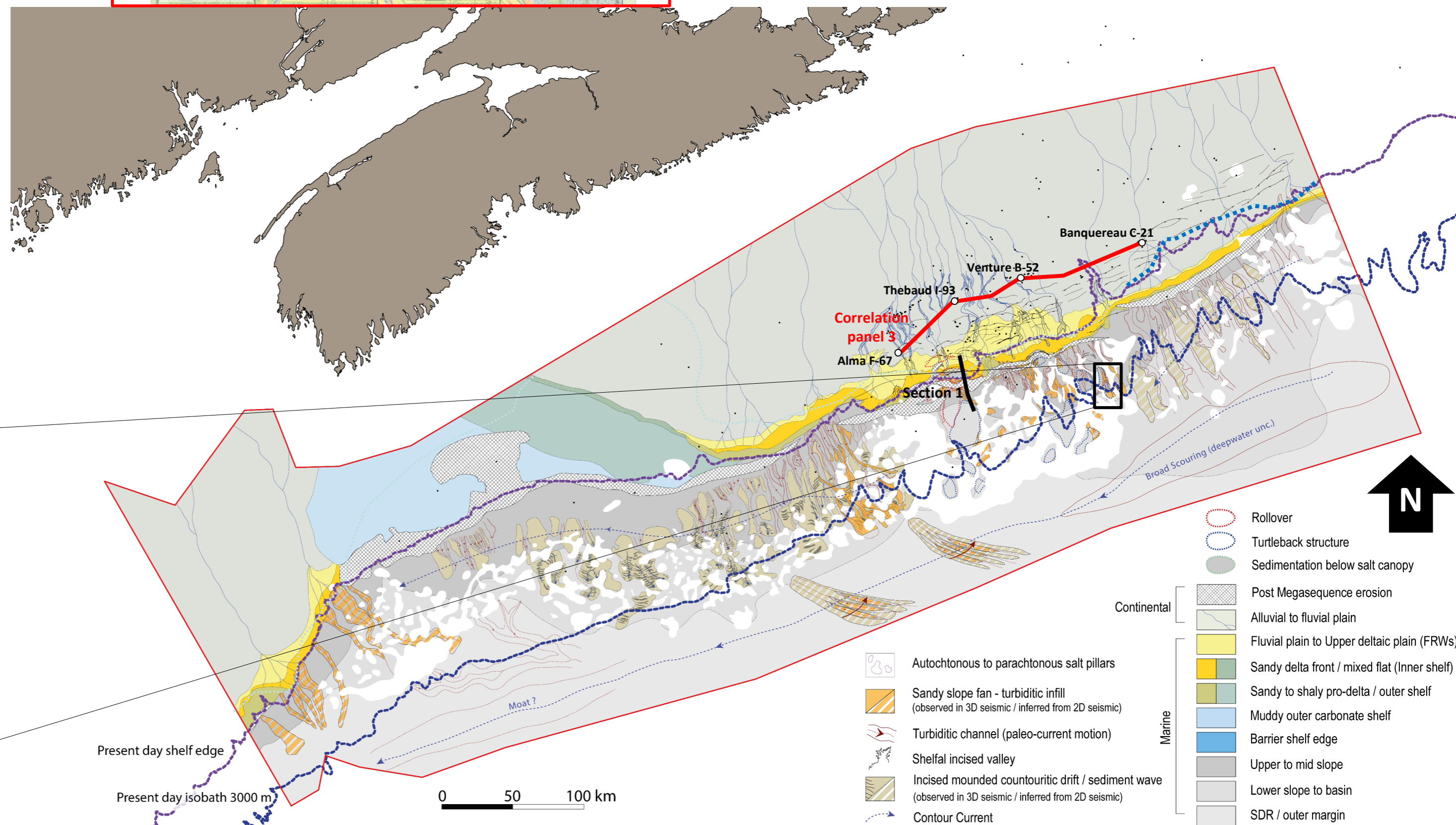


Figure 42: Megasequence 6 – Seismic examples of sedimentary objects and well lithofacies correlation panel

# Gross Depositional Environment Mapping

Scotian Basin Integration Atlas 2023 – CANADA – June 2023

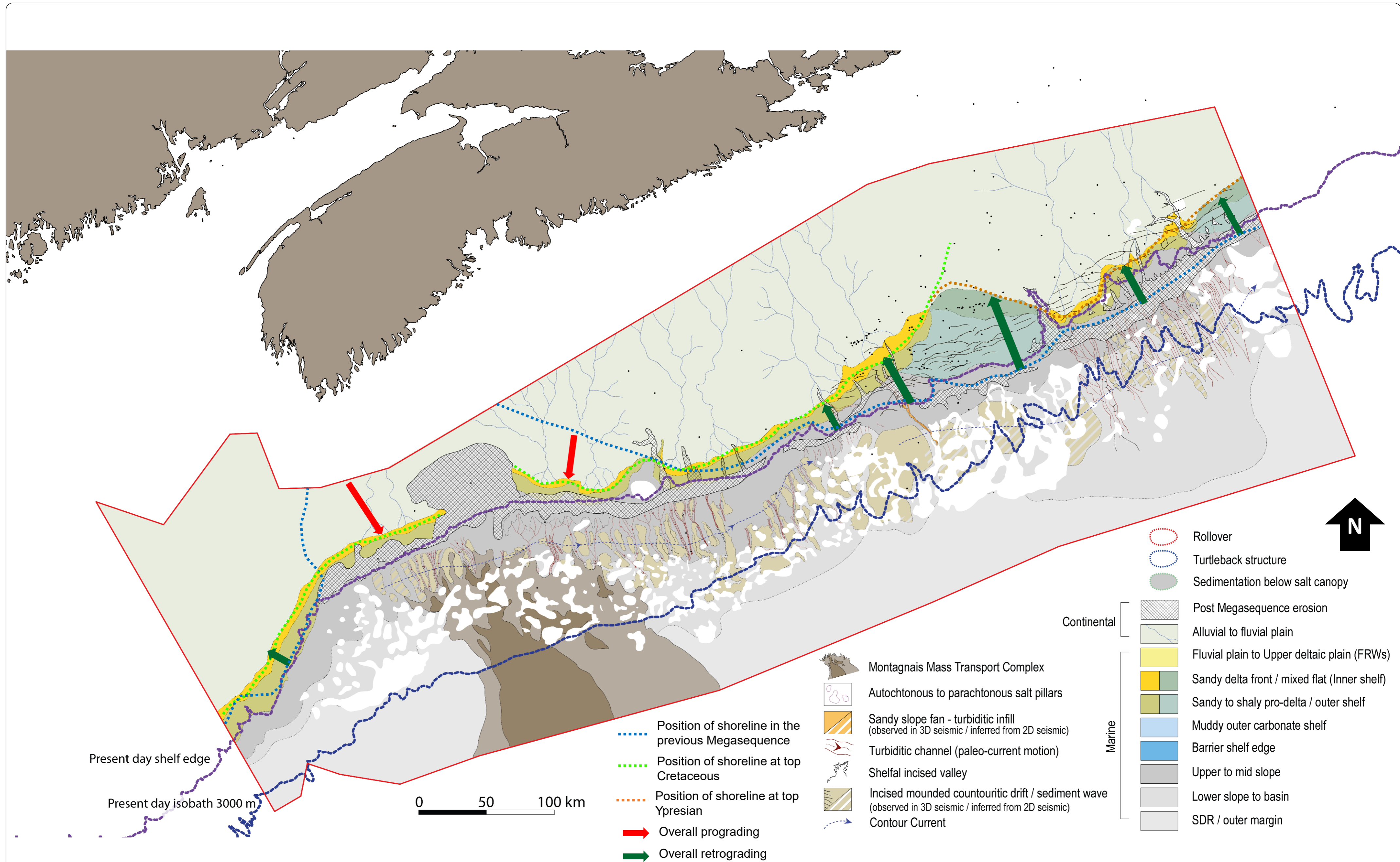


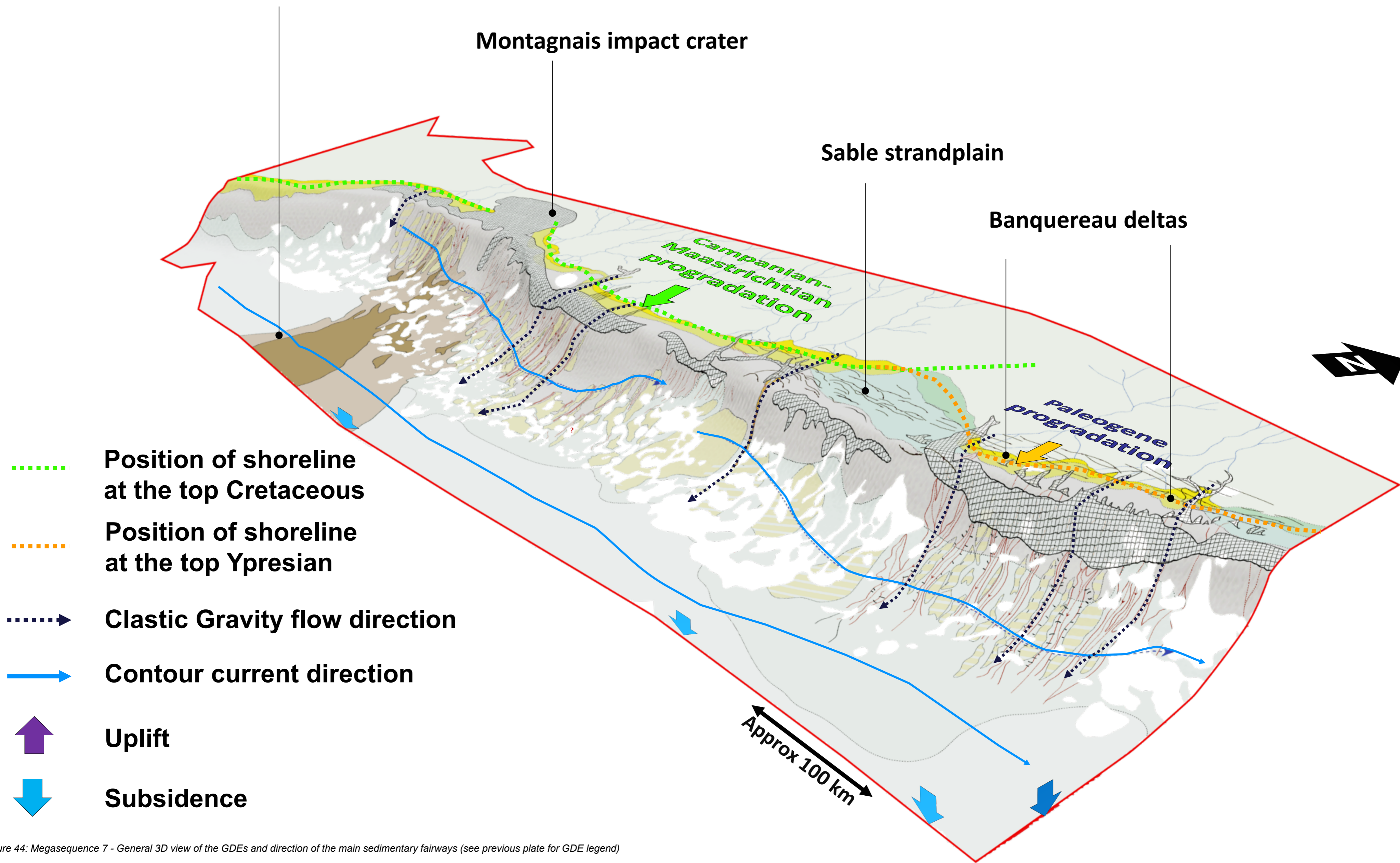
Figure 43: Megasequence 7 - General view of the GDEs and spatial distribution of sedimentary objects

Montagnais Mass Transport Complex

Montagnais impact crater

Sable strandplain

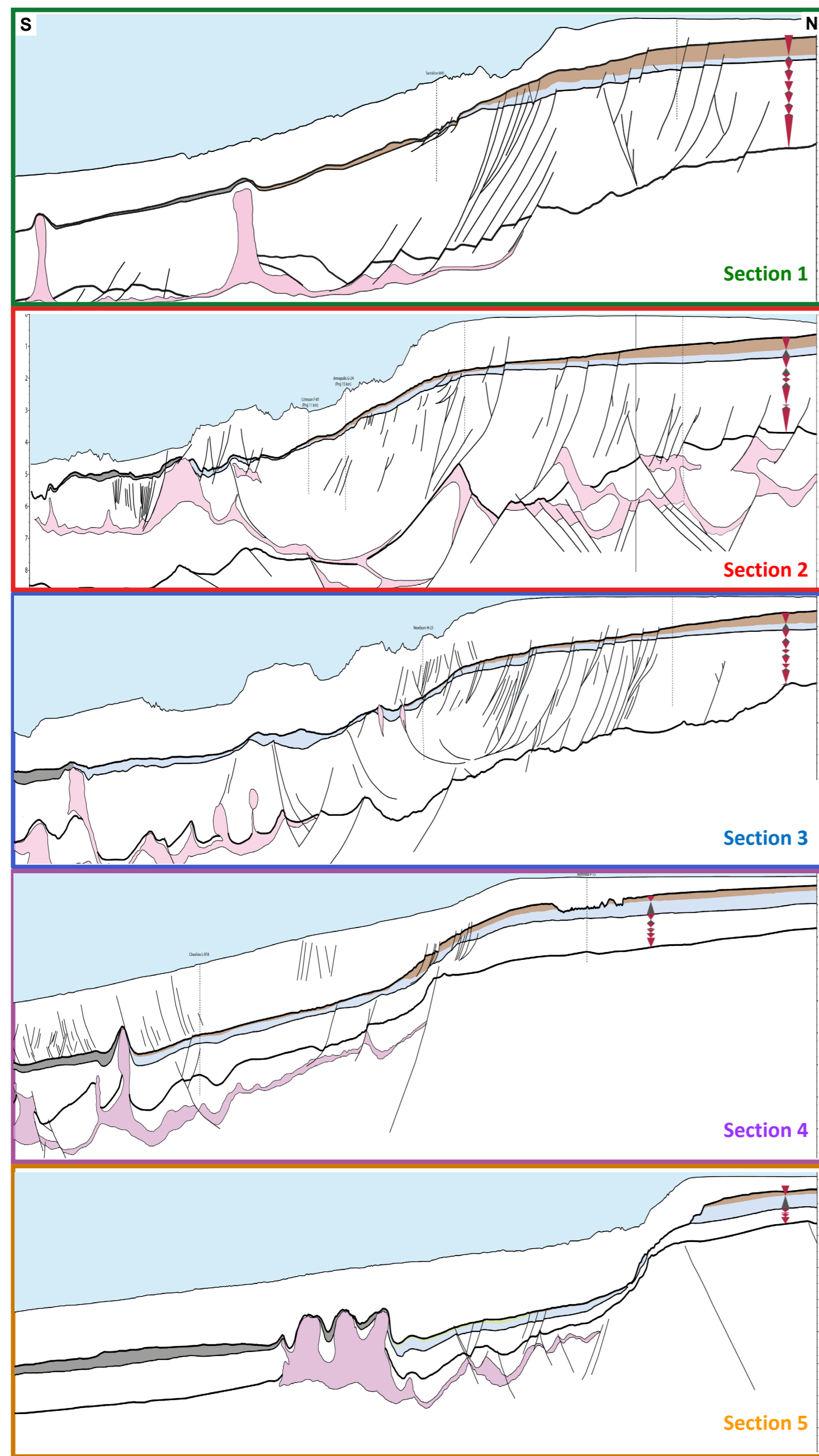
Banquereau deltas



- - - - - Position of shoreline at the top Cretaceous
- - - - - Position of shoreline at the top Ypresian
- - - - - Clastic Gravity flow direction
- — — — — Contour current direction
- ↑ Uplift
- ↓ Subsidence

Figure 44: Megasequence 7 - General 3D view of the GDEs and direction of the main sedimentary fairways (see previous plate for GDE legend)

## Megasequence 7 – Lower Eocene (Ypresian) – Lower Banquereau Formation – Sediment distribution



This GDE map depicts an interval following the Upper Cretaceous major transgression, and characterized by the onset of an overall prograding deltaic system on the shelf.

Fluvial/alluvial systems delivered sediments on the Shelburne/Georges Bank and LaHave platform and further east onto the Abenaki platform and the western Sable region. The eastern Sable region appears starved with more strandplain environments, whilst a remnant deltaic system was active further east above the Banquereau wedge.

The shelf edge displays a large panel of configurations from ramp geometries (Section 2) to clinoform prograding-aggrading systems (Section 1 on PL. 3.41), while pure aggrading trends are observed in the sections 4 and 5 to the west.

Basinal sedimentation was very limited, with thin layers of condensed material alternating with mounded drifts due to strong bottom current activity.

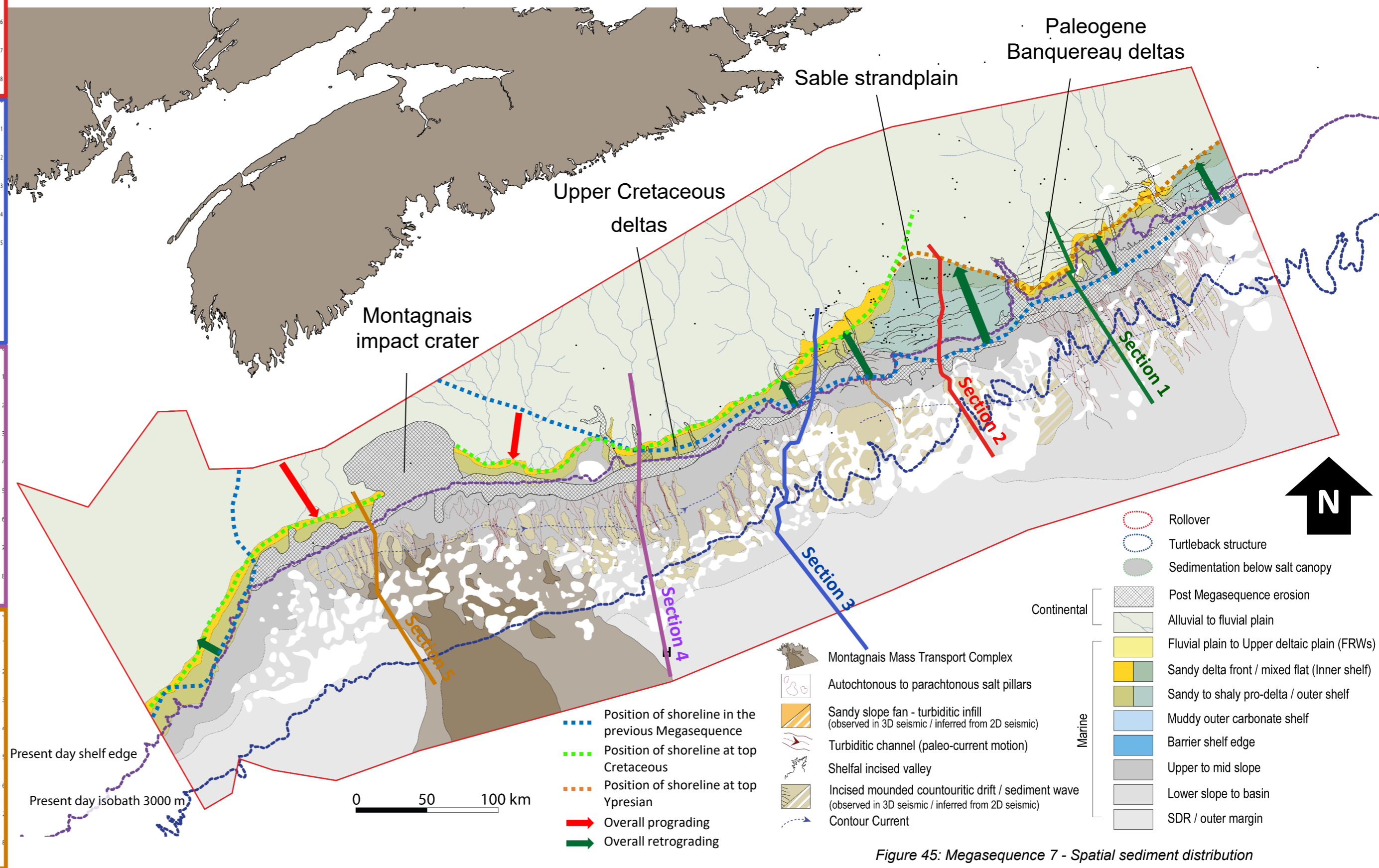
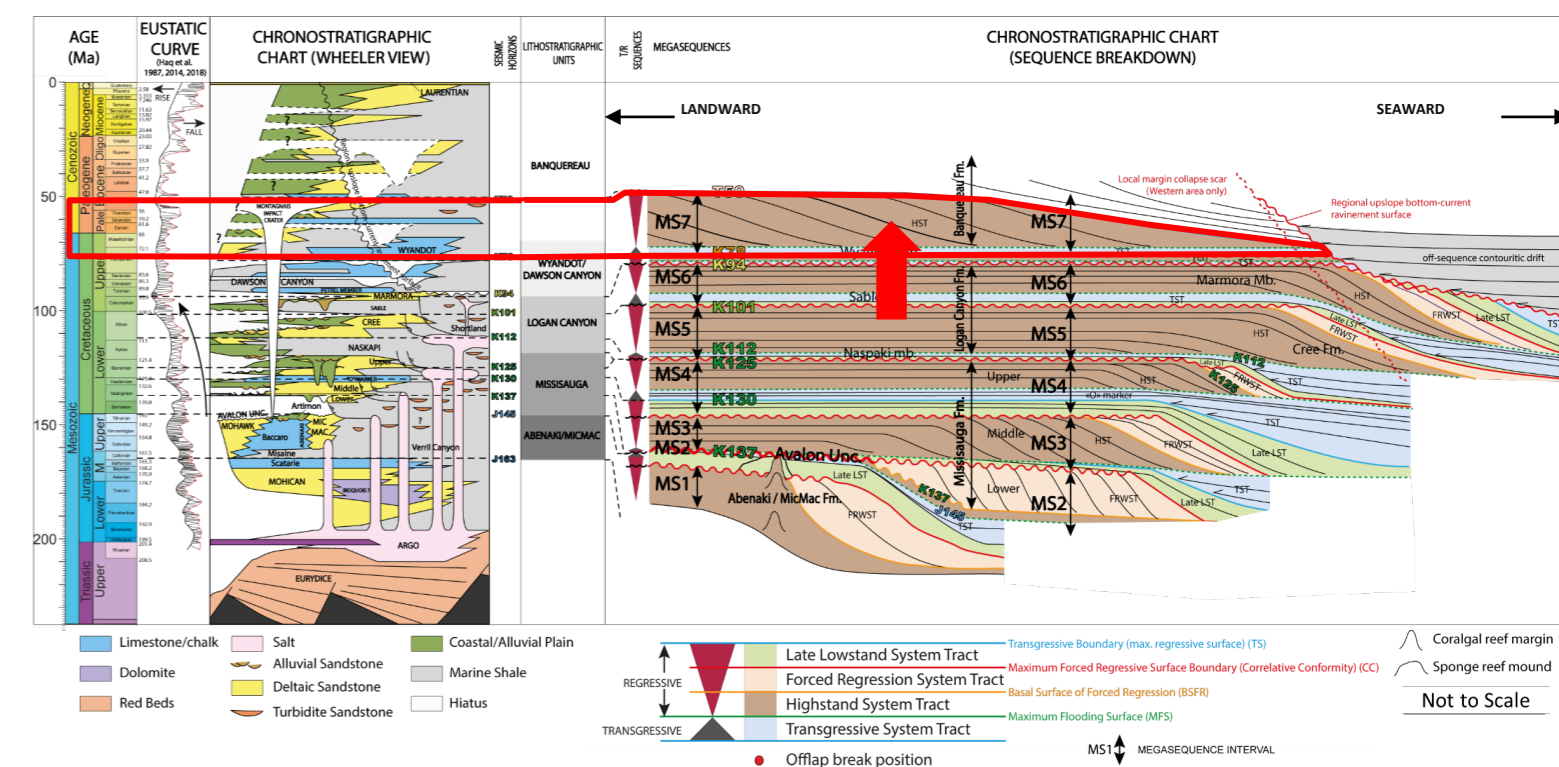
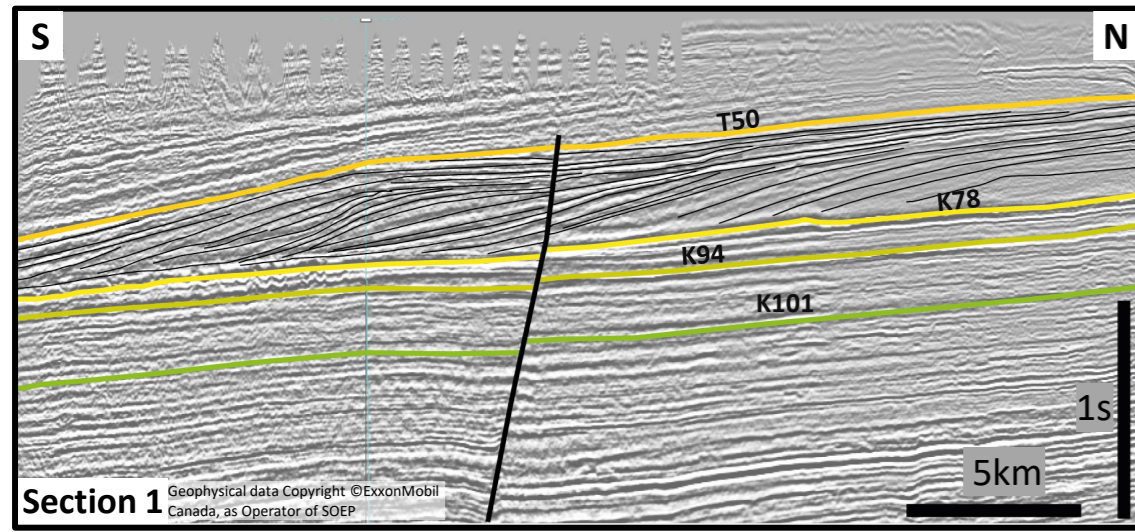


Figure 45: Megasequence 7 - Spatial sediment distribution

## Megasequence 7 – Lower Eocene (Ypresian) – Lower Banquereau Formation – Seismic and Well Information

In the basin, many turbiditic channels developed at the outlet of the deltas, with most strongly reworked by bottom currents (Section 2). The only observed difference is the change of orientation of asymmetric mounded drift, caused by a probable reversal of contour current direction from anticlockwise to clockwise. Such reversal is initiated in the Upper Cretaceous and probably explained by the change of configuration of Northern Atlantic ocean gateways as suggested by Rodrigues et al. (2022), Ladant et al. (2020), and Donnadiu et al. (2016).

The GDE interval also depicts erosional scours and associated mass failure deposits (Section 4) associated with one of the most important Cenozoic geological event offshore Nova Scotia: the Montagnais astrobleme impact event aged 51 Myr (Deptuck and Campbell, 2012: Section 3). A single large debris field covering 93,000 km<sup>2</sup> in the slope to basin area is thought to be the product of a widespread margin collapse caused by a combination of ground shaking and subsequent tsunami triggered by the Montagnais impact, that occurred at the shelf edge during Late Ypresian.



Prograding highstand deltas aged Upper Cretaceous and Lower Cenozoic observed beneath the Sable Island on the shelf.

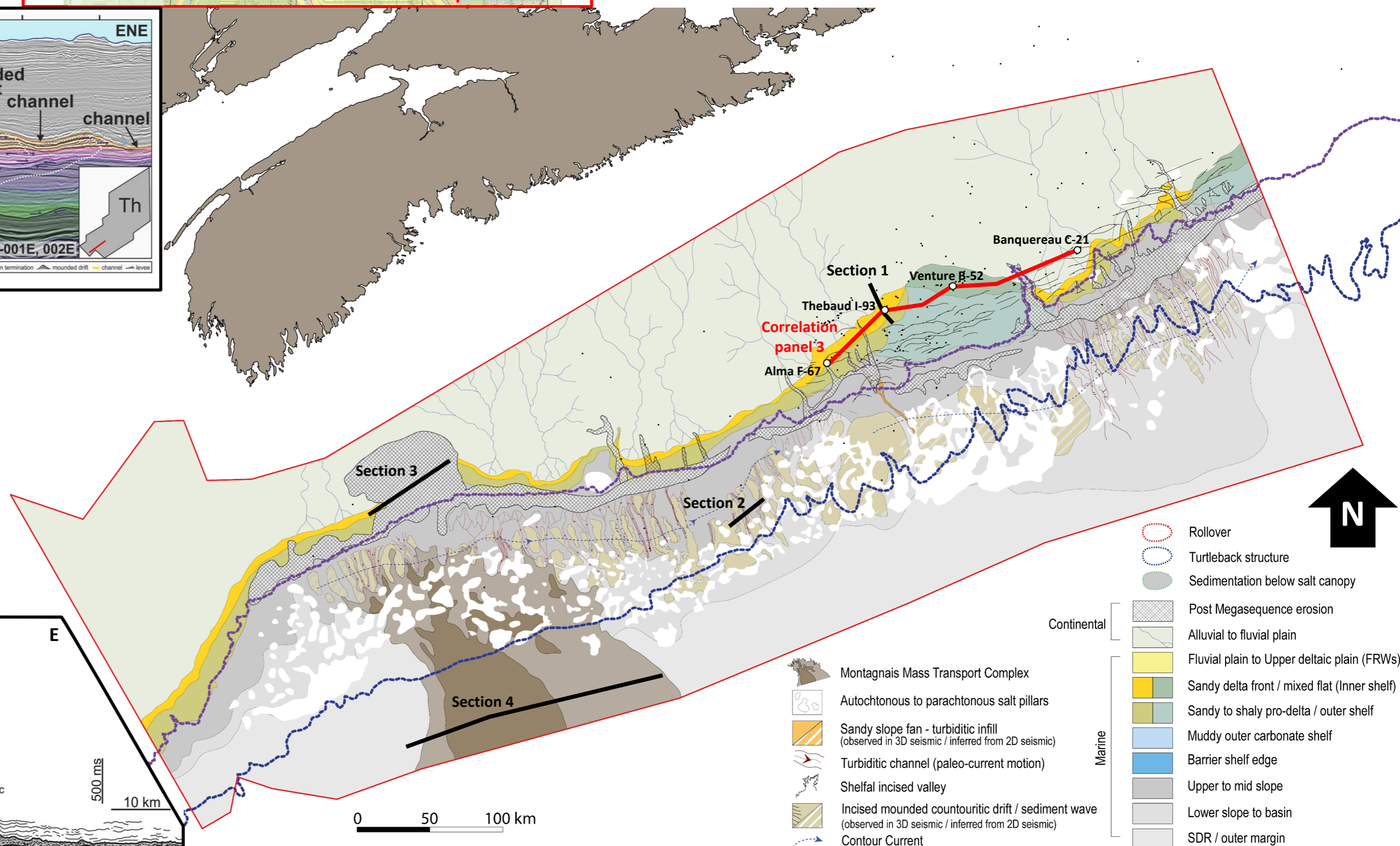
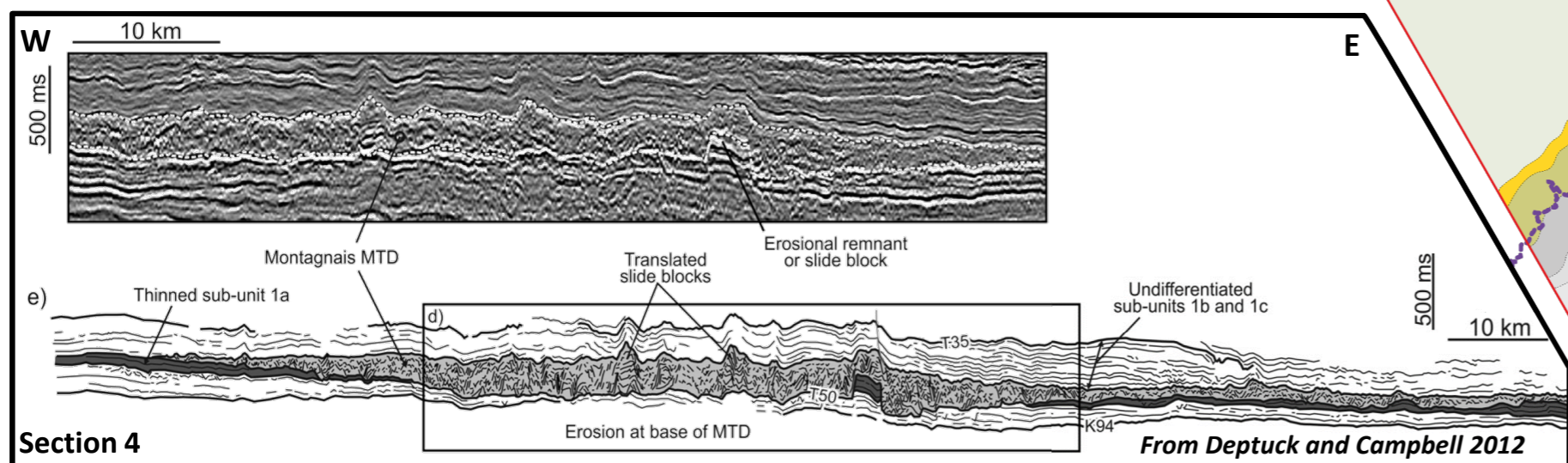
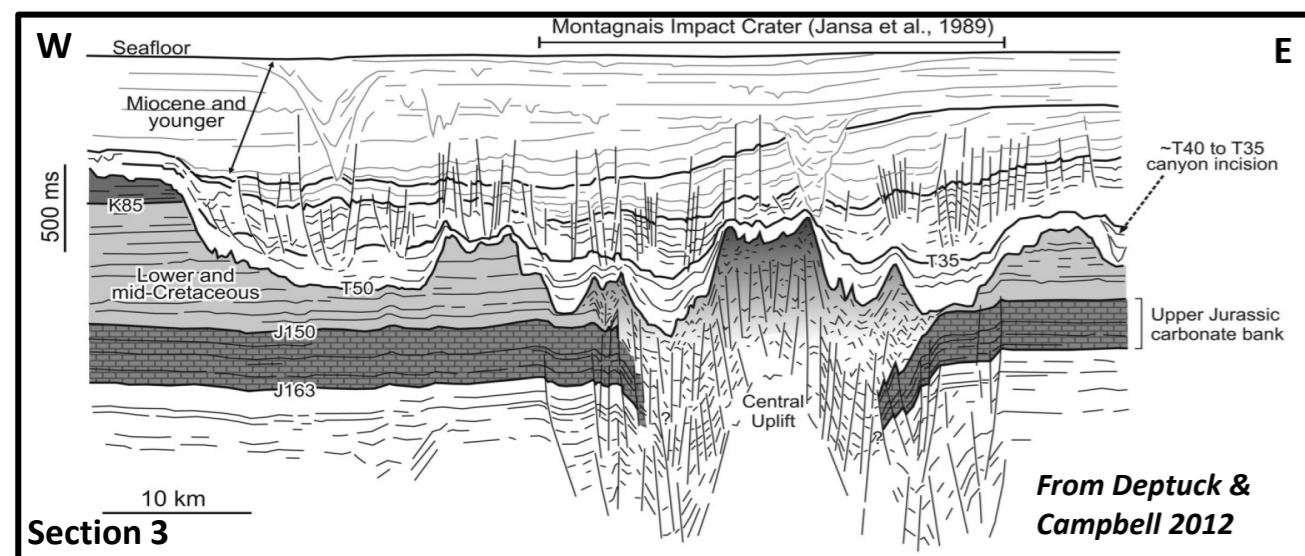
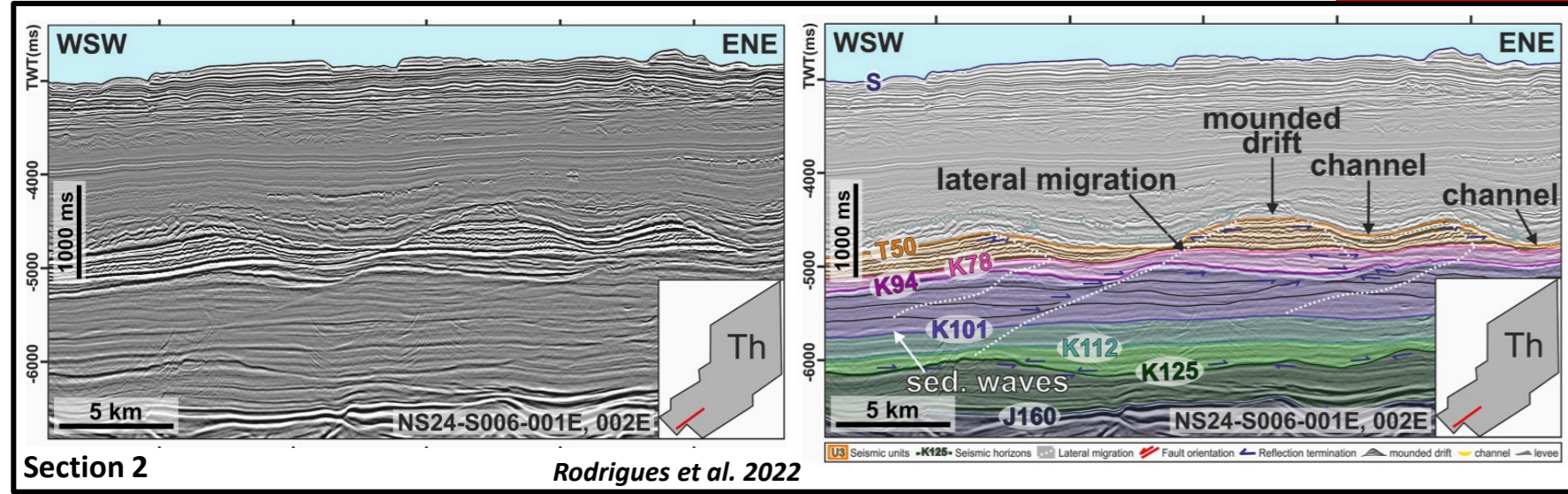
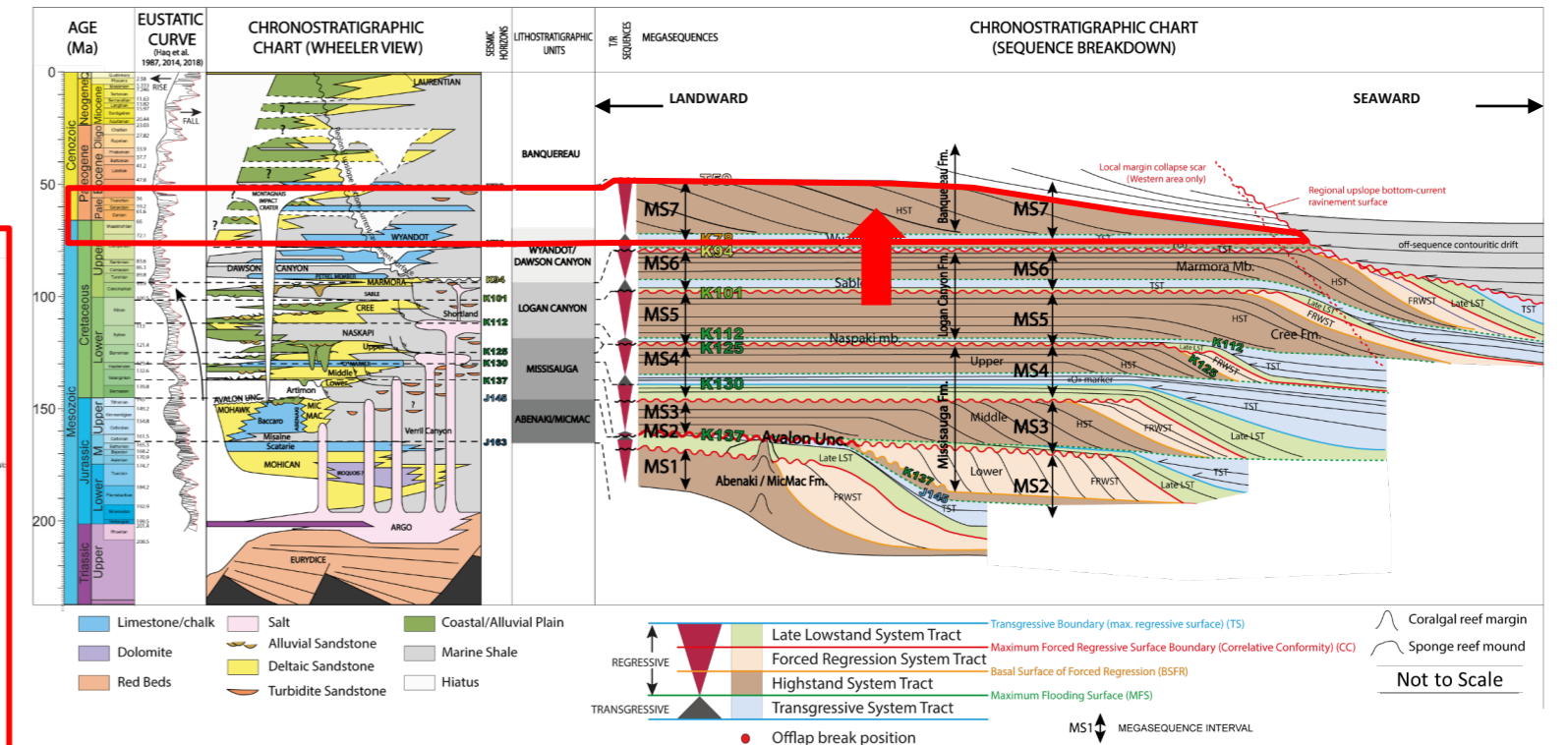
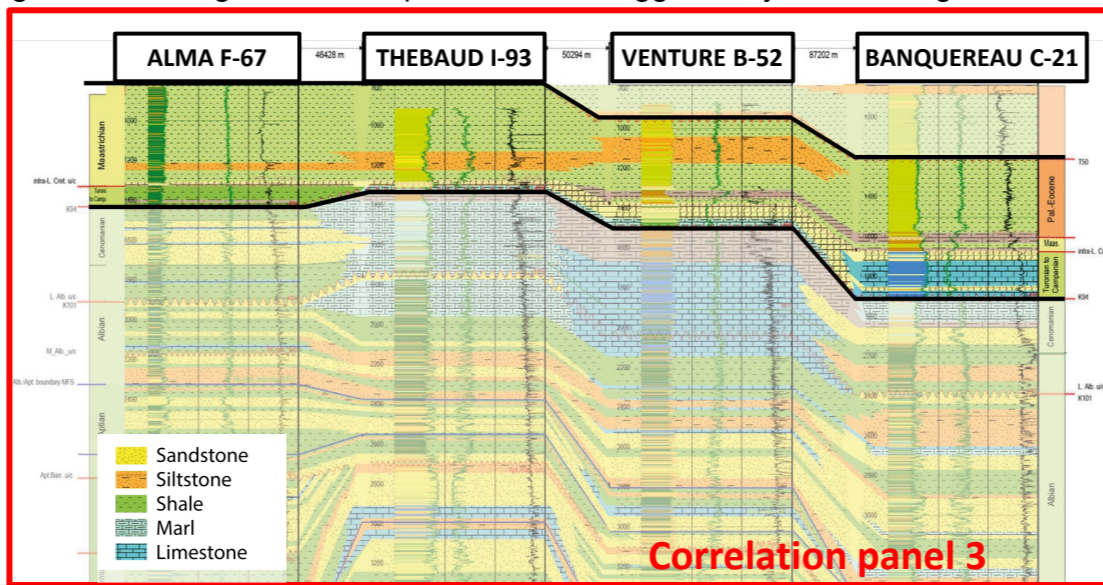


Figure 46: Megasequence 7 – Seismic examples of sedimentary objects and well lithofacies correlation panel