PS Salt-Sediment Interaction in Sable Sub-Basin, Nova Scotia (Canada)*

Francky Saint-Ange[1], Dimitri Savva[2], Bernard Colletta[1], Emerson Marisi[1], Laurent Cuilhe[2], Adam MacDonald[2], and Matt Luheshi[3]

Search and Discovery Article #10971 (2017)**
Posted July 10, 2017

*Adapted from poster presentation given at AAPG 2017 Annual Convention and Exhibition, Houston, Texas, United States, April 2-5, 2017

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Abstract

The Sable Sub-basin is a complex geological sub-basin located in the Central slope of the Scotian margin. It is characterised by an intricate interplay between structural inheritance, salt tectonics and synkinematic sedimentation. One challenge faced during deep-water exploration in the area was to understand reservoirs distribution along the slopes. Part of the challenge is the difficulty in identifying preserved canyons or long-lasting sediment conduits that connect the shelf to the slope. We present here an update on the current view on the evolution of the Central Slope sedimentary system through time in response to salt tectonics. For this purpose, we use newly reviewed and reinterpreted seismic data and related thickness maps on the Central Scotian slope. Results show that the Central Scotian slope can be subdivided into three tectonostratigraphic compartments. The first phase of deformation occurred in the northeast of the study area during Callovian-Tithonian interval, with rapid salt migration over the Alma ridge leading to the creation of the Banquereau Synkinematic Wedge (BSW). Post BSW mechanical adjustment allows the accumulation of a thick Valanginian interval against the main listric faults. The BSW acts as a topographic high and forces the sediment to flow toward the central part of the study area. In the central and southwestern part of the Sub-basin, salt deformation starts at the end of the Jurassic and intensifies shortly after the base Cretaceous unconformity in response to the deposition of the Mississauga Fm. The initiation of a salt canopy by the Hauterivian time disrupts the sediment supply to the deeper part of the basin, and sediment starts to pile up ahead of the salt wall. During the Aptian–early Cenomanian salt canopies are well developed. The significant sediment load over the salt canopy leads to the formation of numerous short-lived intra salt mini-basins. Additionally, due to the amount of growth fault at the shelf edge, several mini–basins appear to form on the upper slopes, which would tend to trap sandstones early on. Because of the intense salt tectonics, canyons do not last very long and sediment conduits are perpetually evolving. The southwestern part of the study area is characterised by the development of a large roho system. Salt movements and withdrawal creates a large turtle back structure bordered by two large permanent sediment conduits. These conduits allow a direct connection between the shelf to the basin.

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Salt – Sediment Interaction in Sable Sub-basin, Nova Scotia (Canada) - PART 1

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ABSTRACT:

The Sable Sub-basin is a complex geological sub-basin located in the Central slope of the Scotian margin. It is characterised by an intricate interplay between structural inheritance, salt tectonics and synkinematic sedimentation. One challenge faced during deep water exploration in the area was to understand reservoirs distribution along the slopes. Part of the challenge is the difficulty in identifying preserved canyons or long-lasting sediment conduits that connect the shelf to the slope. We present here an update on the current view on the evolution of the Central Slope sedimentary system through time in response to salt tectonics. For this purpose, we use newly reviewed and reinterpreted seismic data and related thickness maps on the Central Scotian slope.

Results show that the Central Scotian slope can be subdivided in three tectonostratigraphic compartment. The first phase of deformation occurred in the northeast of the study area during Callovian - Tithonian interval, with rapid salt migration over the Alma ridge leading to the creation of the Banquereau Synkinematic Wedge (BSW). Post BSW mechanical adjustment allows the accumulation of a thick Valanginian interval against the main listric faults. The BSW acts as a topographic high and forces the sediment to flow toward the central part of the study area. In the central and southwestern part of the Sub-basin, salt deformation starts at the end of the Jurassic and intensifies shortly after the base Cretaceous unconformity in response to the deposition of the Missisauga Fm. The initiation of a salt canopy by the Hauterivian time disrupts the sediment supply to the deeper part of the basin, and sediment starts to pile up ahead of the salt wall. During the Aptian – early Cenomanian salt canopies are well developed. The significant sediment load over the salt canopy leads to the formation of numerous short lived intra salt mini-basins. Additionally, due to the amount of growth fault at the shelf edge, several mini – basins appear to form on the upper slopes which would tend to trap sandstones early on. Because of the intense salt tectonics, canyons do not last very long and sediment conduits are perpetually evolving. The southwestern part of the study area is characterised by the development of a large roho system. Salt movements and withdrawal creates a large turtle back structure bordered by two large permanent sediment conduits. These conduits allow a direct connection between the shelf to the basin.

It appears that where the autochthonous salt has a broader extent, the deformation is more complex and therefore creates numerous trapping systems. In the central area, where the salt is more restricted, the deformation is more concentrated and creates deep small basins. To the northeast were the BSW is found, deformation is less important because of the limited amount of salt and with the exception made of the BSW itself, geometries are smoother with longer wavelength, leading to fewer trapping systems. There large turbidite fans are more likely to be recorded.

Introduction:

The Sable Sub-basin corresponds to the central slope of the Scotian Margin and has been the main focus of offshore oil and gas exploration in Nova Scotia, with several commercial discoveries since the 1970s leading to the development of the Sable Offshore Energy Project in the late 1990s early 2000s (Figures 1 and 2). One of the main issue faced across the margin during exploration phases is the the geological complexity of the area and the significant impact of salt tectonics leading to synkinematic sedimentation.

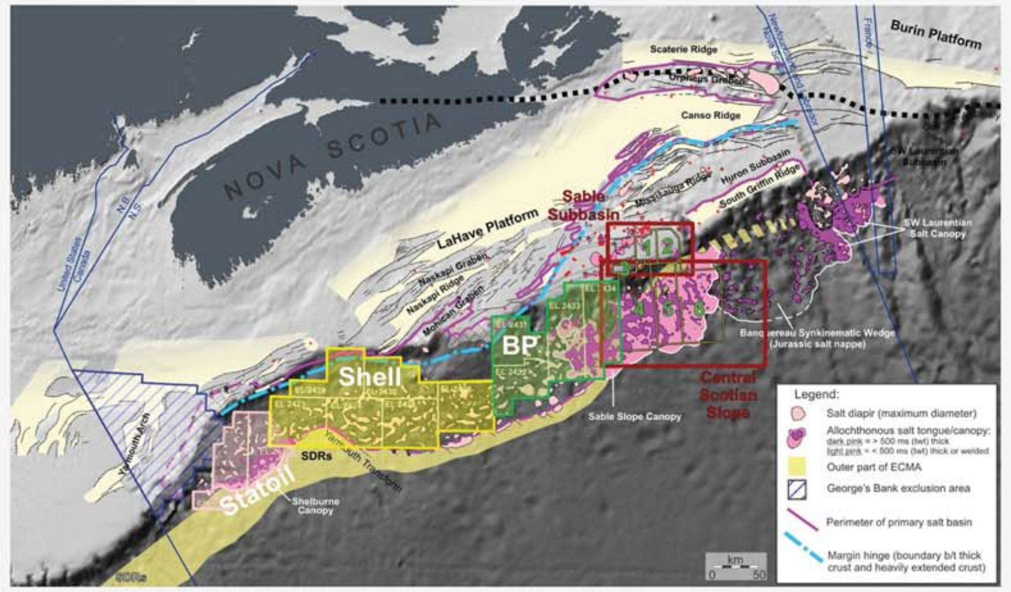
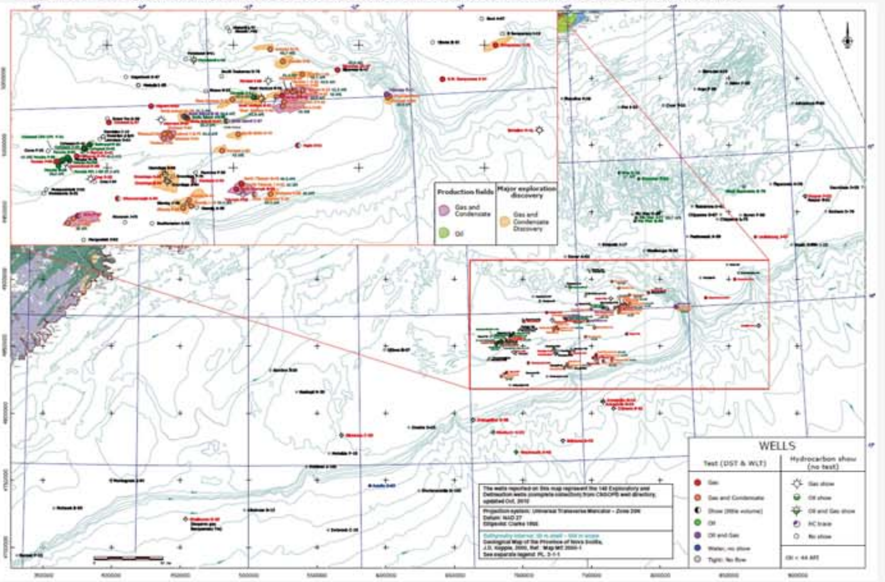


Figure 1: Basemap of the Scotian Margin showing distribution of key structural elements (From Kendell et al., 2016; some structural elements are from Deptuck and Kendell, in prep).

Figure 2: Regional hydrocarbon distribution from wells (from OERA, 2011).



The main conclusions from the established work on salt tectonics were that:

- Lower and Upper Cretaceous deposits are strongly controlled by salt tectonics (synkinematic wedge and salt structures) (Deptuck et al., 2014)
- Two major salt layers (autochthonous and allochthonous) inducing a Roho system were active during Cretaceous reservoir deposition (Kendell, 2012)

Focusing on the slope in Sable Sub-basin, postmortem analysis completed on Balvenie B-79, Crimson F-81 and Annapolis G-24 wells showed that targeted traps are located in Cretaceous "synkinematics wedges" controlled by basal detachments in allochthonous salt, but the wells were not optimally located.

Structural analysis and Postmortem

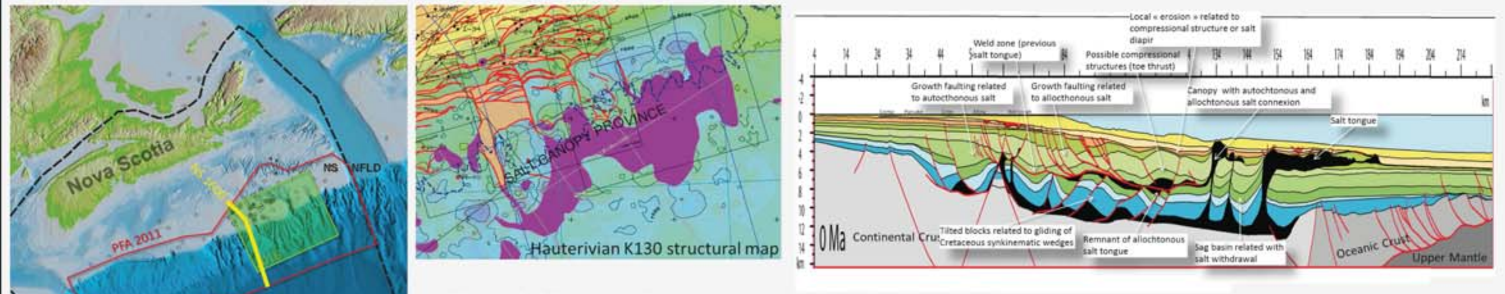


Figure 3: PFA 2011 / Structural analysis Bible Line NS 1600; Very cplx area controlled by salt tectonic; synkinematic sedimentation; study superior area of reservoir.

Principal results from the PFA (2011) (Figures 3 and 4):

- Lower and Upper Cretaceous deposits are strongly controlled by salt tectonics (synkinematic wedge & salt structures).
- Two major salt layers (autochthonous and allochthonous) induced Roho system which was active during Cretaceous reservoir deposition.
- Autochthonous salt basins are bounded by structural high at COB.
- Transverse faults (diapirs) induce structural segmentation of the slope area.

Figure 4: PFA 2011- Restoration of section NS1600

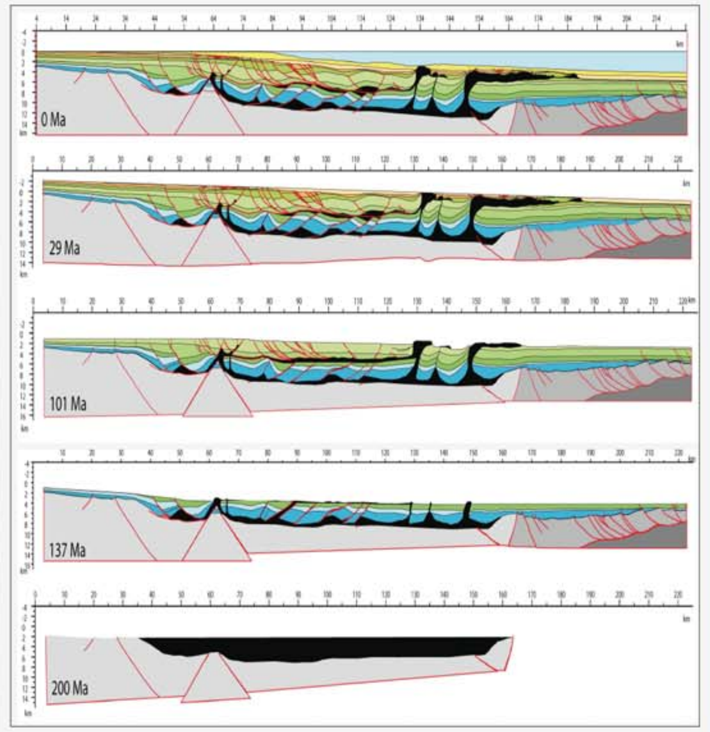
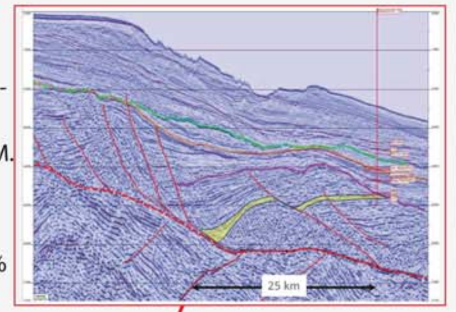
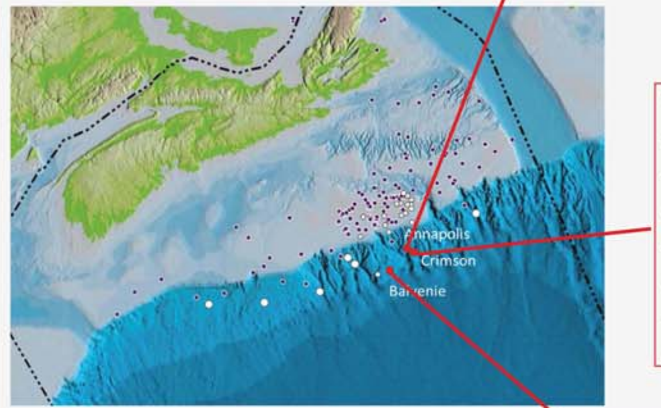
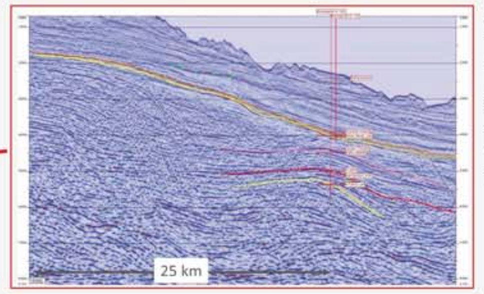


Figure 5: Extract from postmortem analysis for Annapolis, Balvenie and Crimson wells (PFA, 2011)

Annapolis 2001 Marathon
1740m water depth
Major kick @ 3496m, lost well
TD 6182m Lwr. Missisauga (Berriasian)
27m net pay over 3 zones, H, L, M.
H - mid Barremian
L - mid Barremian f~17%
M - late Hauterivian f=12-25% 18.2m

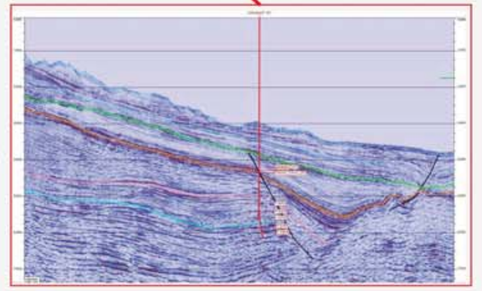






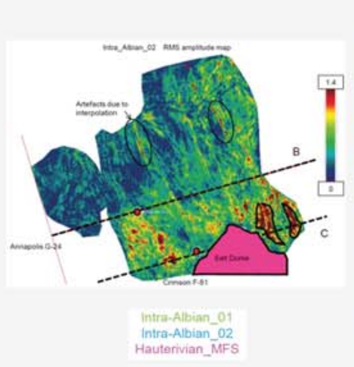
Crimson 2004 Marathon
2091m water depth
9km SE Annapolis
TD 6676m Early Hauterivian
13m wet sand f=13%

Balvenie 2003 Imperial:
1803m water depth
Only 515m tested.
TD 4750m Early Aptian (C30)
Gas charged in siltstone.



From the Postmortem the following conclusions were drawn (Figure 5):

- Reservoirs are thin in wells (27 m of net pay over 3 zones in Annapolis well);
- RMS amplitude analysis on Marathon 3D seismic data (Figure 6) show that both Annapolis and Crimson wells were not located in the best location to reach high amplitude reflectors either in Albian or Hauterivian units.
- The main exploration risk in the slope area is mainly a reservoir issue;



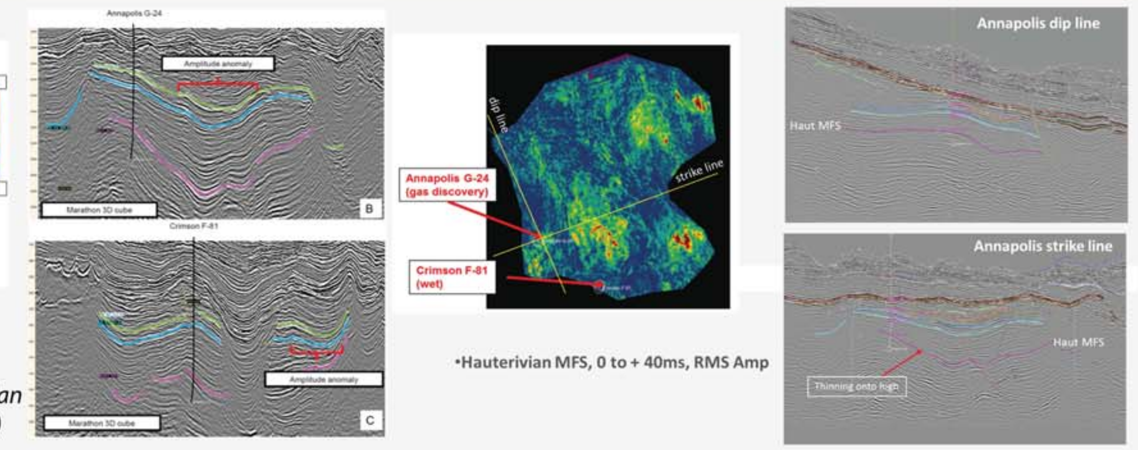
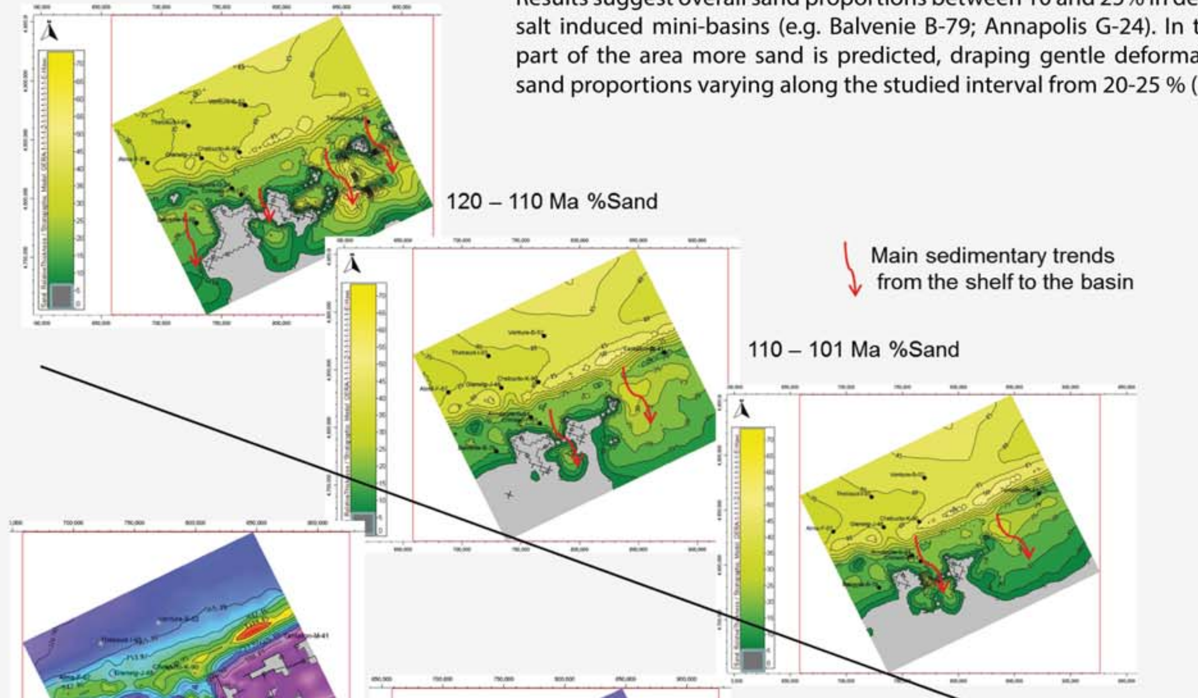


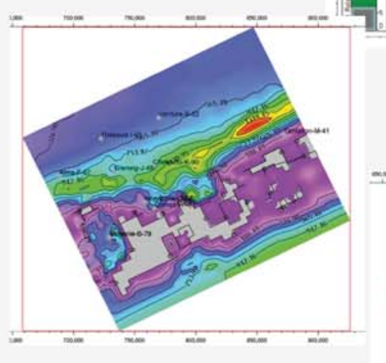
Figure 6: Intra Albian and Hauterivian RMS amplitude analysis (PFA, 2011)

Evidence for Reservoirs:

The presence of hydrocarbon reservoirs bearing significant resources is proven on the shelf. Finding reservoirs on the slope is riskier, given the history of failed deep water wells. The Annapolis G-24 well provides evidence for good reservoirs, even at depths of about 5000m. Detailed work on sequence stratigraphy, lithostratigraphy and seismic stratigraphy shows that reservoirs are well distributed across the slope for each key interval, but that their location is difficult to predict because of salt tectonics. In fact, the most challenging aspect is not finding reservoirs, but finding thick reservoirs. Because of the salt tectonics and related margin deformation, significant sediment trapping systems may have formed at the shelf edge and upper slope for a specific time interval, particularly during the Barremian – Albian interval, which corresponds to the formation of the salt canopy. DionisosFlow™ stratigraphic modelling performed for the Upper Missisauga – Logan Canyon interval (*Hawie et al., submitted*) shows that an efficient trapping system does exist at the shelf edge and upper slope, but that a significant part of sands reach the lower part of the system (Figure 7; *Hawie et al., submitted to AAPG Bulletin*).

Results suggest overall sand proportions between 10 and 25% in deep water in salt induced mini-basins (e.g. Balvenie B-79; Annapolis G-24). In the eastern part of the area more sand is predicted, draping gentle deformations, with sand proportions varying along the studied interval from 20-25 % (Figure 7).





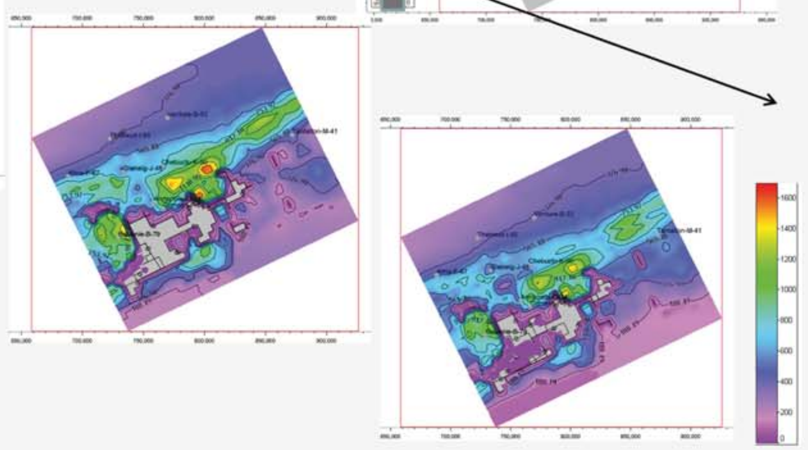


Figure 7: Weighted average sand proportion evolution from 130.5 to 101 Ma as well as the modeled thickness trends (From Hawie et al., submitted)

Salt – Sediment Interaction in Sable Sub-basin, Nova Scotia (Canada) - PART 2

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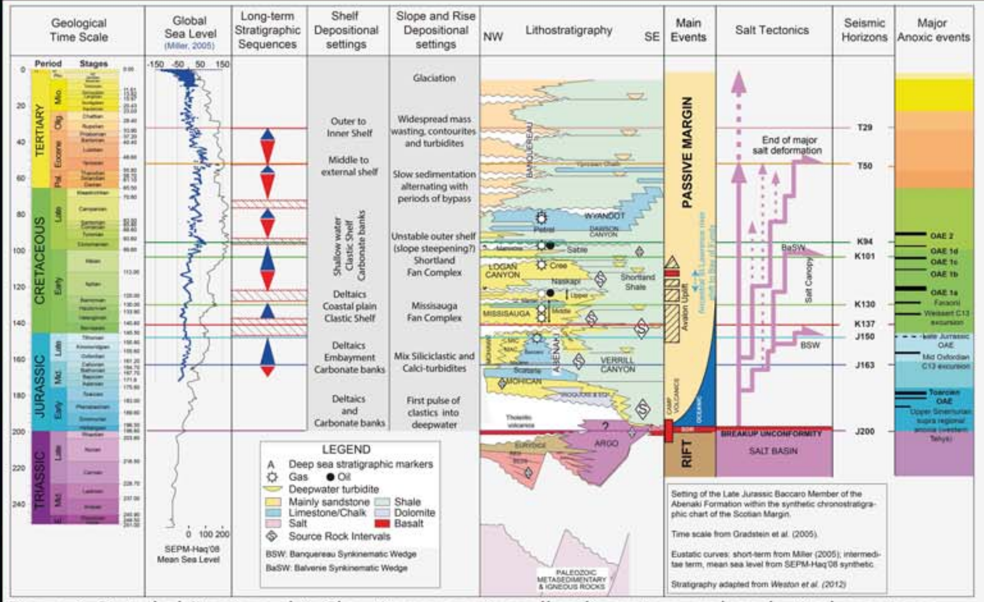


Figure 8: Detailed Stratigraphic Chart incorporating all sedimentary and geological events as well as major anoxic events. (Modified and updated from PFA 2011).

Geological Setting

The sedimentary record of the Sub-basin spans the last 250 million years with continuous sedimentation from the initial opening of the Atlantic Ocean to the recent post-glacial period (Figures 8). The Sub-basin was fed by clastic sediments from a large drainage system over the northeastern Canadian Shield corresponding to the proto St Lawrence estuary. The exact size of the drainage system and organisation of related tributaries are not yet well understood, although recent work has revealed a complex history of shift in drainage areas in response to the Avalon uplift (Figure 9).

The Sable Sub-basin may correspond to the thickest post-rift sediment accumulation of the entire margin, with a total average thickness exceeding 14 km (Kendell et al., 2016).

During the Jurassic, prominent carbonate banks alternated with deltaic successions until the Early Cretaceous. The main sediment source is located more or less at present day St Lawerence outlet location.

During the early Cretaceous, sources are broadly distributed across the margin. During the late Hauterivian – Late Cenomanian interval, the main river systems are blocked by uplift south of the Cobequid-Chedabucto fault zone and related volcanism and therefore rerouted to the Bay of Fundy (Pe-Piper et al., 2011; Tsikouras et al., 2011)

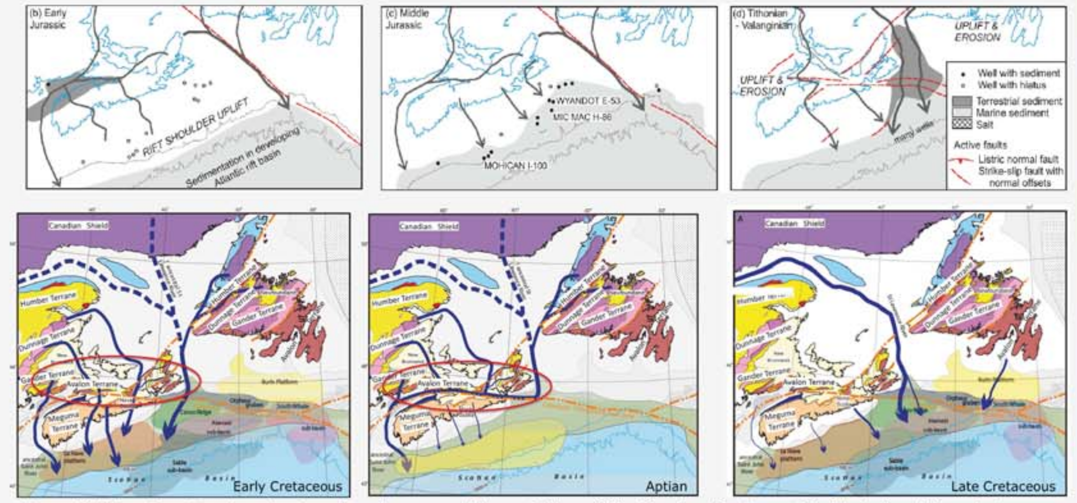
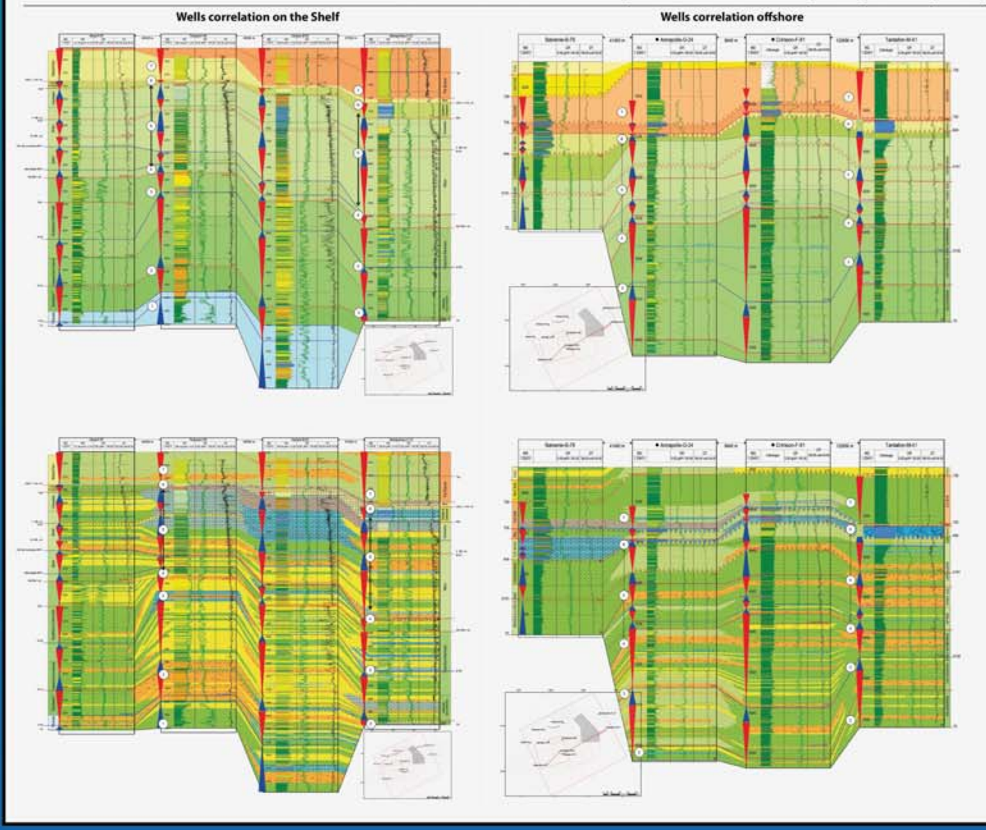


Figure 9: Map showing the structural and geomorphic evolution of the Scotian Basin and its hinterland from late Triassic to late Cretaceous (from Tsikouras et al., 2011; Li et al., 2012; Strathdee, 2012)

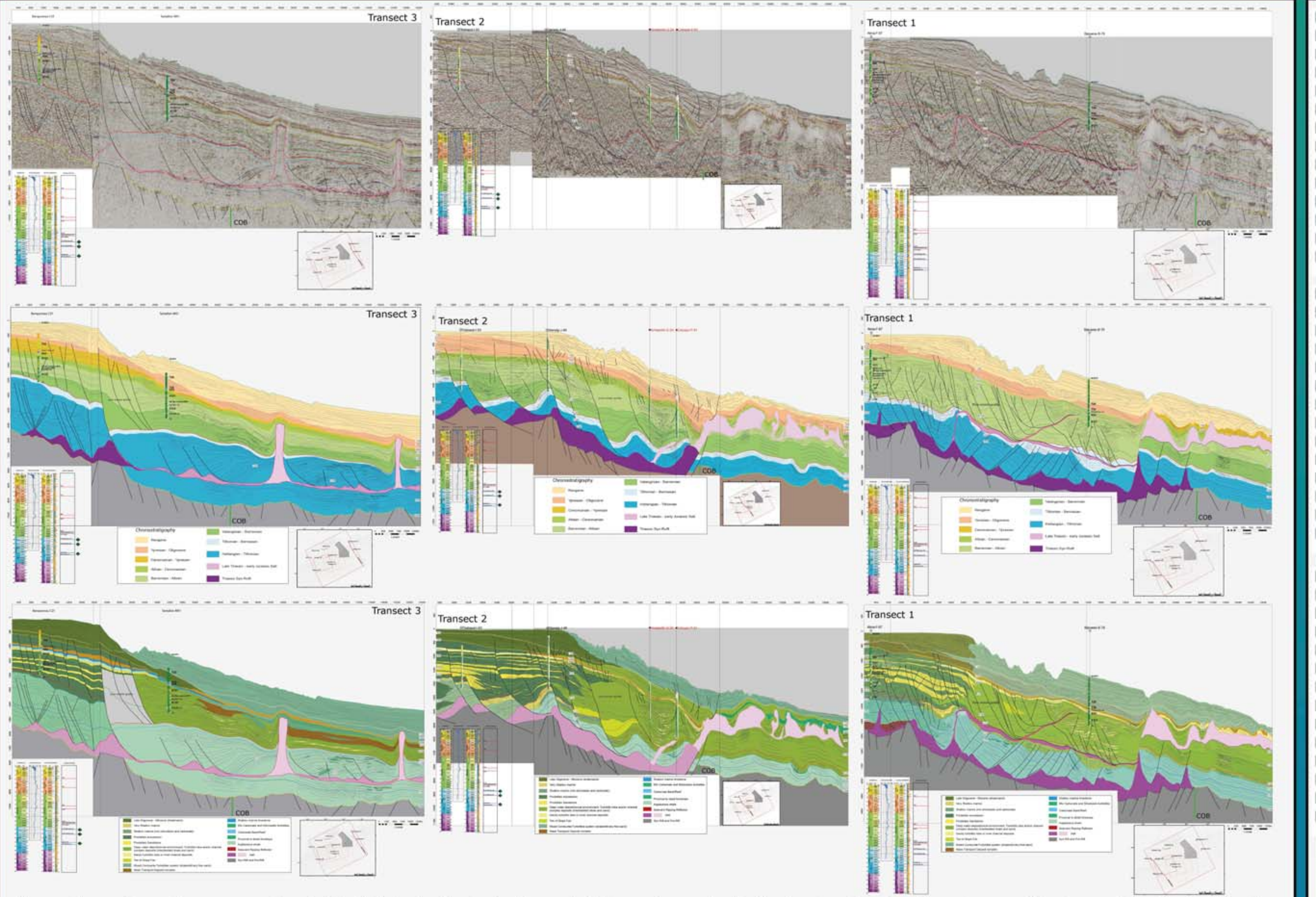


Wells Correlation:

Wells on the shelf reached the upper Jurassic, but most of the section show a ~3500 m thick Cretaceous succession. Most of preserved accumulation is Berriasian - Cenomanian of age. Jurassic sediment are caracteristic of a mixed Clastic / Carbonate system, whereas Cretaceous series are related to deltaic / prodeltaic systems with well developed meandering system landward of the study area.

Wells offshore didn't reach the Jurassic but similarly to the shelf they show ~ 2 to 3000 m of Cretaceous succession. Contrarily to the wells on the shelf, sediments are mostly shaly with very little sand layers interpreted as thin turbiditic sandstones.

Significant differences in sediment thicknesses are observed laterally due to the control that salt tectonic has on sedimentation, particularly during the Valanginian - Barremian interval. Pass the Cenomanian interval, the impact of the salt tectonic is not observed in the wells. Significant lateral thickness variability particularly during Valanginian – Barr.



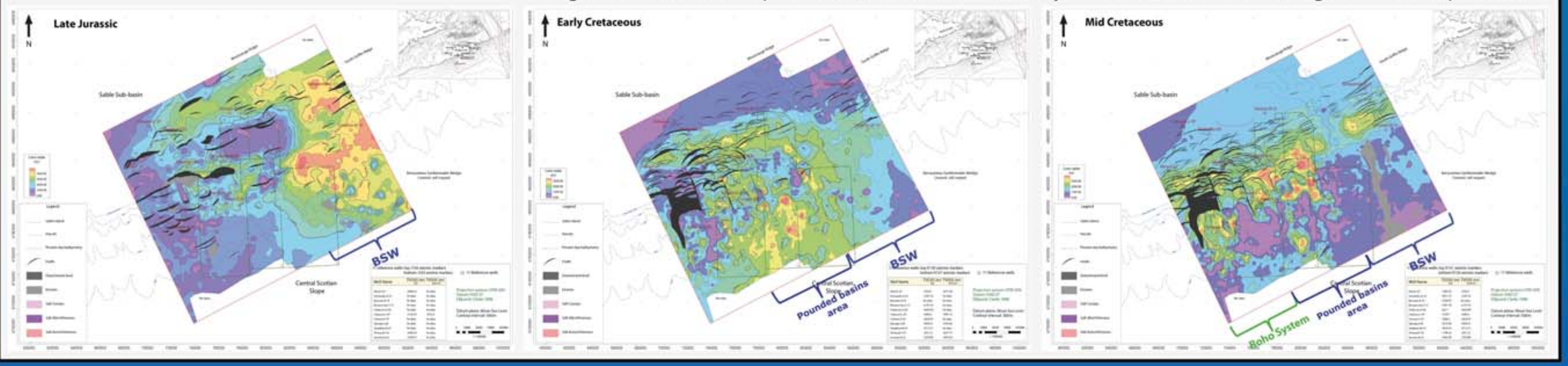
These three dip sections across the Sable Sub-basin illustrate the variability and complexity in structural and sedimentary architecture of the Central Scotian Margin since the Breakup Unconformity (J200). Salt tectonics is the key feature as it controls the majority of the faulting systems, as well as sediment distribution and the resulting architecture. Decreases in the size of the salt basin coincides with changes in salt tectonic styles, with changes occurring rapidly along the 200 km of the study area. The main structures observed are:

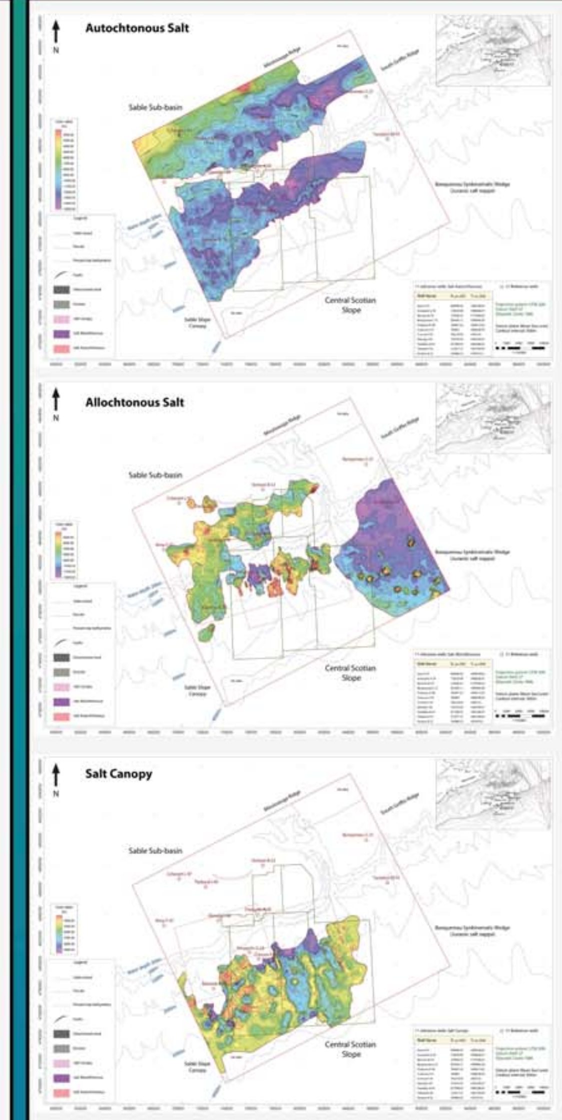
Growth faults system rooted to the top of salts; Synkinematic wedges (Transects 1 and 2) characterized by extension in the upper part and compression in the downward part (rafted structures, turtle back structures); A roho system with autochthonous salt feeders (Transect 1); Salt canopy in Transects 1 and 2 as well as diapirs in Transect 3.

In summary, the study area is divided into three distinct structural zones. It appears that where the autochthonous salt is more extensive the deformation is more complex and therefore numerous trapping systems are created. To the northeast in proximity to the BSW deformation is less developed because of the limited amount of salt and (except for the BSW itself), geometries are smoother and longer wavelength, leading to fewer trapping systems. In the Annapolis area where the salt has a greater extent, vertical movement is more important which eventually evolved into salt canopy above which developped small basins.

As shown below (Figure 10), during the Jurassic the main depocenter was located on the eastern side of the study area. There the salt body was restricted behind the Alma ridge and coincide with the first location to be destabilized. During the Cretaceous a switch of depocenters from the northeast to the southwest occured which coincide to a trend of increasing extent of the salt unit.

Figure 10: Thickness maps in (m) for the late Jurassic, early and mid Cretaceous showing the shift in depocenters





Maps on the left show successively the distribution of autochtonous salt, allochtonous salt and salt canopy. We can observed that the largest synkinematic wedge occured where salt had the least extension, whereas complex Roho system and salt canopy occured where the salt had the largest extent. Largest concentration of mini basin occurs in between the two areas.

Reconstruction of salt movement in response to sediment load:

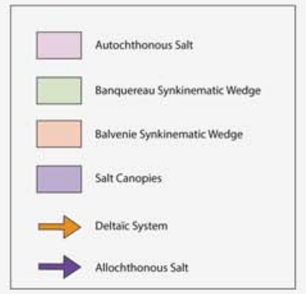
J200: End of Argo salt deposit

J200-J163: Sediment input from the NE; Salt passes over the South Griffin Ridge into the basin starting the Banquereau Synkinematic Wedge

J163-J150: The Banquereau Synkinematic Wedge is formed but salt deformation remains active

J150-K137: Low sedimentation rates. Shift of deformation locus to the SW

K137-K94: Development of Sable deltaic system; increase in salt deformation expending to the south progressively. Initiation of the Sable Salt canopy and then the Roho system.



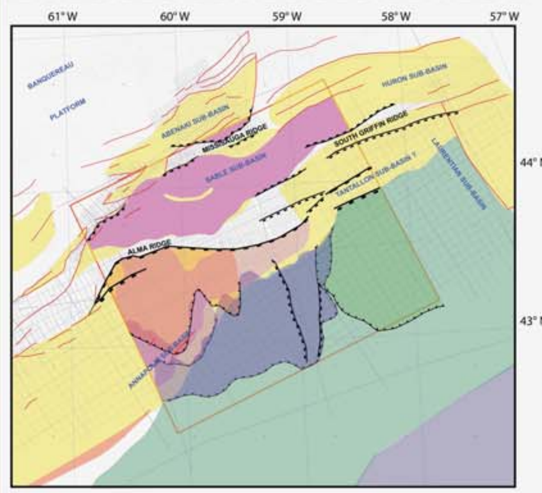
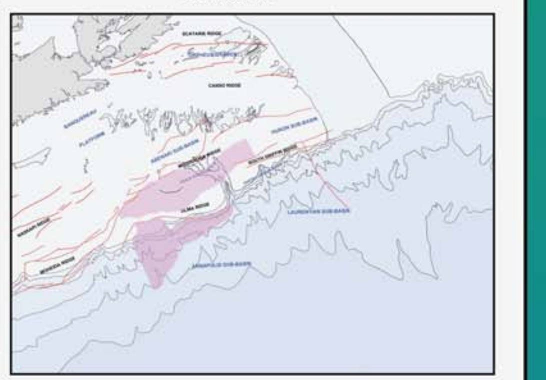
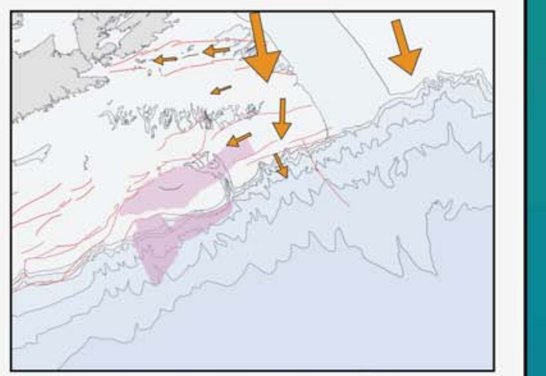


Figure 11: Structural sketch map of salt domains

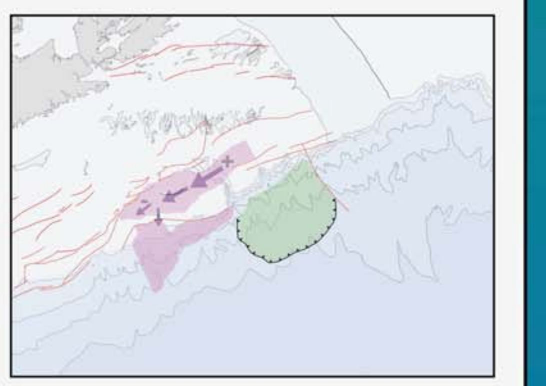
J200: Post rift



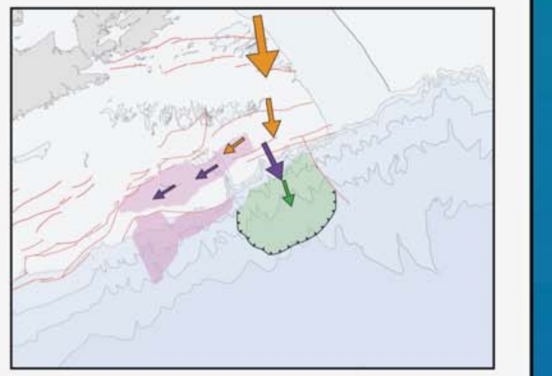
J200-J163: Jurassic Deltaïc System



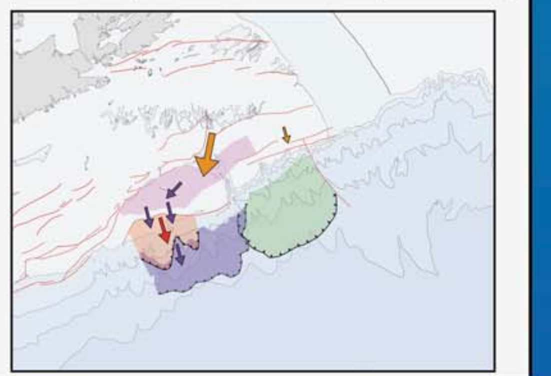
J150-K137: Avalon Uplift +Autochtonous salt Creeping



J163-150 : Jurassic Deltaïc System + Banquereau Synkinematic Wedge



K137-K94 : Deltaïc System + Salt Canopies + Balvenie Synkinematic Wedge



Conclusion:

Three distinct are of salt tectonic have been defined. From NE to SW, a Jurassic synkinematic wedge, a Cretaceous pounded basin area and a Cretaceous complex roho system. Salt deformation is diachronous across the study area and seems to answer not only to the sedimentary load but also to the size and geometry of the basin where the salt deposited. Thus, the first and rapid salt related deformation occured where the salt was at its minimum extent, whereas complex roho system and diapirism occured where salt was at its maximum extent.

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