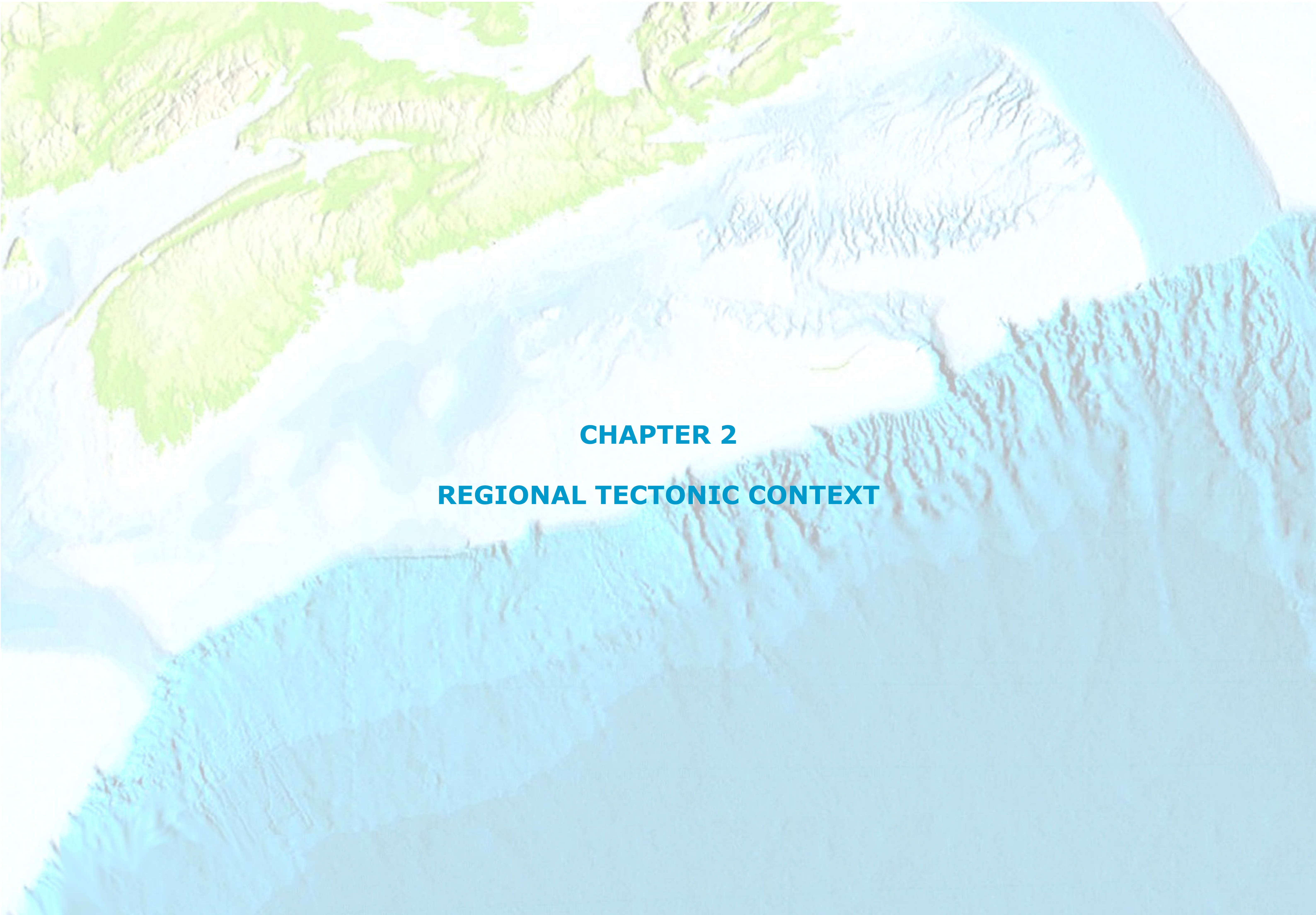


CHAPTER 2

REGIONAL TECTONIC CONTEXT

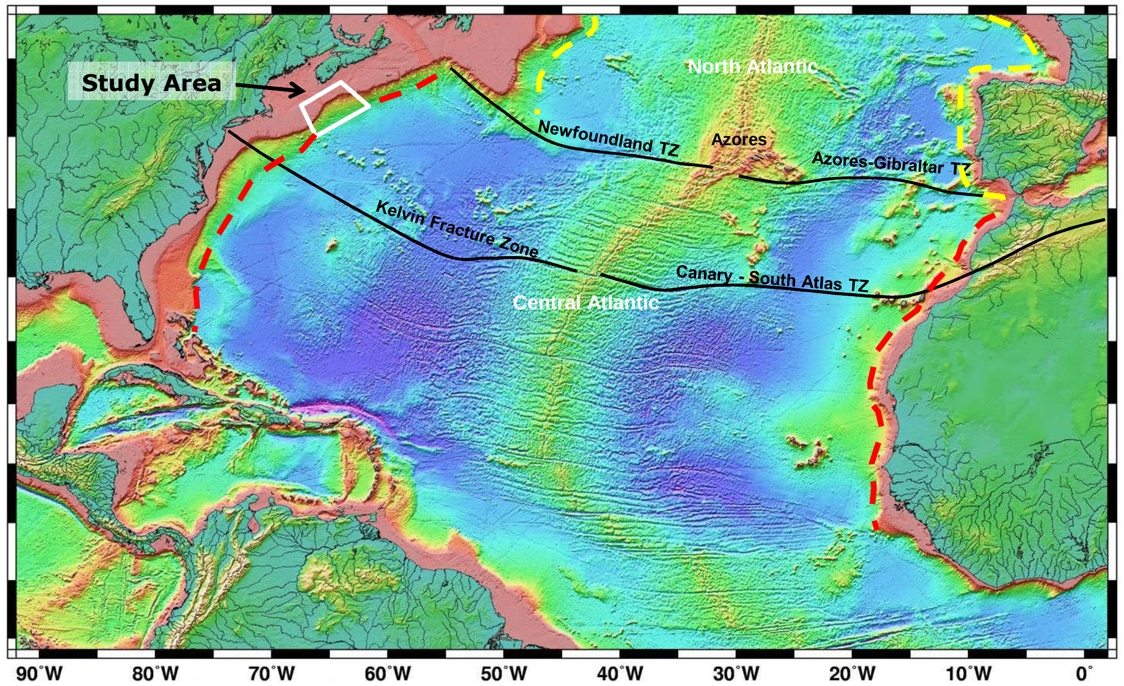


Figure 1: Topography of the Central and North Atlantic and location of the study area (white polygon).and distribution of different margin types (Boillot & Coulon 1998, Louden et al. 2010). The magma dominated (volcanics) margins (red dot line) of the North Atlantic and Central Atlantic are separated by a magma poor (non volcanic) segment (yellow dot line) encompassing Newfoundland and Europe.

Origin and architecture of the Nova Scotia margin

The Nova Scotia passive margin results from the break up of the Pangean continental block at the end of Triassic time (approximately 225-220 My ago). As mentioned in Beaumont et.al (2011) report of the special project : "*we have only a rudimentary understanding of the way of the final crustal structure, as observed today, is linked to the Triassic-Jurassic lithospheric extension and rifting between Nova Scotia and Morocco. In particular, the form of the syn-rift and early post-rift sedimentary basins can only be determined approximately from either the large-scale crustal structure or interpretation of the ION/GXT NovaSpan seismic reflection images of the deep sedimentary structures.*"

Magma dominated or magma poor margin

Nova Scotia margin is located between a magma dominated (volcanic margin) province of the US margin and the magma poor province (non volcanic margin) of Newfoundland (Figure 1). The southwestern part of the margin (until 62° W) has all the characteristics of magma dominated margin with clear seaward dipping reflectors (SDR) (SMART 3, Figure 3a) meanwhile the northeastern part (between 62°W and 55°W), just South of the Newfoundland-Azores fault zone cannot be characterized by direct seismic reflection imaging (Figure 1).

Forewords : Definition of volcanic margin

A volcanic rifted margin is characterized by a thick wedge of volcanic flows manifested in multichannel seismic reflection data as seaward dipping reflectors (SDRs) and high-velocity (*Vp* > 7.2 km/s) lower crust, seaward of the continental rifted margin (Figure 2). Because the quick generation of voluminous amounts magma requires large and rapid amounts of melting in the mantle, *White* (1989) proposed that an anomalously hot mantle (150-200° above normal) must be present under the rift shortly before continental breakup to enable the formation of volcanic rifted margins. Subsequently it has been proposed that either such temperature anomalies, or mantle plumes by themselves, cause the breakup of continents.

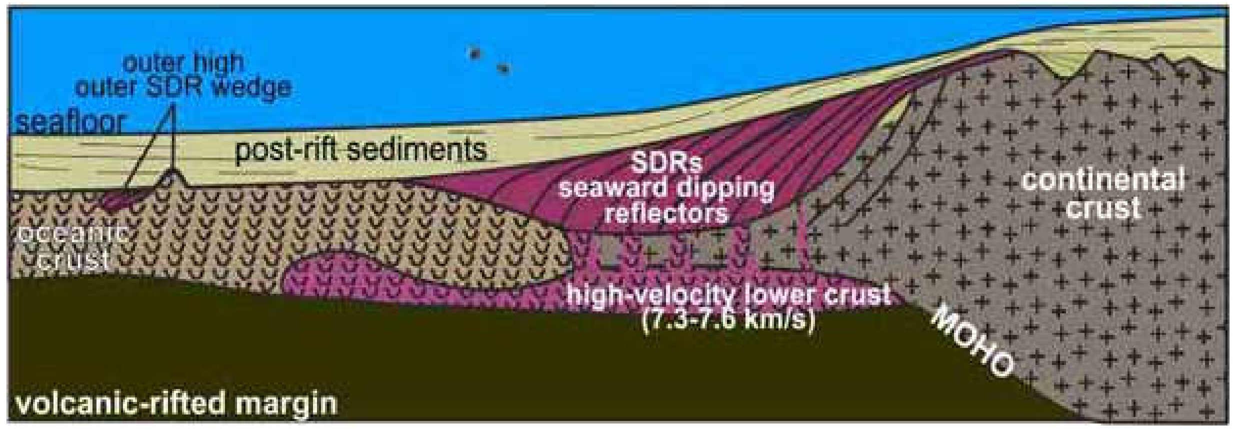


Figure 2: A volcanic margin is characterized by a thick sequence of Seaward Dipping Reflector above a high velocity body localized in the lower crust (from Franke, 2014).

Velocity modeling description

The continental crust is divided in three layers: the upper, middle and lower crust (Figure 3). SMART3 shows a continental crust thinning over 100 km wide zone. The middle crust dips landward and appears to have been removed, perhaps broken, after x = 100 km. In this area, the sediments are directly overlying on the lower crust. A high velocity lower crustal (HVLC) layer with Vp > 7.2 km/s has been identified at x = 120 km, exactly at the interception of the ECMA. This HVLC is interpreted as an underplated intrusive body. This hypothesis is supported by Seaward Dipping Reflectors sequence observed on the seismic reflection line (Figure 3b).

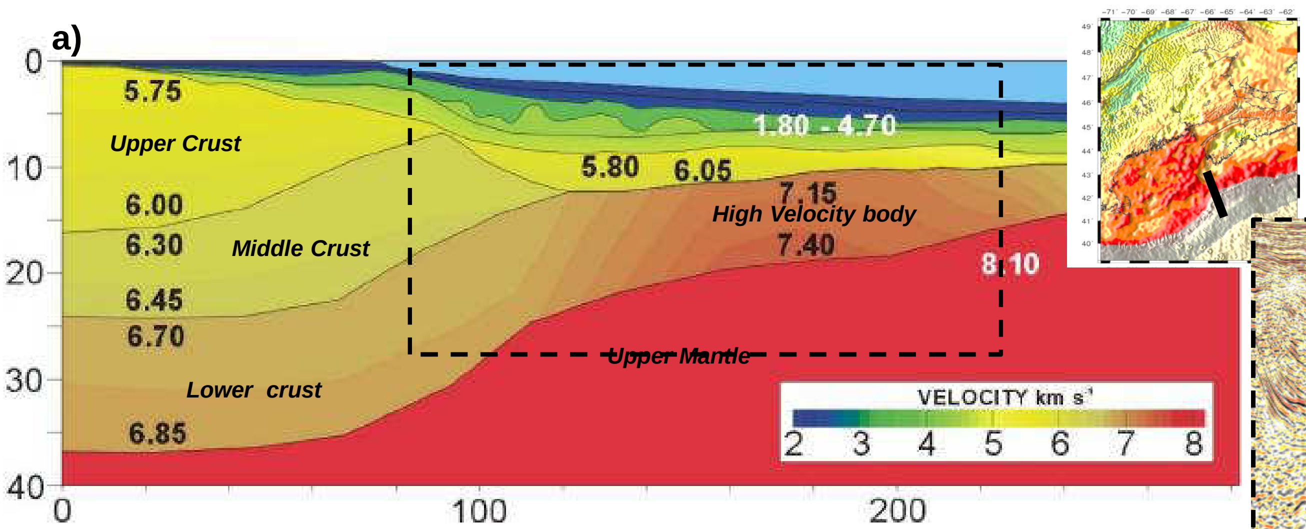
Interpretation

The comparison of various crustal transects from the US east coast and SMART3 illustrates that the character of SMART3 is consistent with the magma-rich U.S. margins to the south. These transects are similar in terms of the total width of stretched continental crust, thickness of oceanic crust, the presence of an interpreted magmatic underplate, and seaward dipping reflectors.

This magma-rich part of the margin therefore has the following set of characteristics:

1. Narrow region (100km wide) continental crust thinning
2. Thick magmatic underplate separating thinned continental and oceanic crust;
3. Seaward dipping reflectors (SDR's) above the seaward end of the high velocity body (Figure 3b);
4. Normally-thick oceanic crust;
5. Thin sedimentary basin;
6. Wedge of low velocity material above underplated region.

Based on these characteristics, the southwest Nova Scotia margin can be interpreted as the northern extension of the magma-rich margin domain that characterizes the US East Coast.



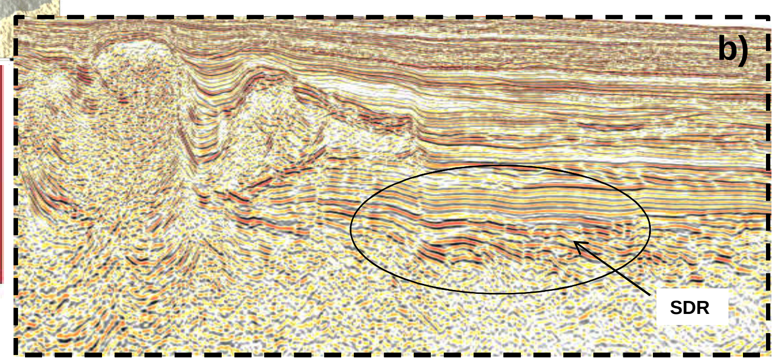


Figure 3: a) P-wave velocity model of the magma-rich or volcanic margin of the SW Nova Scotia.
b) Seaward Dipping Reflectors observed above the High velocity body on the seismic line.

What could be the impact on the petroleum system?

The deep rifting processes and the deep architecture of the margin have a direct impact on thermal regime and subsidence history that control deposition and maturation of source rocks and reservoir. In particular the radiogenic heat flow of the continental crust which contribute to the maturation of the source rocks meanwhile serpentinized mantle and oceanic crust have no primary influence on the thermal regime. The Continent Ocean Transition or Boundary (COT or COB) zone, as well as the thinning factor of the continental crust are important parameters of the basin modelling.

If the rift followed an essentially volcanic process it would imply uplift and sub-aerial extrusive deposits characterized by seaward dipping reflectors (SDR), which would in turn imply a much longer period of shallow restricted marine environment during the late phase of the rift to early postrift stages. During this relative uplift phase one could expect deposition of evaporite, carbonate and shallow marine source rocks. Such a source bed system of Early Jurassic age could then be argued to be present along the whole margin and be of a high richness because of the restricted marine environment of deposition.

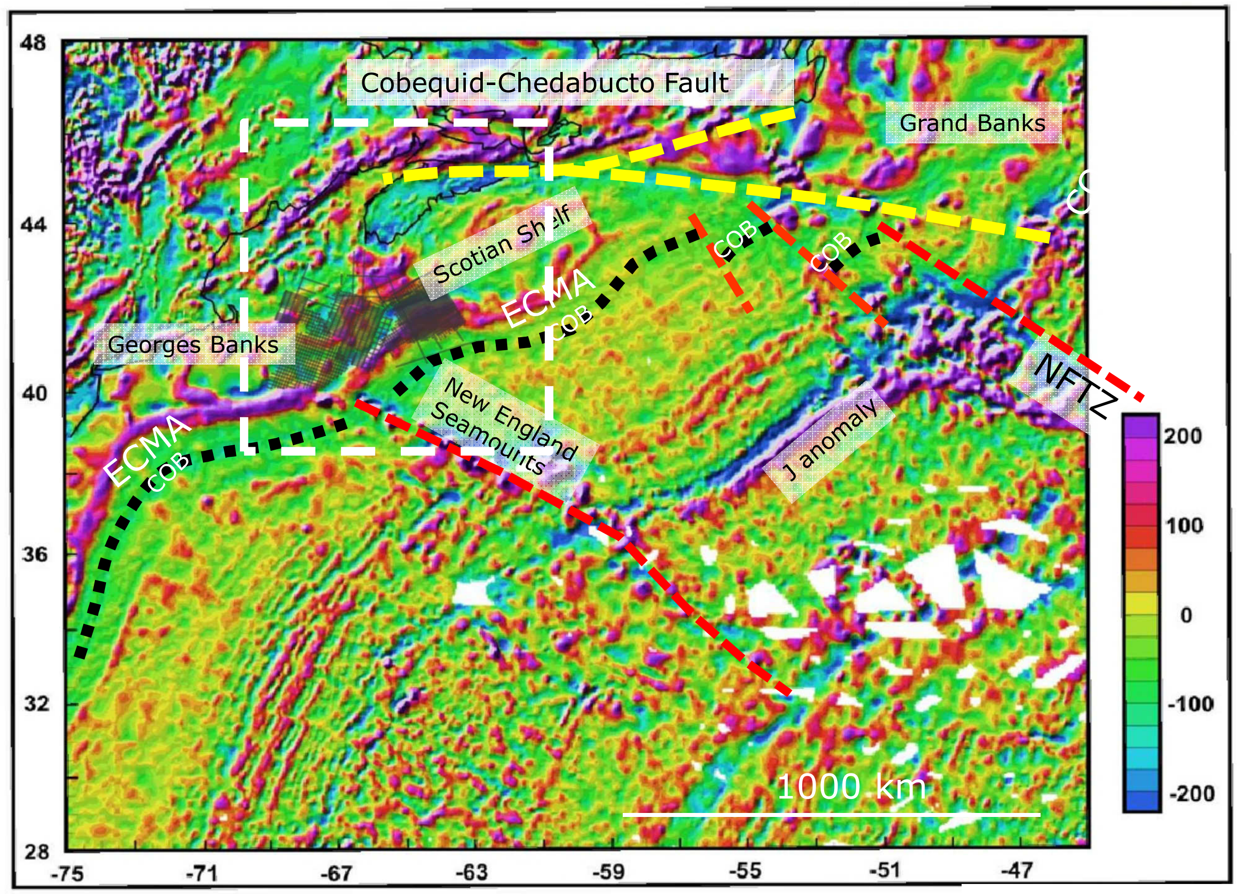


Figure 4 : Magnetic anomaly map (Dehler, 2010) and main tectonic features. The oceanic domain is characterized by typical succession of normal and reverse linear magnetic anomalies. Georges banks and Scotian Shelf are separated form the oceanic domain by the strong positive regional anomaly of the East Coast Magnetic Anomaly (ECMA). Continent Ocean Boundary (COB) is deduced from previous PFA studies (Sibuet, 2011; Labails, 2010)

From potential data (gravimetric + magnetic anomaly maps) several major tectonic elements of the Nova Scotia margin – Georges Banks area can be traced (Figure 4):

1) The East Coast Magnetic Anomaly and the Continent Ocean Boundary (COB). This latter major limit is clear and easy to define in the Georges Bank and Scotian shelf area (Figures 4 & 6). It is more difficult to define in the Laurentian sub-basin where the ECMA and COB signals become poor and along the Grand Banks where ECMA no more exists.

2) The Newfoundland Transform Zone (NFTZ) is one of the most prominent fault system. It constitutes the main escarpment of the South Bank High and form a sharp limit just north of the J ridge and Newfoundland ridge anomaly. Its trace along the South Bank High is less well expressed on potential data and was constrained by seismic data.

3) The Cobequid-Chedabucto fault clearly imaged by gravimetric and magnetic data. Its trace is clear offshore and onshore, where it constitutes a major fault separating the Middle Paleozoic Terranes of the Meguma block from the Upper Paleozoic (mainly Carboniferous) units. To the East of the Nova Scotia, the main fault seems to split in various splay faults but does not seem to be connected directly to the Newfoundland Transform Zone (NFTZ).

4) The Appalachian front, mainly shown by the contrast between (Figure 6)
a) gravimetric “lows” of the Appalachian foreland corresponding to the Carboniferous flexural basin
b) gravimetric “highs” of the deformed belt.

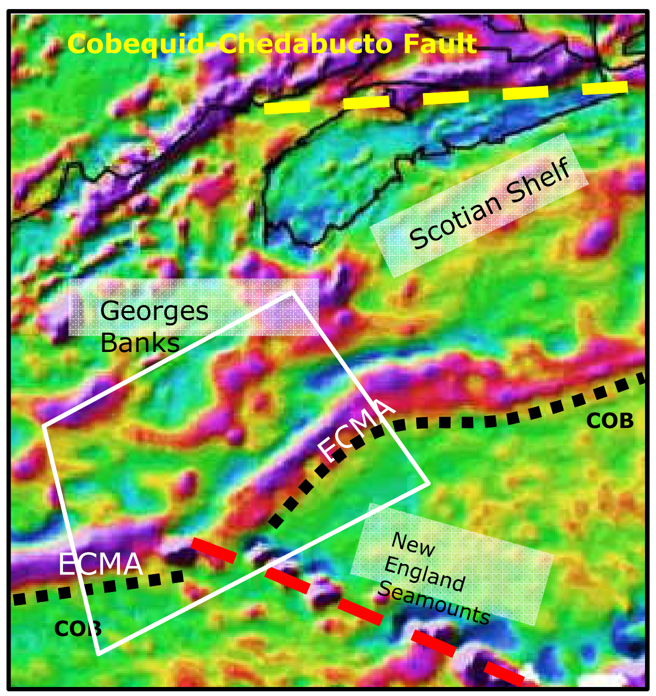


Figure 5 : Enlargement of the magnetic anomaly map from Dehler, 2010. Study area is shown by the white polygon.

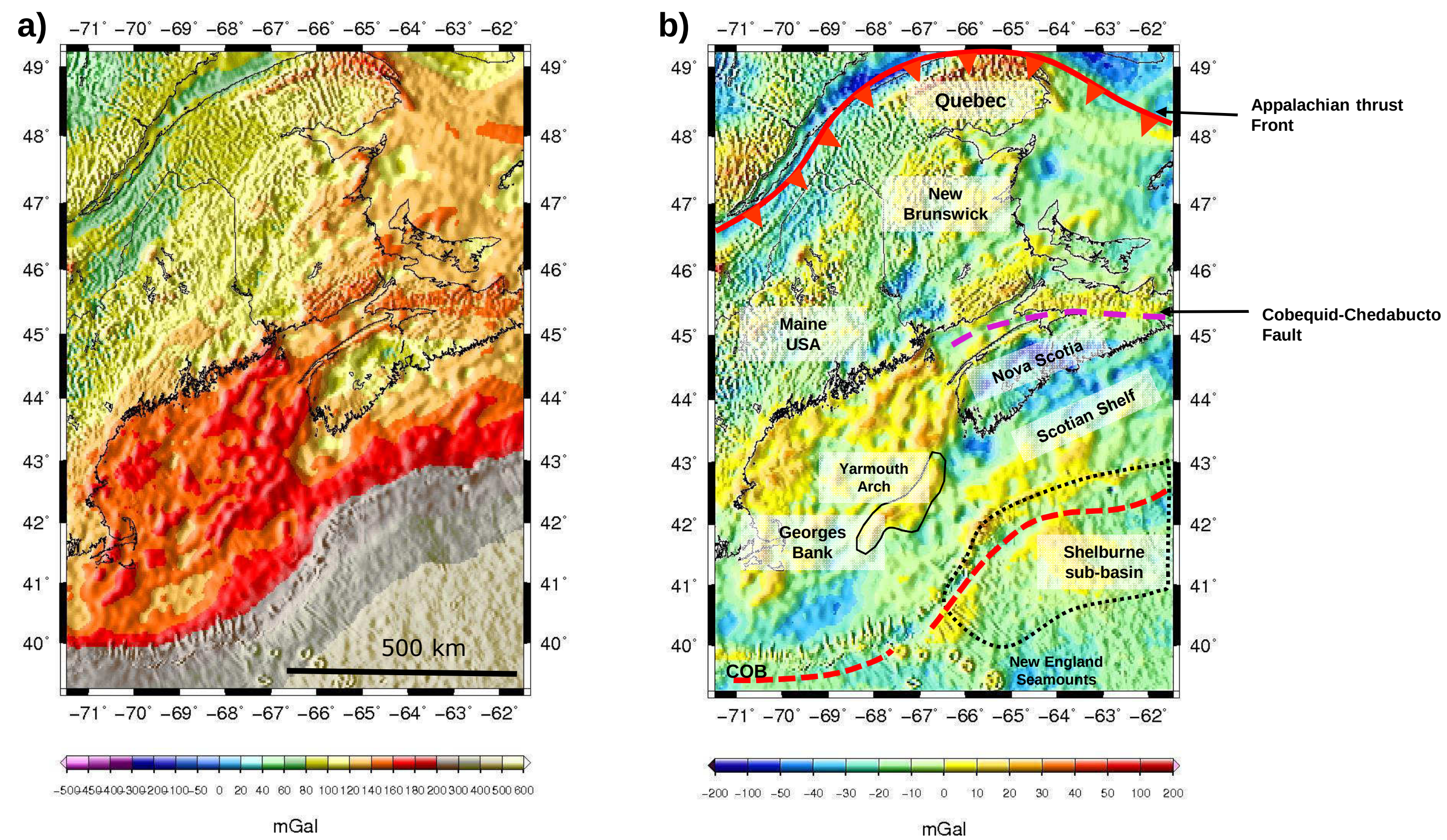


Figure 6 : Bouguer Gravimetric anomaly map (a) and Isostatic gravity anomaly map (From BGI) and main tectonic features (b). Mesozoic sedimentary basins of the Georges Bank (West Georges Bank Basin) and of the Shelburnesub-basin are clearly imaged by positive values of the Isostatic gravity anomaly. The Appalachian thrust front is also shown by the Isostatic Gravity anomaly. Other tectonic features such as main faults and Continent Ocean Boundary (COB) are mainly deduced from the magnetic anomaly map.

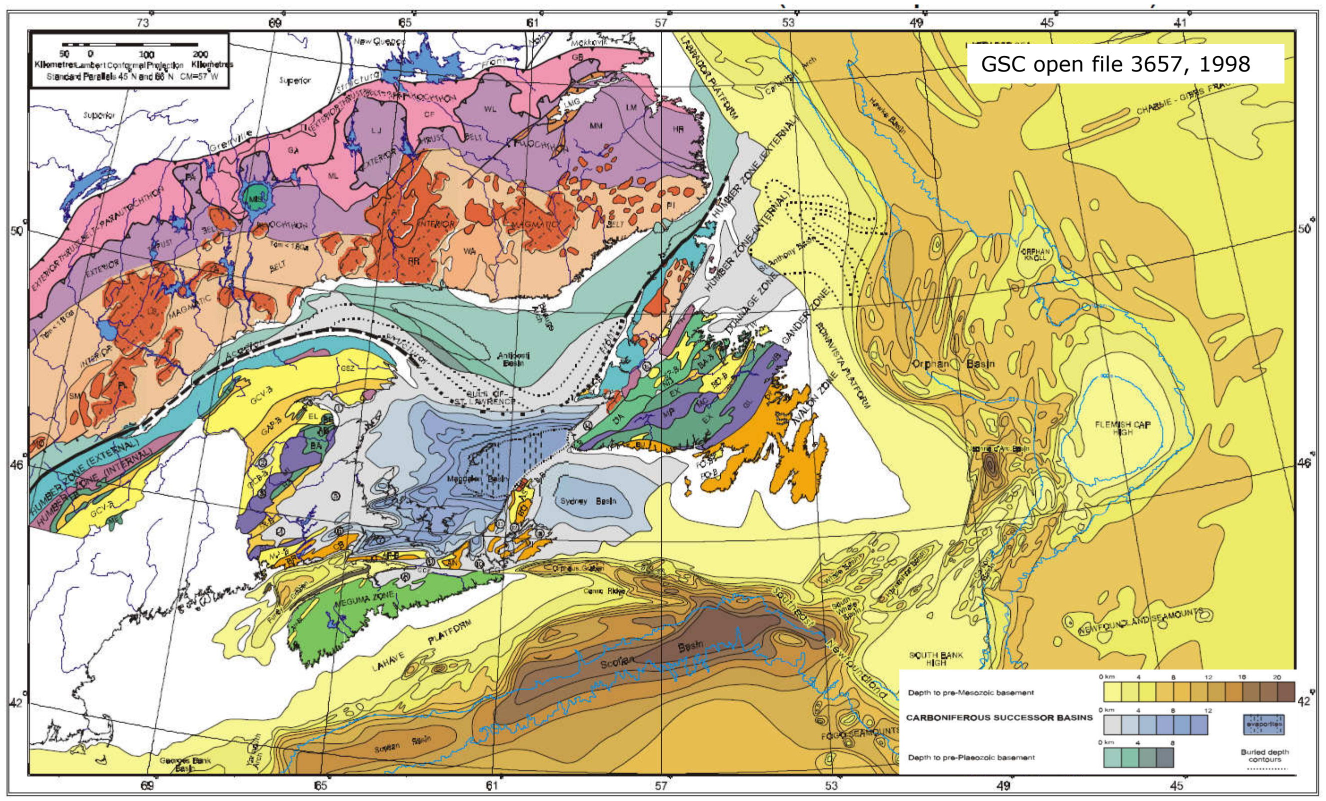


Figure 7 : Geological map of Proterozoic and Paleozoic basement. Contours indicate:
1) Depth to pre-Mesozoic basement (brown and yellow colors)
2) Depth to pre-Carboniferous basement (grey-blue colors)
3) Depth to pre-Paleozoic basement (grey-green colors)

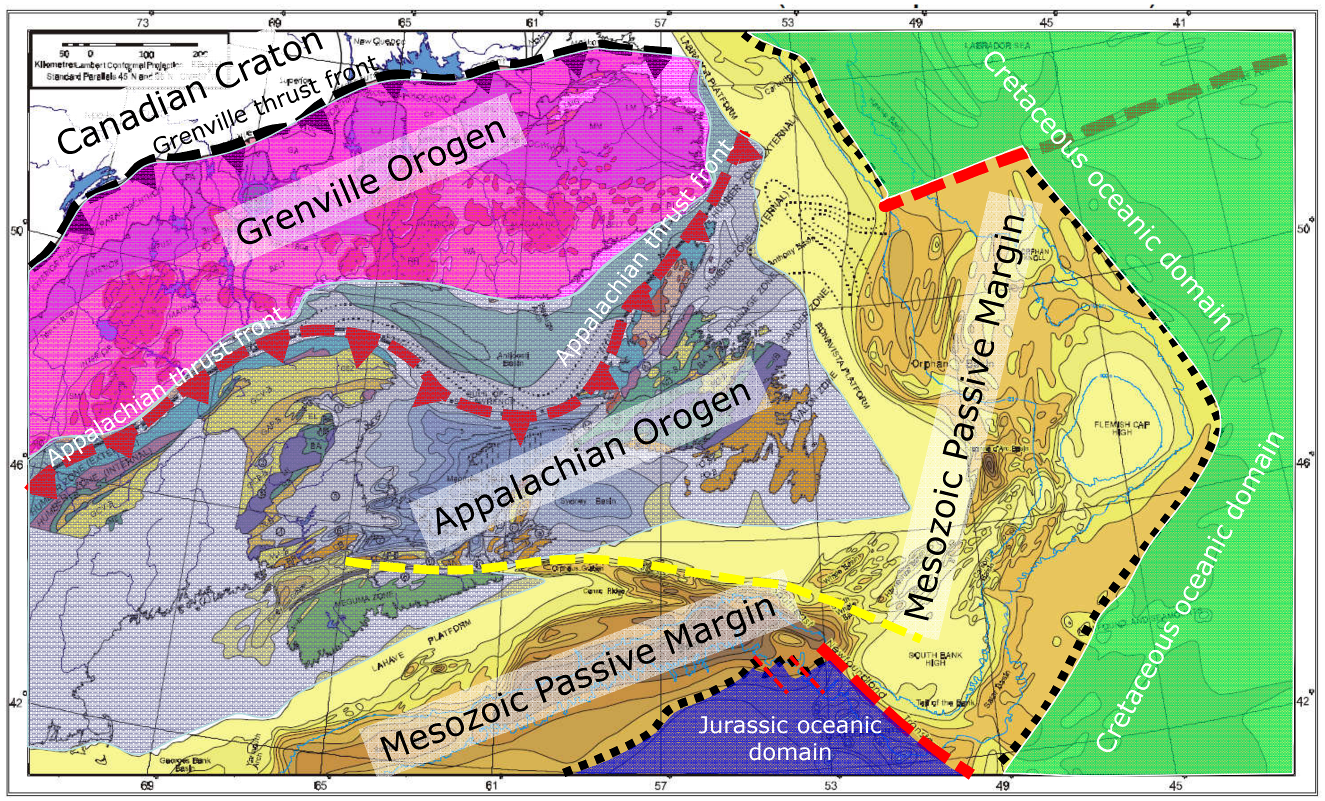
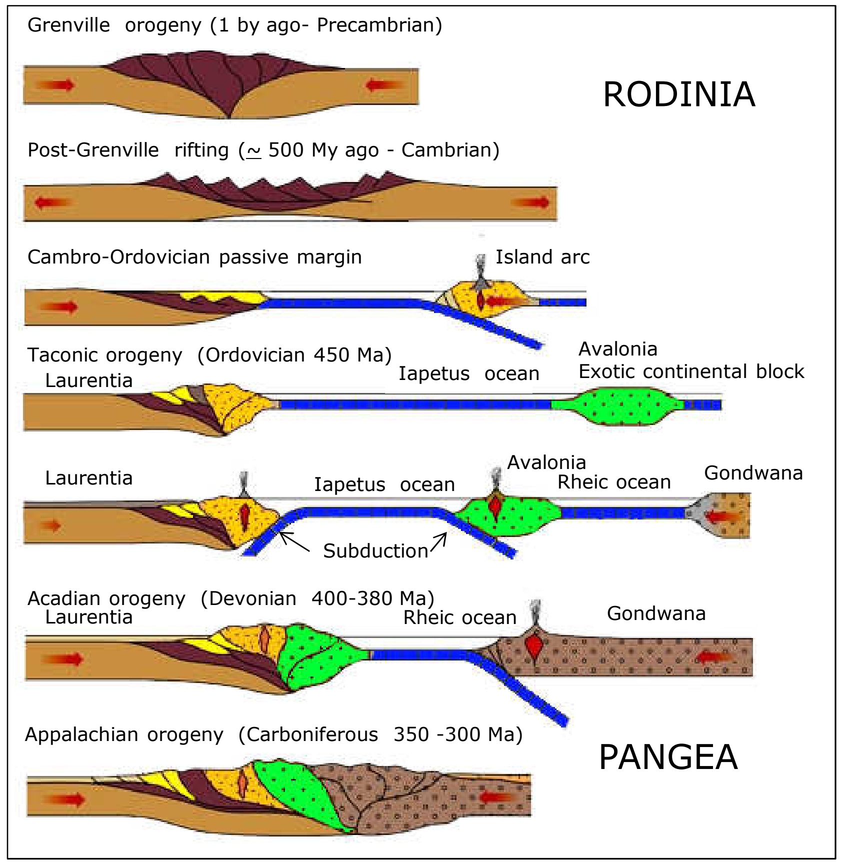


Figure 8 : Nova Scotia Newfoundland island main tectonic units. 1) Canadian Archean and Proterozoic Craton (white) 2) Proterozoic Grenville Orogeny (Pinkish) 3) Paleozoic units including Appalachian foreland and Appalachian orogeny (Greyish) 4) Mesozoic passive margin (yellow and brown contour map) 5) Jurassic oceanic domain (Purple) 6) Cretaceous oceanic domain (Green)



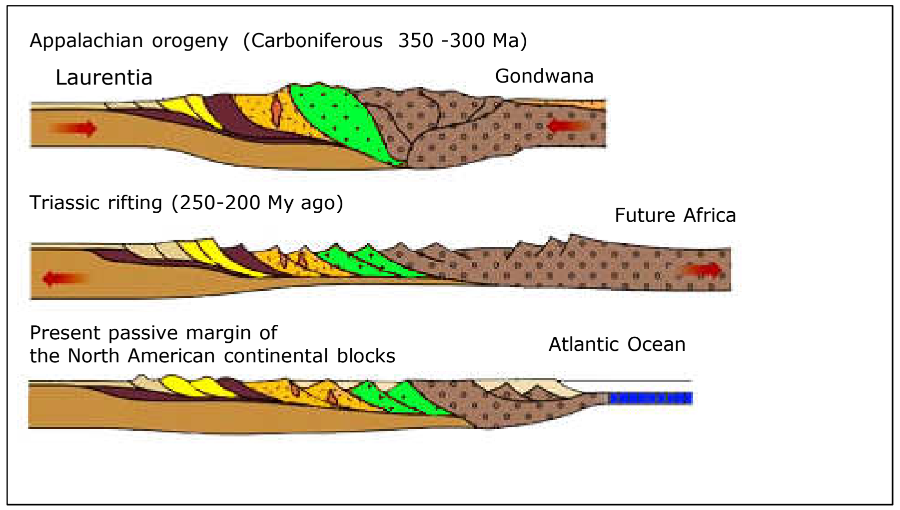


Figure 9 : Schematic cross-section showing the pre-Mesozoic evolution of Nova Scotia margin.
Modified from https://mountainbeltway.wordpress.com/category/west-virginia

The Nova Scotia margin results of a complex evolution since Proterozoic times (Figures 7 & 8). The present day passive margin stage appeared after a first complete Wilson cycle with the breakup of the Rodinia super continent, the formation of the Pangea supercontinent and the breakup of the Pangea. Breakup of Rodinia and formation of Pangea result of the following events (Figure 9).

- **Grenville Orogeny** (1 000 Ma)

Grenvillian rocks are subdivided into a set of allochtonous terranes arranged in the form of a south-easterly dipping thrust stack emplaced over a continental margin of Archean age and intruded by numerous post orogenic plutons.

- **Post-Grenville rifting:** Iapetus Ocean (~ 500 My ago - Cambrian)

After the Grenville orogeny, resulting of two continental blocks collision, the newly formed Rodinia continent is broken during a rifting event in Cambrian times. This break-up leads to the formation of a new ocean (the Iapetus Ocean) separating two large continental blocks (Laurentia and Gondwana)

- **Taconic orogeny** (Ordovician 450 Ma)

During Ordovician times Island arc material is accreted to the Cambro-Ordovician passive margin inducing a first major orogeny.

- **Acadian orogeny** (Devonian 400-380 Ma)

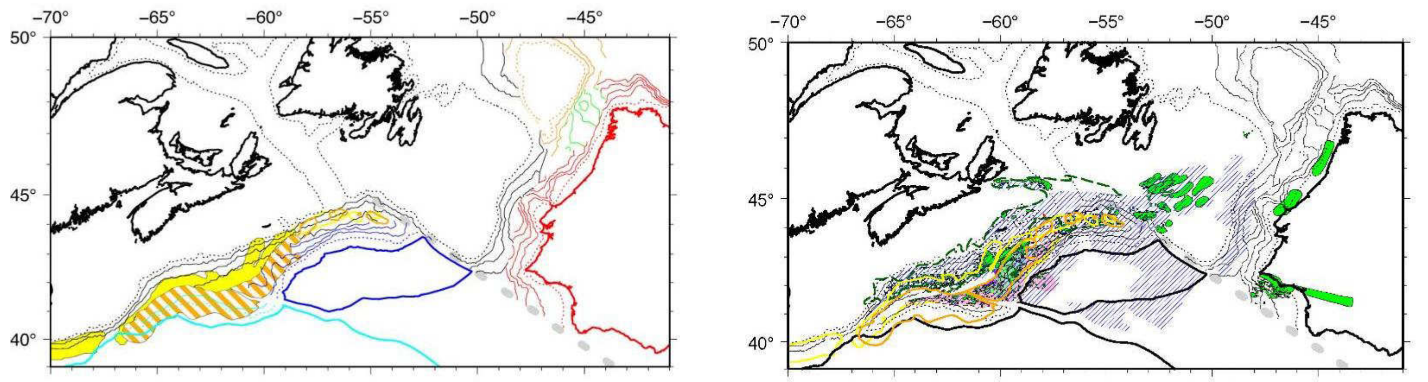
During Ordovician times, the collision of an isolated continental block (Avalonia block) induced the closure of the Iapetus ocean and the second major orogeny.

- **Appalachian orogeny** (Carboniferous 350 -300 Ma)

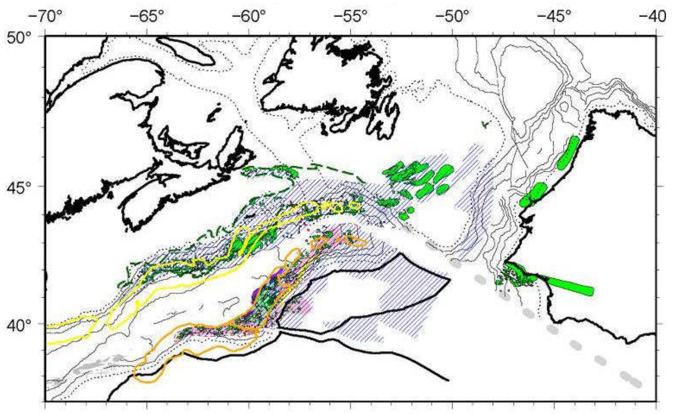
During Carboniferous times the collision of the future African continental block (Gondwana) with the north America continental plate (Laurentia) caused the closure of the Rheic ocean, the formation of the Appalachian orogen and the Pangea supercontinent.

- **Triassic rifting**: Atlantic Ocean (250-200 My ago)➔ Passive margin history

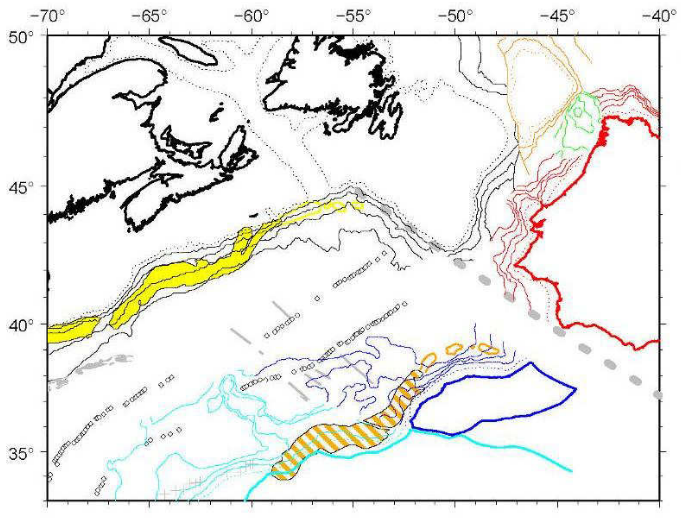
The next step of this evolution is the Triassic rifting, initiating a new Wilson Cycle (Figure 9).



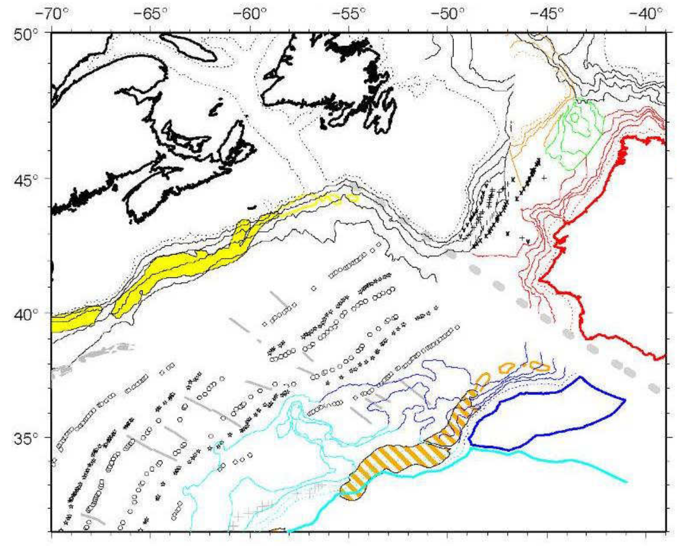
Kinematic reconctruction at the Chron ECMA (Sinemurian/Pliensbachian limit, 190 Ma).



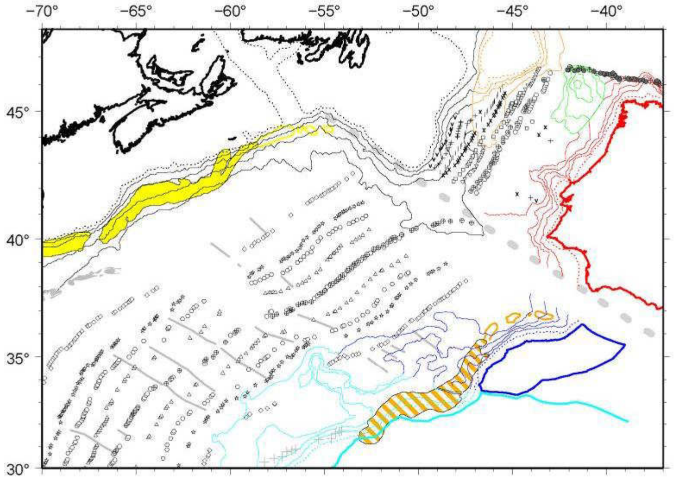
Kinematic reconstruction at chron BSMA (Middle Bajocian, 170 Ma).



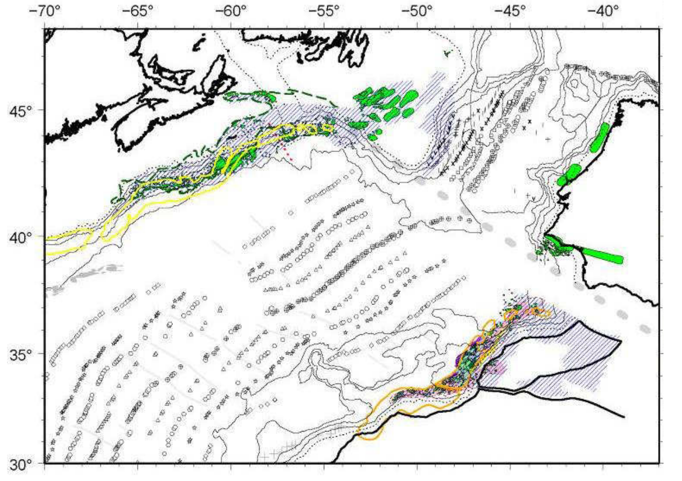
Kinematic reconstruction at chron M22(Middle Tithonian, 150 Ma).



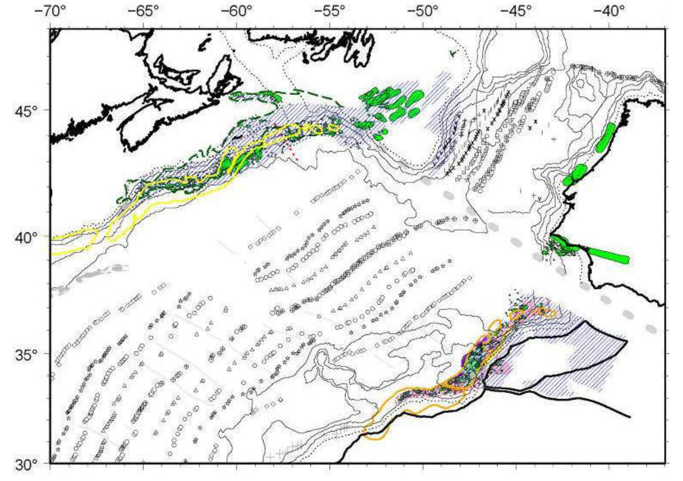
Kinematic reconstruction at chron M11(Middle Valanginian, 136 Ma).



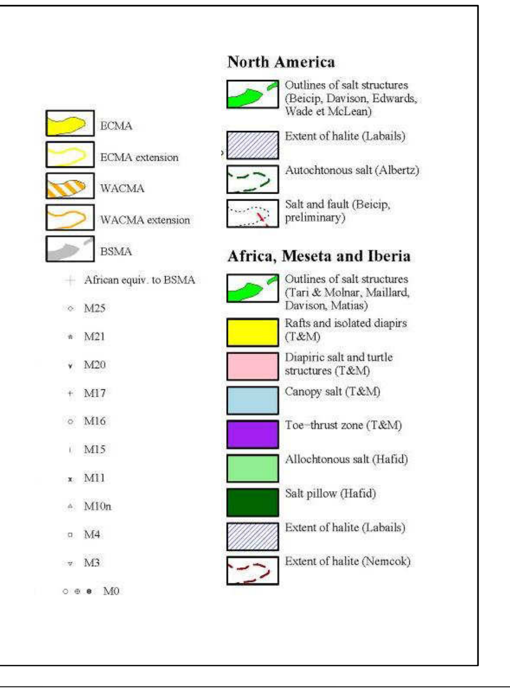
Kinematic reconstruction at chron M0(late Barremian/Early Aptian, 125 Ma



Kinematic reconstruction at chron M0(late Barremian/Early Aptian, 125 Ma



Kinematic reconstruction at chron C34(Santonian, 83.5 Ma).



Early Cretaceous volcanism is widespread in the Scotian Basin. The volcanic rocks within wells, along the Scotian margins have been correlated to basalts flows outcrops (e.g. Scatarie Ridge) and dated from Hauterivian to Albian (Figure 11). These widespread volcanic activity indicates a regional and long-lived magma source, which implies a high regional heat flow. Thus the different seamounts observable on the oceanic crust result from this volcanic activity (e.g. Fogo Seamount, New England Seamount). Sleep (1990), Bowman et al. (2012) and Pe-Piper (2015) correlate them to a long-lived mantle plume system.
In the Georges Banks area, Sleep (1990) correlate the New England Seamount with the Withe Mountains range (igneous province). Thus, the hotspot seems to be active from the Jurassic (150Ma) with the White Mountains range to the late Early Cretaceous with the New England Seamounts (Figures 10 & 11).
This hotspot coincide with the Avalon Uplift (rifting of North Atlantic) and with the Volcanic center of the Scatarie Ridge. Thus, this widespread volcanic activity indicate a regional magmatic activity wich result in an elevation of the regional heat flow (Figure 12). Moreover a regional Uplift is also recorded which could be estimated from 500m to 1300m over 600km in the Georges Banks area and seems to be a main local sedimentary input (Figure 11).

Moreover the high value of the hit flow could have an impact on the vitrinite reflectance and hence on the hydrocarbon maturation (E.G. sedimentary rocks of the Sable sub-basin, Bowman et al., 2012).

From Campbell (2005) it's possible to define a maximum plume diameter around 2000km with an extension of maximum heat flow between 500 to 700km which cover all the study area (Figure 11).

From Sleep (1990), this hotspot could be comparable to La Reunion hotspot and 20-30% of current Hawaï hotspot.

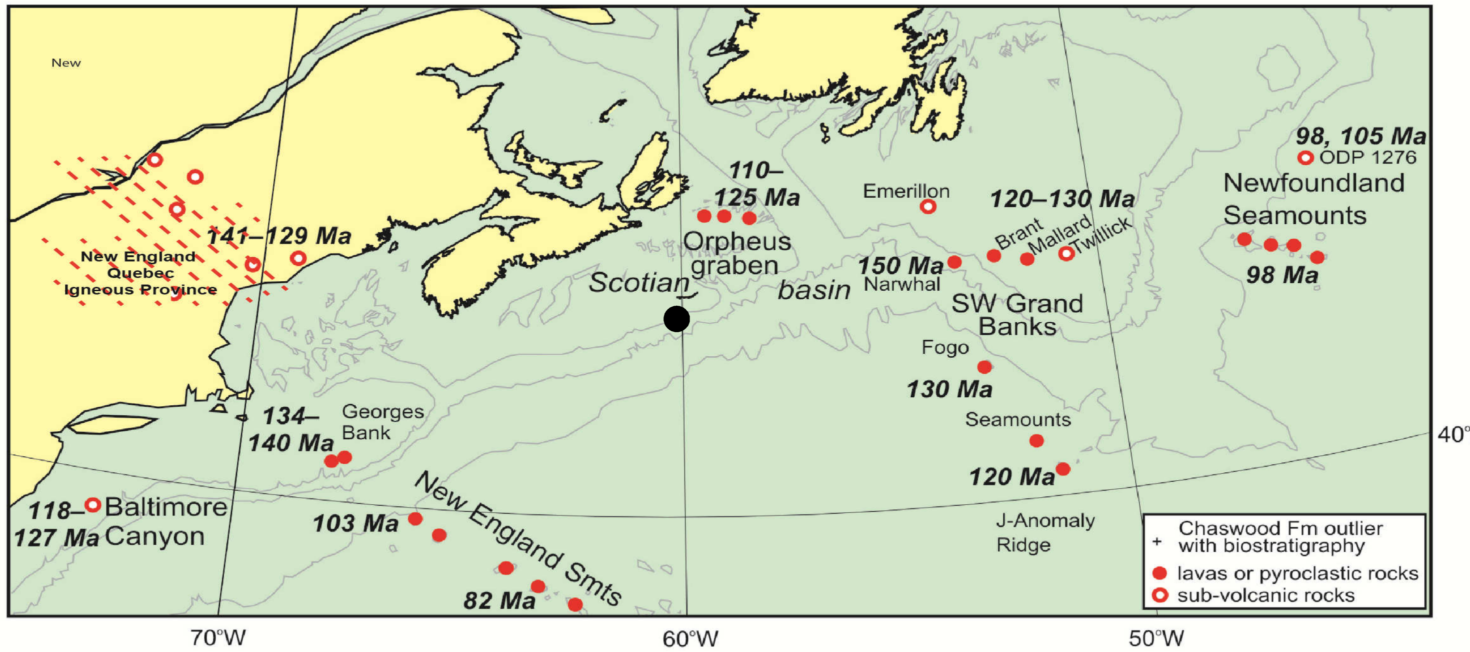


Figure 10: Regional extent of Early Cretaceous volcanism, showing wells penetrating volcanic rocks and the positions of the seamounts and flows at seabed (from Bowman et al., 2012).

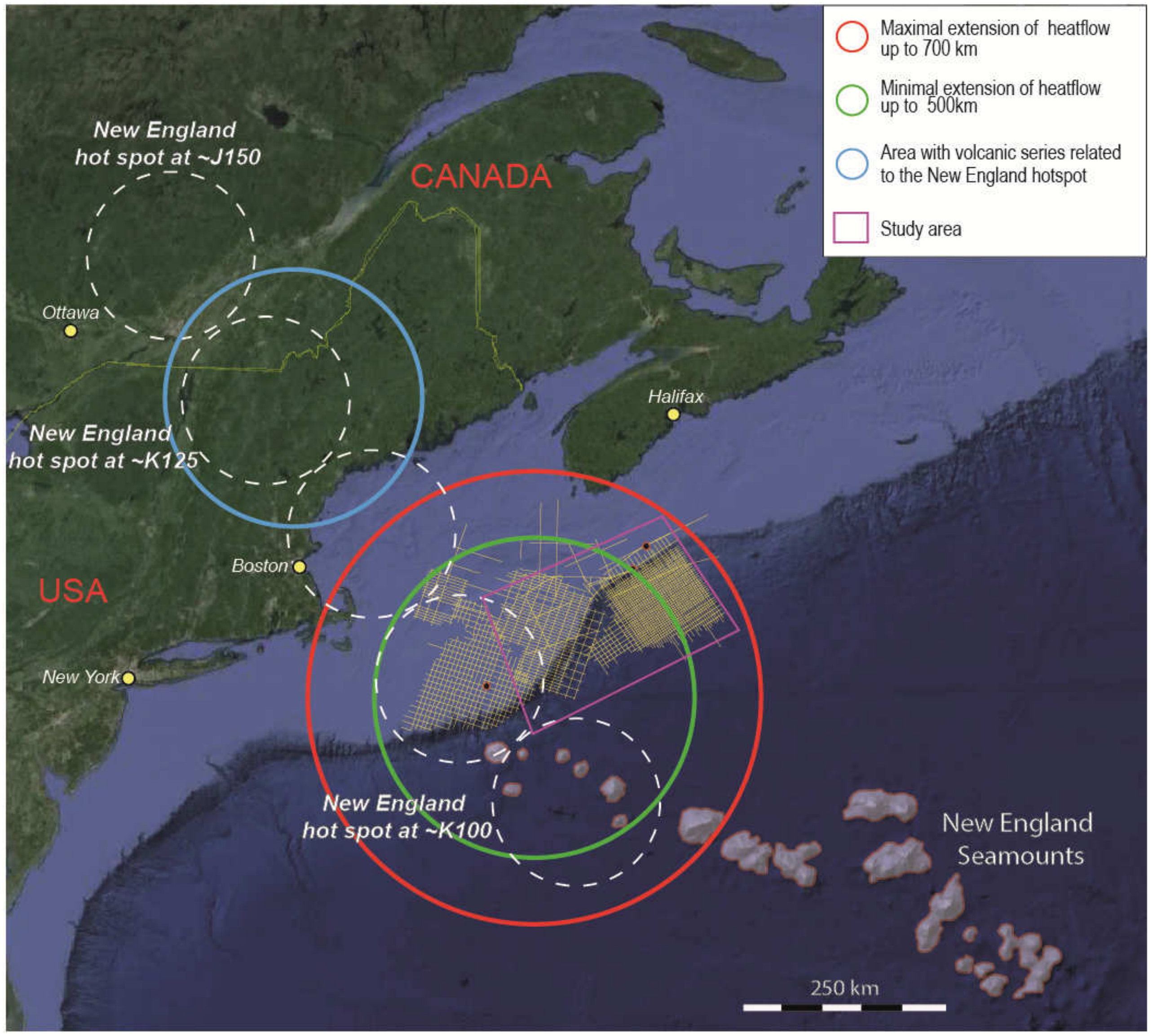


Figure 11: Map of the New England hotspot position throw the time and the maximum diameter and heat flow extension. This summary map was made based on published work from (Duncan, 1984; Sleep, 1990; Campbell, 2005; Harris and McNutt, 2007; Bowman et al., 2012).

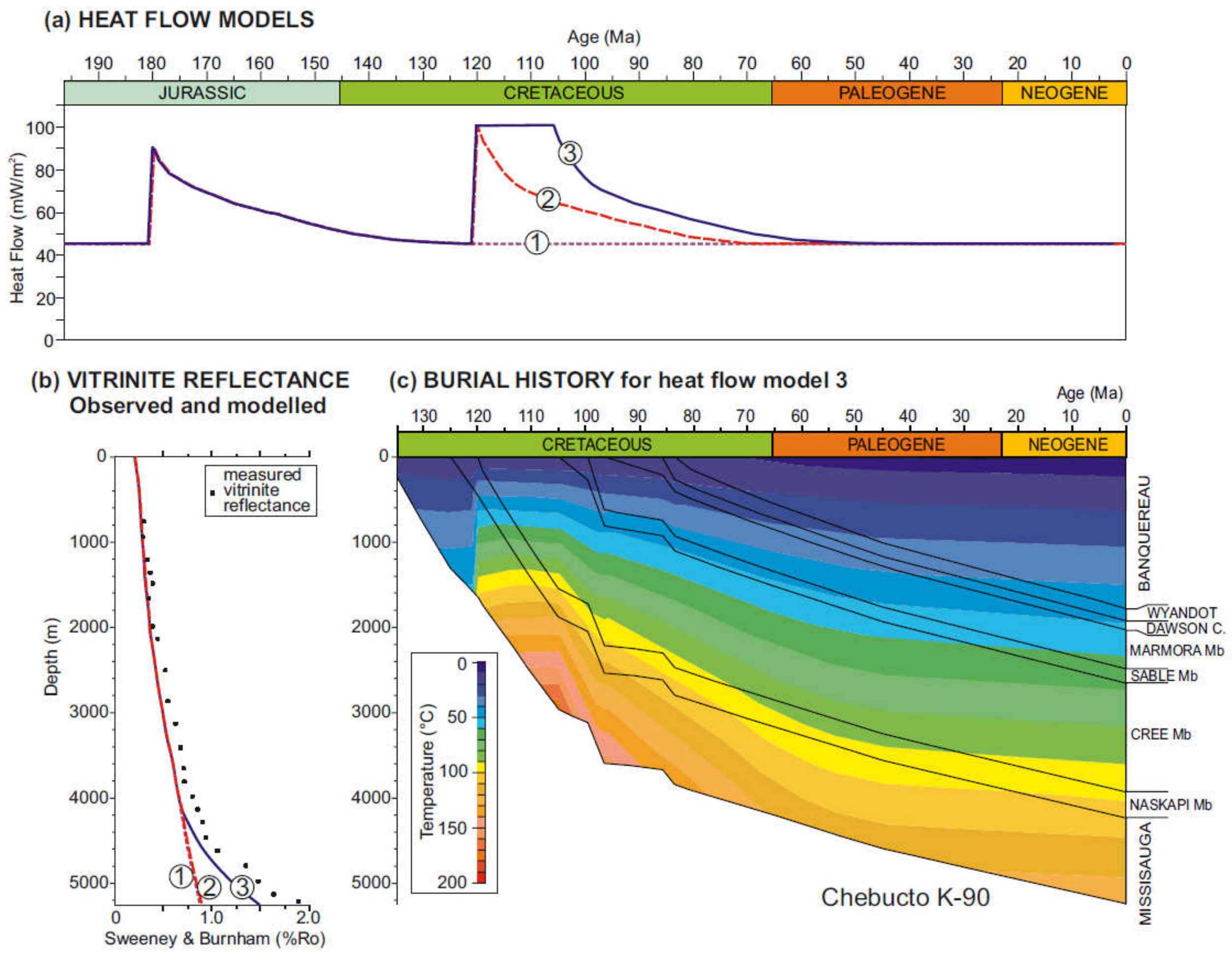


Figure 12: Summery of resultts of thermal modelling of the Chebucto K-90 well (see black dot on Figure 10): (a) Heat flow models ; (b) comparison of vitrinite reflectance observed with modelled; © burial history and predicted temperature for heat flow model 3. (From Bowman et al., 2012).

Georges Bank is the most southwesterly bank on the Canadian Atlantic continental margin. It lies 125km offshore in water depths ranging from 60 meters to >800 meters over the Shelburne basin/East Georges Bank basin. The West Georges Bank and Shelburne basin are separated by a physiographic high, the Yarmouth Arch Figure 13).
The bank has an oval shape and is bounded to the northeast by the Northeast Channel, to the southeast by the continental slope, to the southwest by the Great South Channel and to the northwest by the Franklin and West Georges Bank basins. The entire Georges Bank, including the U.S.A. portion, covers about 40,000km2.

Georges Banks area was initially a part of a broad lowland within the supercontinent Pangaea (Wade & MacLean, 1990). This area could be divided in three main elements which are the West Georges Banks Basin, The Yarmouth Arch and the Yarmouth Sub Platform (Figure 13). The Yarmouth Arch and the Yarmouth sub-platform are the eastern limit of the area (Figure 14).

The West Georges Bank Basin is a block-faulted basin developed during the Trias due to the Central Atlantic rifting stage. The axis of the basin strikes N30° (main fault trend) and plunges to the Southwest. This basin is still an important depocenter during the Early to Mid-Jurassic with more than 4km of siliciclastic and carbonate deposits which are deformed by a thick layer of rifting salt (Wade & MacLean, 1990; Figure 15).

The Yarmouth Arch which is the structural high of the Georges Banks area, is a buried complex of approximately N-NE trending basement element with metamorphic and plutonic rocks from the Precambrian to the Paleozoic (Wade & MacLean, 1990). This Arch is also oriented N30° but it is bounded by "zig-zag" faults pattern with two directions : North-South and NE-SW (Figure 14).
Moreover the Arch is oblique to the main extensional direction suggest inga possible right lateral transtensional structure along the East side.
This Arch is well expressed on the magnetic anomaly map, due to a layer of Early Jurassic volcanic deposits above the basement (Figure 13).

The Yarmouth SubPlatform is bounded by the Yarmouth Arch to the West and the Shelburne Basin to the East (Figure 15). These sub-platform plunges to the North and is bounded by a NW-SE fault. The basement is overlied by a layer of salt to the North which completely disappear to the South.

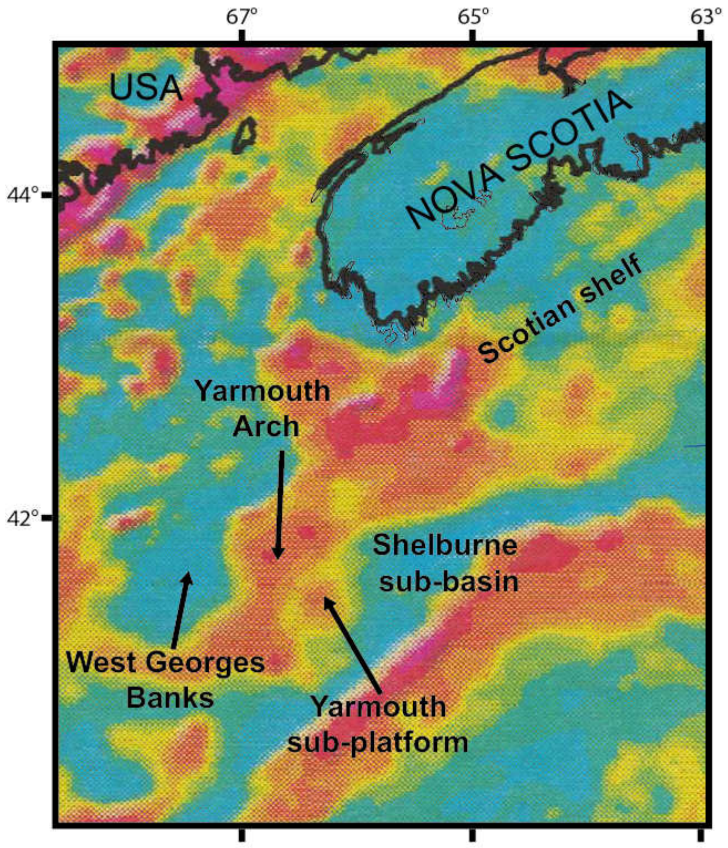


Figure 13: Magnetic Anomaly map of the Georges Banks Area showing the different tectonics features :
- *Yarmouth Arch*
- *Yarmouth sub-platform*
- *West Georges Banks basin.*

(GSC magnetic map, 1998).

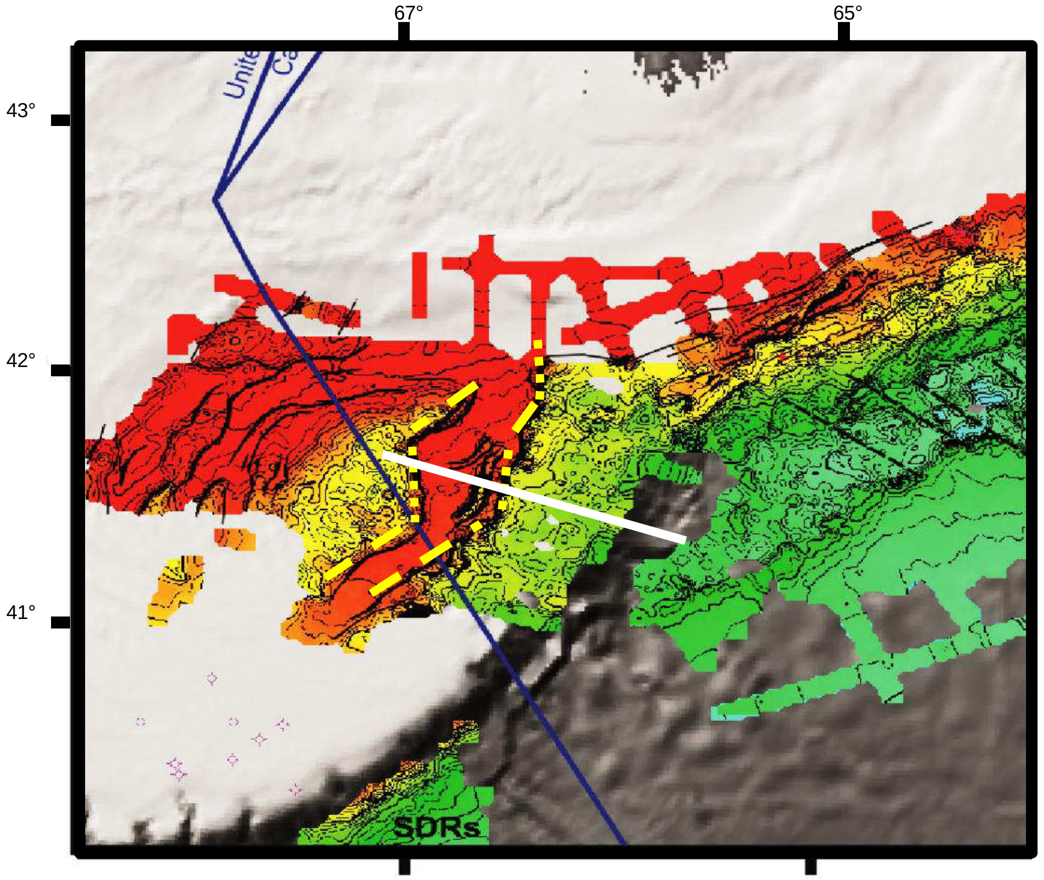


Figure 14: Basement map from Deptuck & Kendell on the Nova Scotian margin and the Georges Banks area. This map highlight the zig-zag pattern of the Yarmouth Arch wich is due to pre-existing faults (N-S trend) and the new formed faults (NE-SW trend). On the East side we can also observed NW_SE faults which are interpreted as dextral strike-slip faults due to the accommodation of the oceanic crust spreading. In white, the location of the Figure 15.

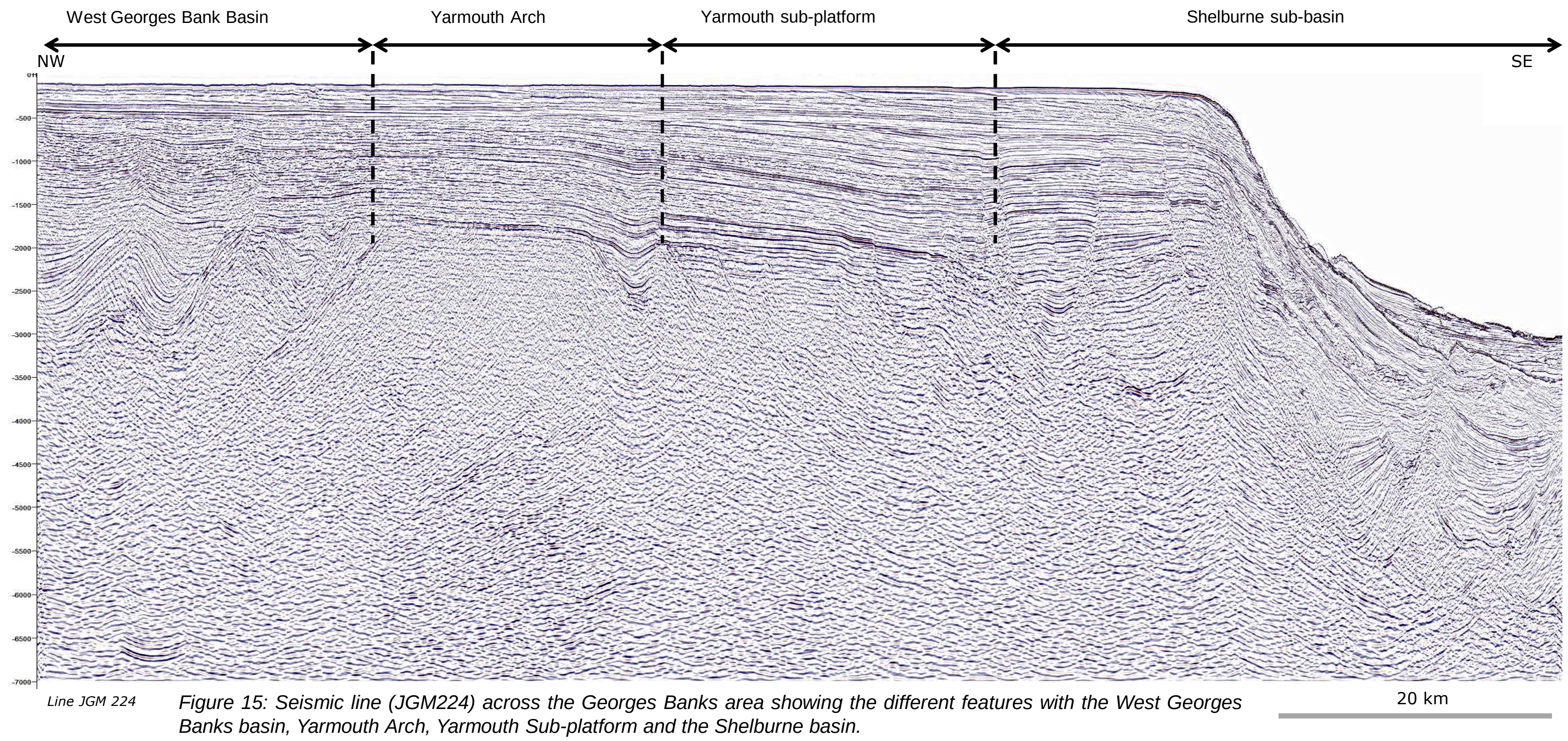


Figure 15: Seismic line (JGM224) across the Georges Banks area showing the different features with the West Georges Banks basin, Yarmouth Arch, Yarmouth Sub-platform and the Shelburne basin.

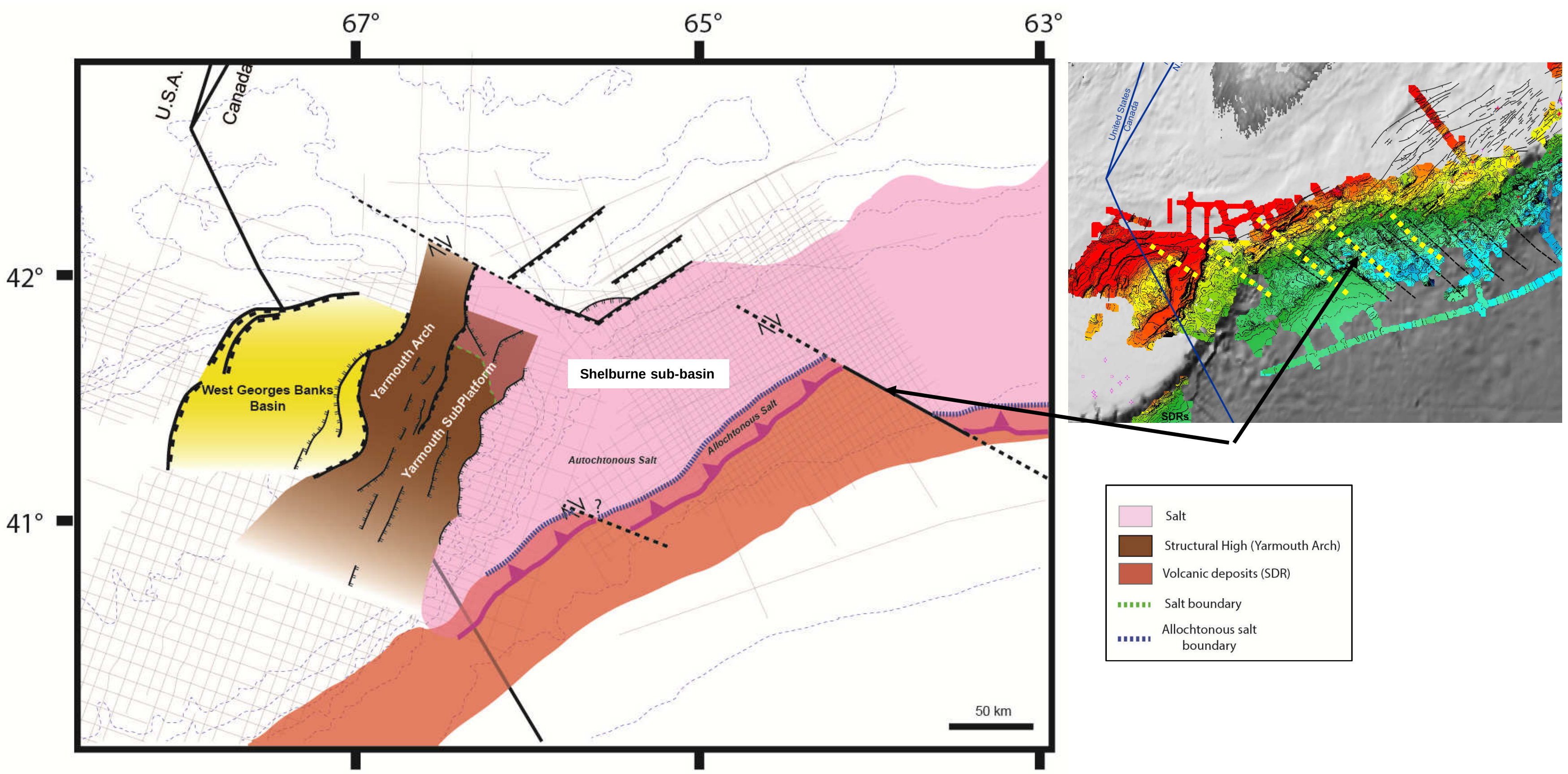


Figure 16: Structural map of the Georges Banks and the Shelburne basin. The Georges Banks is highlight by a structural high individualized during the rifting of the Central Atlantic (Triassic horst): the Yarmouth Arch which play the role of a locked zone. The rifting propagate from the West to the East over the arch. The salt layer allow to highlight a NW-SE fault trend.

The Georges Banks area is an important feature which play a major role during the Central Atlantic opening and the Nova Scotian margin rifting and in particularly on the Shelburne basin.

The structural study shoes that the **West Georges Banks basin** is an half-graben basin bounded to the East by basement faults which have been initiated in part by the rifting of the Atlantic (NE-SW) and the others by reactivation of inherited structure (Precambrian to Paleozoic). These both directions are observed on each side of the Yarmouth Arch (Figure 16).

The **Yarmouth Arch** seems to be a strong feature (few rifting faults affect it) which has been individualized during the Atlantic rifting. On the seismic line the Arch is mainly composed of inherited structure from the Paleozoic or older (thrust or folds, Figure 17) and is affected by few rifting faults (only seen on the central part). As it is affected by few faults we can consider that the Yarmouth Arch is a locked zone as described by Courtillot in 1982. That mean that the rifting don't manage to progress throw the arch and need to jump from the West side to the East side (Figure 16 & 18).

The **Yarmouth Subplaform** is bounded by basement faults to the Yarmouth Arch and is affected by rifting faults with a NE-SW trend (Figure 16). This SubPlatform plunges to the north and is partially cover by a salt layer which disappears to the South. In the north corner, the salt layer is bounded by a NW-SE fault which is interpreted as a dextral strike-slip fault by Deptuck and Kendell (in prep). Theses faults allow to accomodate the drifting stage. The eastern boundary (with the Shelburne basin) is defined by a major listric fault rooted on the salt layer (Figure 18).

The **Shelburne sub-basin** is made of two major tectono-sequences: a rift sequence with (NE-SW fault trend) followed by a passive margin sequence highlighted by a thick layer of salt at the bottom. Thus two tectonic regimes are observed:

- a thick-skinned deformation with the stretching of the crust during the rifting stage (Triassic to Early Jurassic).
- a thin-skinned deformation with the salt creeping during the passive margin stage (Early Jurassic to Present day) (Figure 18).

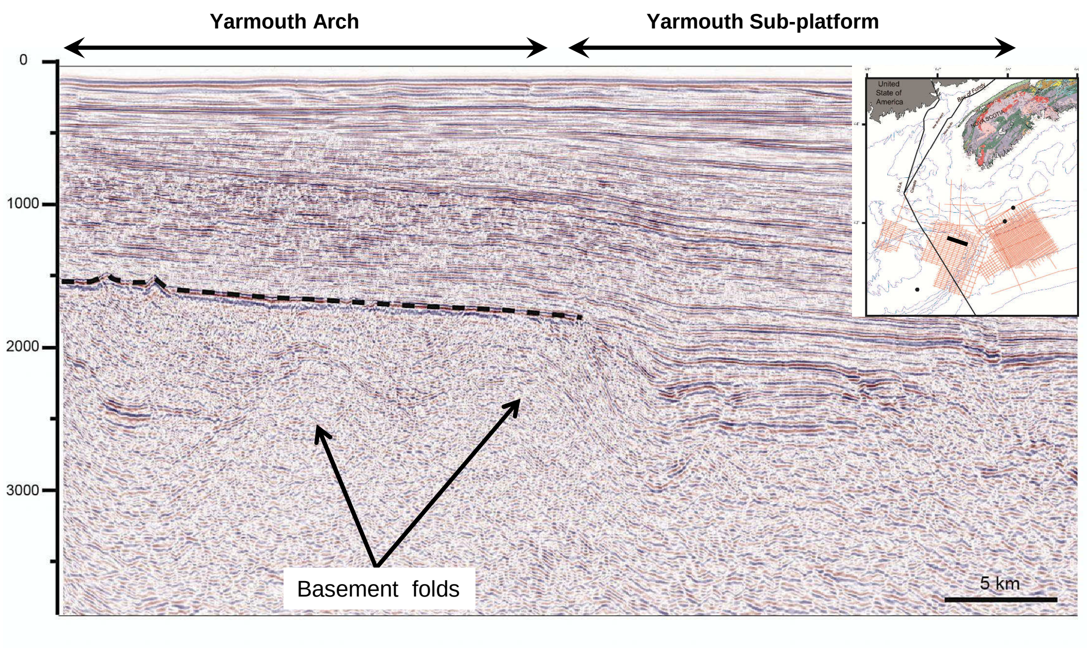


Figure 17: Seismic line (JGM227) showing the folds structures in the basement on the Yarmouth Arch.

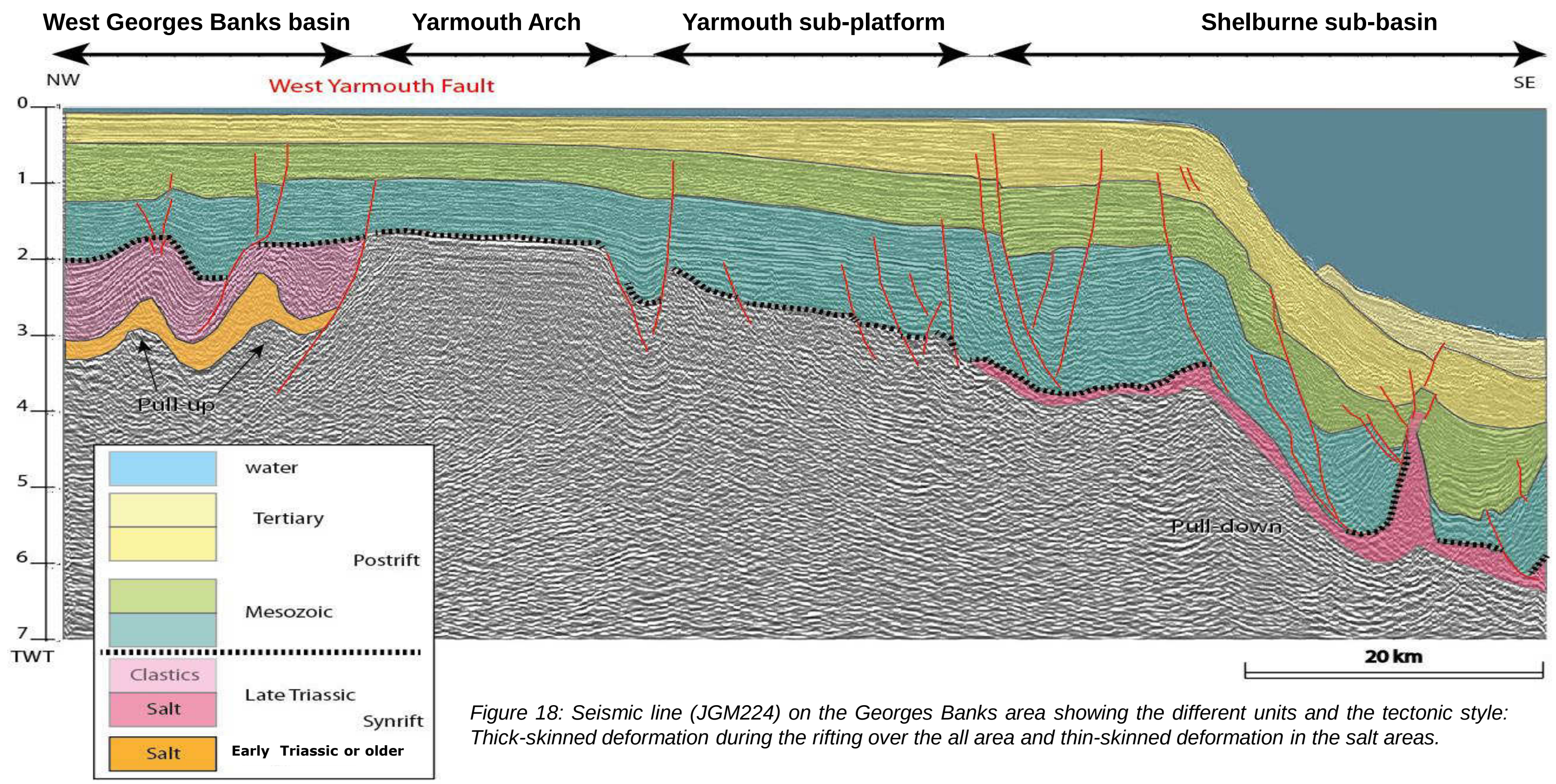


Figure 18: Seismic line (JGM224) on the Georges Banks area showing the different units and the tectonic style: Thick-skinned deformation during the rifting over the all area and thin-skinned deformation in the salt areas.

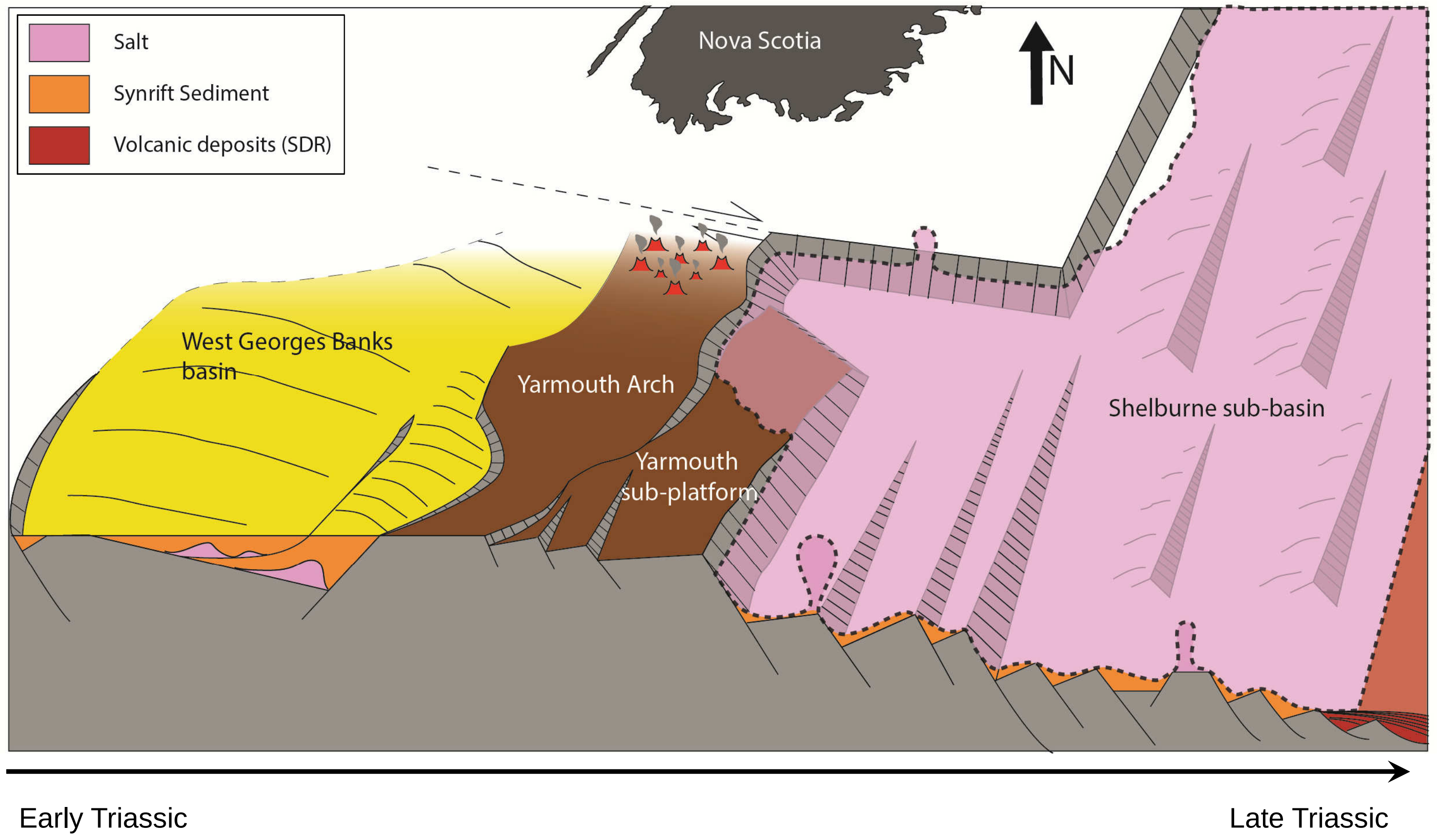


Figure 19: 3D bloc diagram of the Georges Banks and Shelburne Basin showing the tectonic framework. The Yarmouth Arch is individualized during the Trias. This Arch is bounded by NE-SW and N-S faults on each side and by a dextral strike-slip fault to the North.

Base on the seismic and well data and the bibliography a tectonic setting can be proposed (Figures 19 & 20) :

- From **Early to Late Trias**, rifting of the Central Atlantic begins in the West Georges Banks Basin with two trends of faults: N-S (inherited) and NE-SW (new-formed) . A thick layer of salt is deposited above the basement and overlied by a thick carbonate layer.
- During the **Mid-Triassic**, the rifting propagates to the NE throw the Yarmouth Arch. But the Arch act as a 'locked zone' and the rifting propagate over it. Thus, the Arch is individualized during the Trias as a subaerial horst.
- From **Mid-Trias to Early Jurassic**, the rifting propagates to the Shelburne sub-basin with a NE-SW tilted-blocks trend. Synrift sediments are deposited (Red Beds and Eurydice Fm) followed by a thick layer of salt (Argo Fm) (Figures 19 & 20).
- At **200Ma** (Early Jurassic) the rifting ceases and the drifting stage begins. This transition, also called Breakup, is associated with a strong volcanic episod (with volcanoes and flows) knwon as the CAMP. The passive margin stage begins.
- From **Early to Late Jurassic**, a new set of NW-SE strike-slip faults appear and allos to accomodate the oceanic acccretion. These faults will create the NE corner observed between the yarmouth Arch and the Shelburne sub-basin.

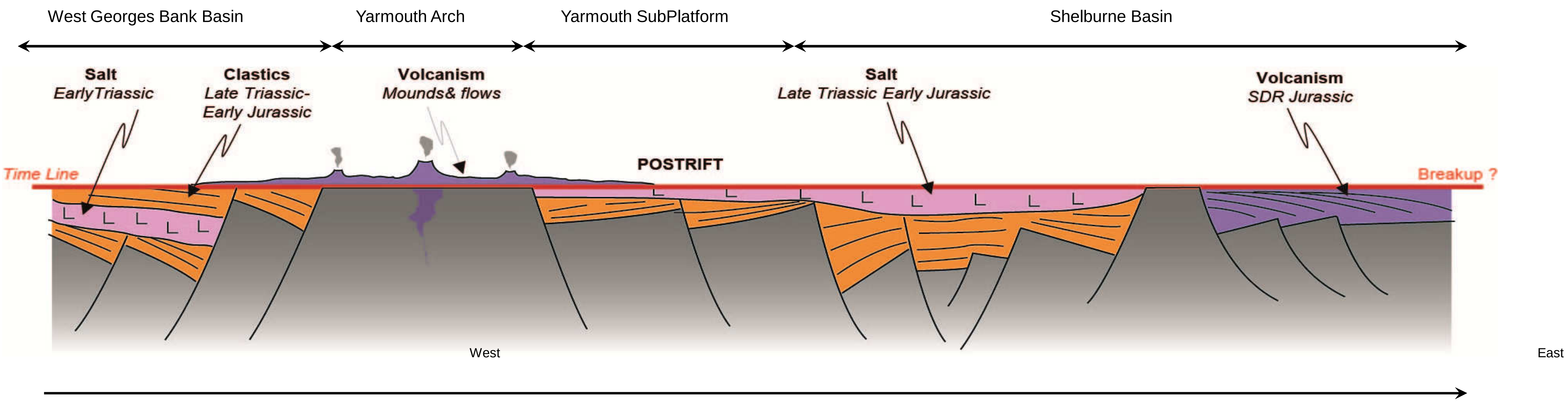


Figure 20: Synthetic cross-section from West Georges Banks to the Shelburne Basin showing the rifting propagation from West to East.

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