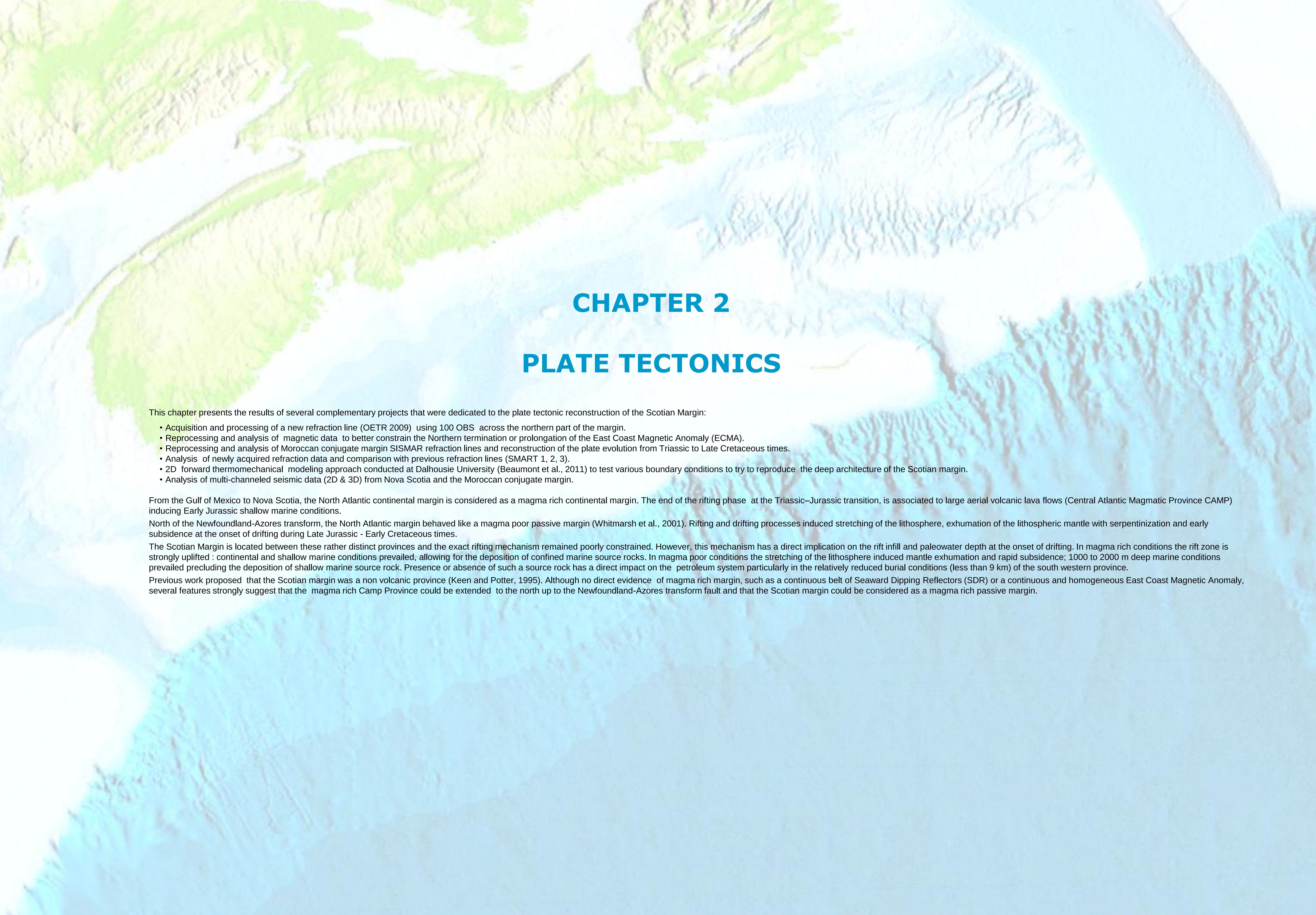


CHAPTER 2

PLATE TECTONICS

This chapter presents the results of several complementary projects that were dedicated to the plate tectonic reconstruction of the Scotian Margin:

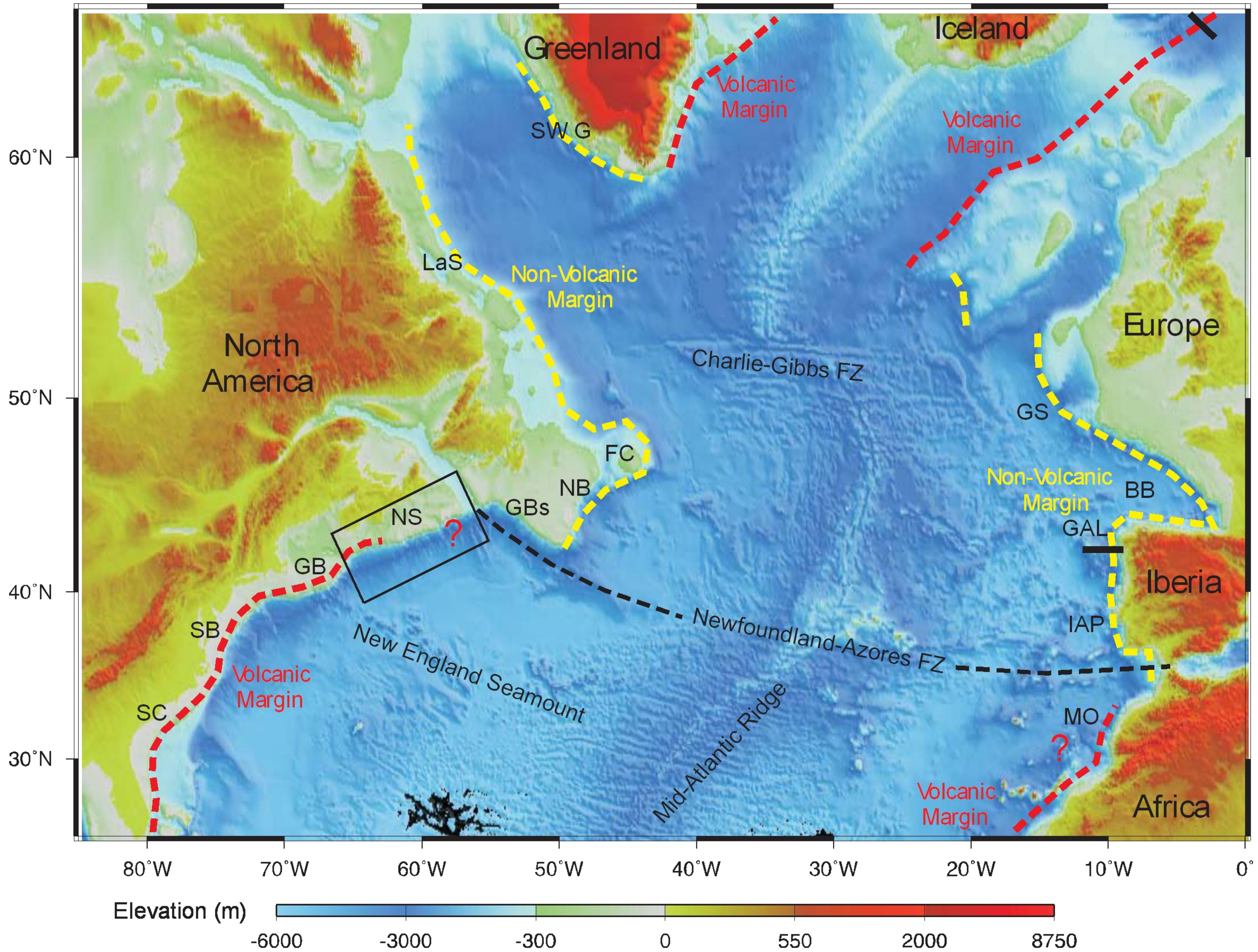
- Acquisition and processing of a new refraction line (OETR 2009) using 100 OBS across the northern part of the margin.
- Reprocessing and analysis of magnetic data to better constrain the Northern termination or prolongation of the East Coast Magnetic Anomaly (ECMA).
- Reprocessing and analysis of Moroccan conjugate margin SISMAR refraction lines and reconstruction of the plate evolution from Triassic to Late Cretaceous times.
- Analysis of newly acquired refraction data and comparison with previous refraction lines (SMART 1, 2, 3).
- 2D forward thermomechanical modeling approach conducted at Dalhousie University (Beaumont et al., 2011) to test various boundary conditions to try to reproduce the deep architecture of the Scotian margin.
- Analysis of multi-channeled seismic data (2D & 3D) from Nova Scotia and the Moroccan conjugate margin.

From the Gulf of Mexico to Nova Scotia, the North Atlantic continental margin is considered as a magma rich continental margin. The end of the rifting phase at the Triassic–Jurassic transition, is associated to large aerial volcanic lava flows (Central Atlantic Magmatic Province CAMP) inducing Early Jurassic shallow marine conditions.

North of the Newfoundland-Azores transform, the North Atlantic margin behaved like a magma poor passive margin (Whitmarsh et al., 2001). Rifting and drifting processes induced stretching of the lithosphere, exhumation of the lithospheric mantle with serpentinization and early subsidence at the onset of drifting during Late Jurassic - Early Cretaceous times.

The Scotian Margin is located between these rather distinct provinces and the exact rifting mechanism remained poorly constrained. However, this mechanism has a direct implication on the rift infill and paleowater depth at the onset of drifting. In magma rich conditions the rift zone is strongly uplifted : continental and shallow marine conditions prevailed, allowing for the deposition of confined marine source rocks. In magma poor conditions the stretching of the lithosphere induced mantle exhumation and rapid subsidence; 1000 to 2000 m deep marine conditions prevailed precluding the deposition of shallow marine source rock. Presence or absence of such a source rock has a direct impact on the petroleum system particularly in the relatively reduced burial conditions (less than 9 km) of the south western province.

Previous work proposed that the Scotian margin was a non volcanic province (Keen and Potter, 1995). Although no direct evidence of magma rich margin, such as a continuous belt of Seaward Dipping Reflectors (SDR) or a continuous and homogeneous East Coast Magnetic Anomaly, several features strongly suggest that the magma rich Camp Province could be extended to the north up to the Newfoundland-Azores transform fault and that the Scotian margin could be considered as a magma rich passive margin.



Louden et al., 2010

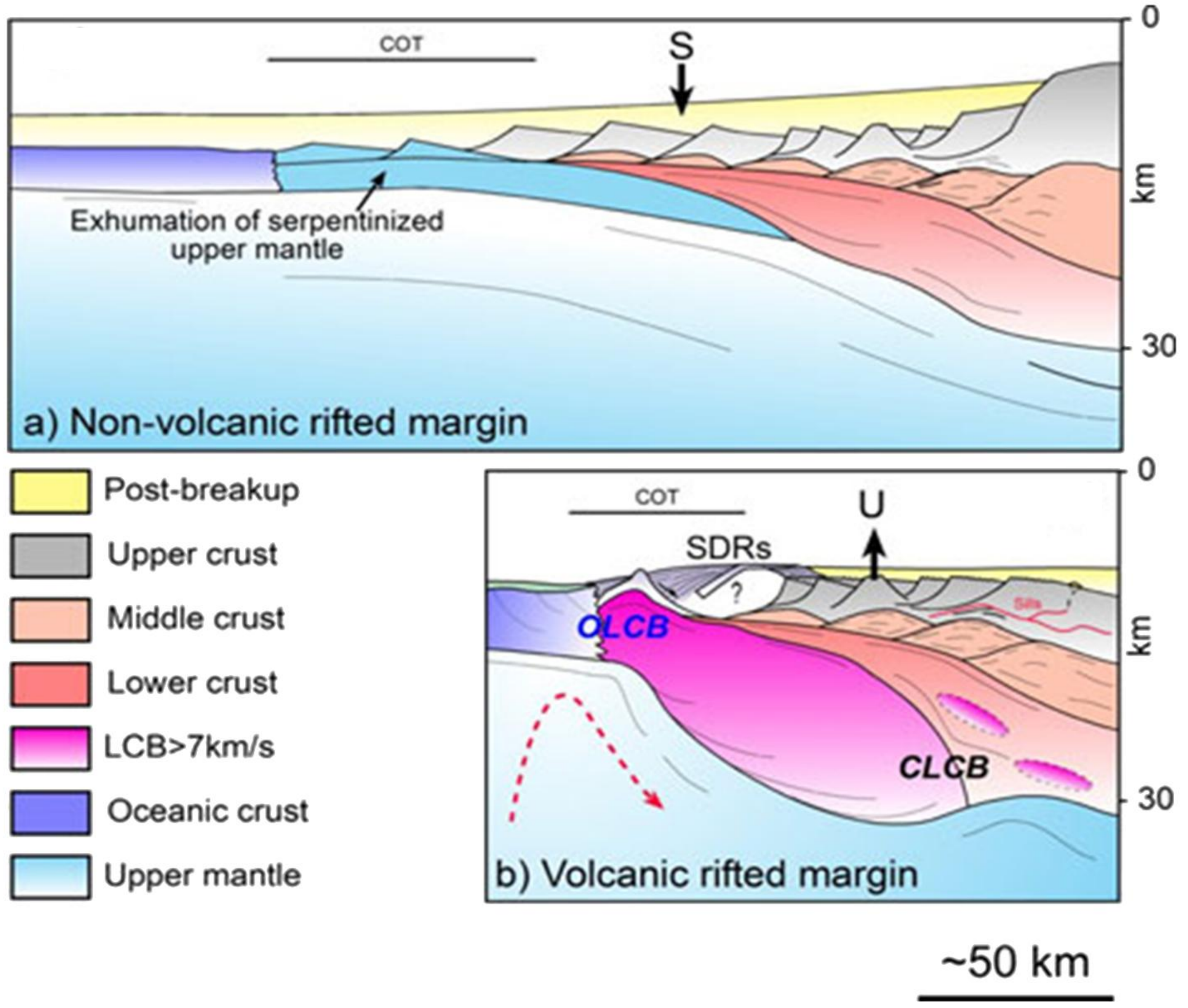
Figure 1: Distribution of different margin types (Boillot and Coulon 1998 and modified from Louden et al., 2010). The magma dominated (volcanic) margins of the North Atlantic and Central Atlantic are separated by a magma poor (non volcanic) segment encompassing Newfoundland and Europe. The approximate location of schematic crustal section from the Norwegian and Galician margins shown in Figure 2 are indicated by black lines.

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 times (approximately 225-200 My ago). As mentioned in the Beaumont et al., 2010 report of the special project (Annex 10), "*we have only a rudimentary understanding of the way 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

The Scotian margin is located between a magma dominated volcanic margin along the U.S. and non-volcanic margin offshore Newfoundland (Figure 1). The southwestern part of the margin (till 62° W) has all the characteristics of a magma dominated margin with clear seaward dipping reflectors (SDR) (SMART 3 and Novaspan 1100 – Figures 2 and 3, in PL. 2-4) 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.
To better understand the architecture of this part of the margin new magnetic maps were created (PL 2-3) and a new refraction line was acquired and processed during this project (OETR 2009, PL 2-7)



Gernigon et al., 2004

Figure 2: Main characteristics of volcanic margins versus non-volcanic passive margins. (a) Schematic crustal section of a wide non-volcanic "Galician type" margin characterized by the progressive exhumation of the underlying serprentinized mantle (Boillot & Froitzheim, 2001). (b) Structure and main characteristics of a narrow volcanic "Vøring type" margin (Gernigon et al., 2004). CLCB: continental lower-crustal body; OLCB: oceanic lower-crustal body; SDRs: Seaward Dipping Reflector sequences. S symbolizes the post-breakup subsidence of the non-volcanic margin, U represents the relative uplift recorded along the volcanic margin as an isostatic consequence of thick high velocity underplating observed along the continent-ocean transition (COT).

Magma Dominated or Magma Poor : Why Does it Matter for the Petroleum System?

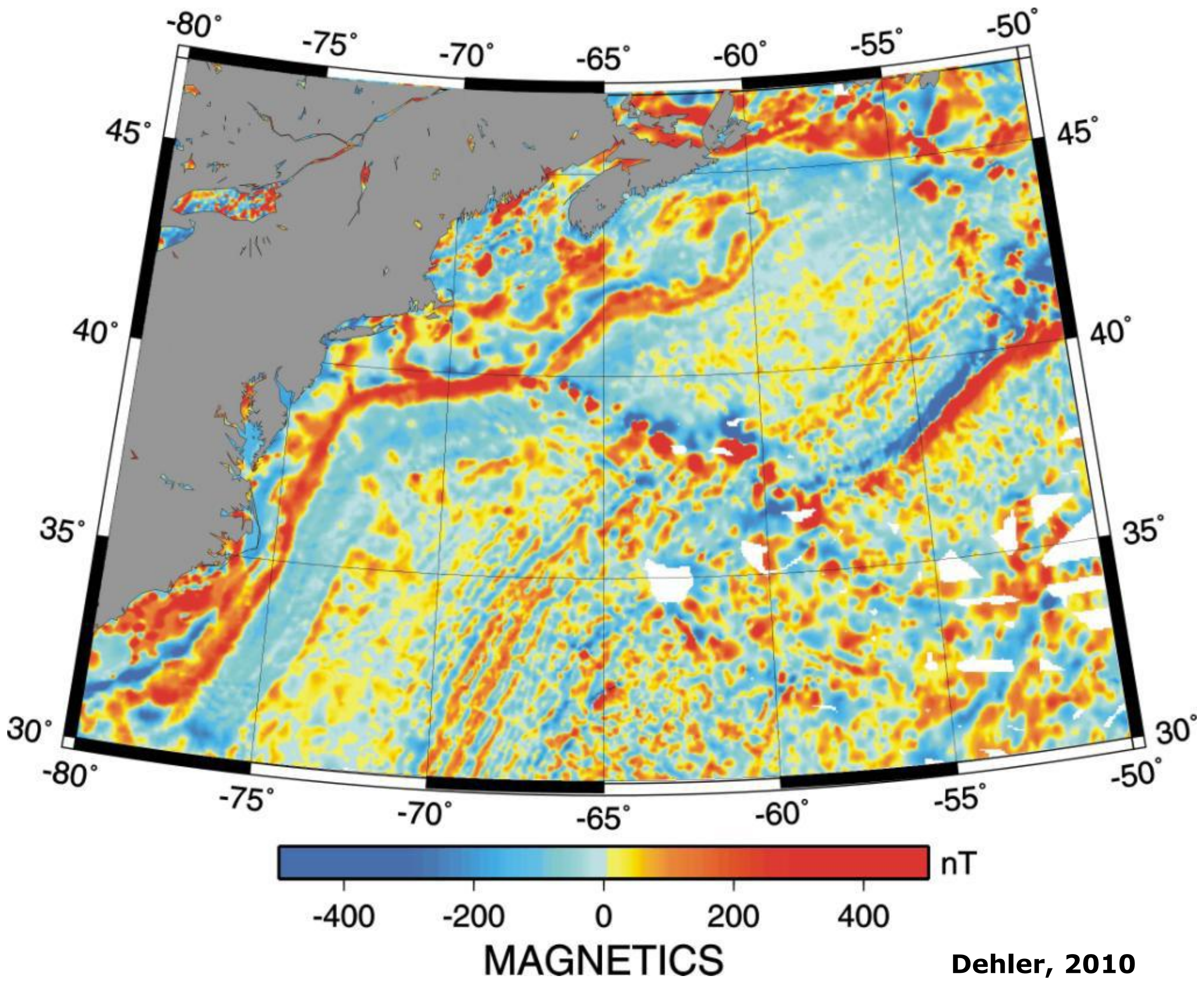
The deep rifting processes and the deep architecture of the margin have a direct impact on thermal regime and subsidence history that control maturation of source rocks and deposition of source rocks and reservoir. In particular, the radiogenic heat of the continental crust contribute to the maturation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

A primarily non-magmatic rift to drift process (Figure 2a) would most likely imply a deep water environment, due to relatively rapid subsidence during the syn-rift and early post rift phases. This would almost certainly preclude the possibility of a shallow restricted anoxic marine environment and hence the possibility of a rich Early Jurassic source rock system.

If the rift followed an essentially volcanic process (Figure 2b) it would imply uplift and sub-aerial extrusive 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 post rift. 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.

Magma Dominated (Volcanic) / Magma Poor (Non Volcanic) Margin Distribution in Central Atlantic

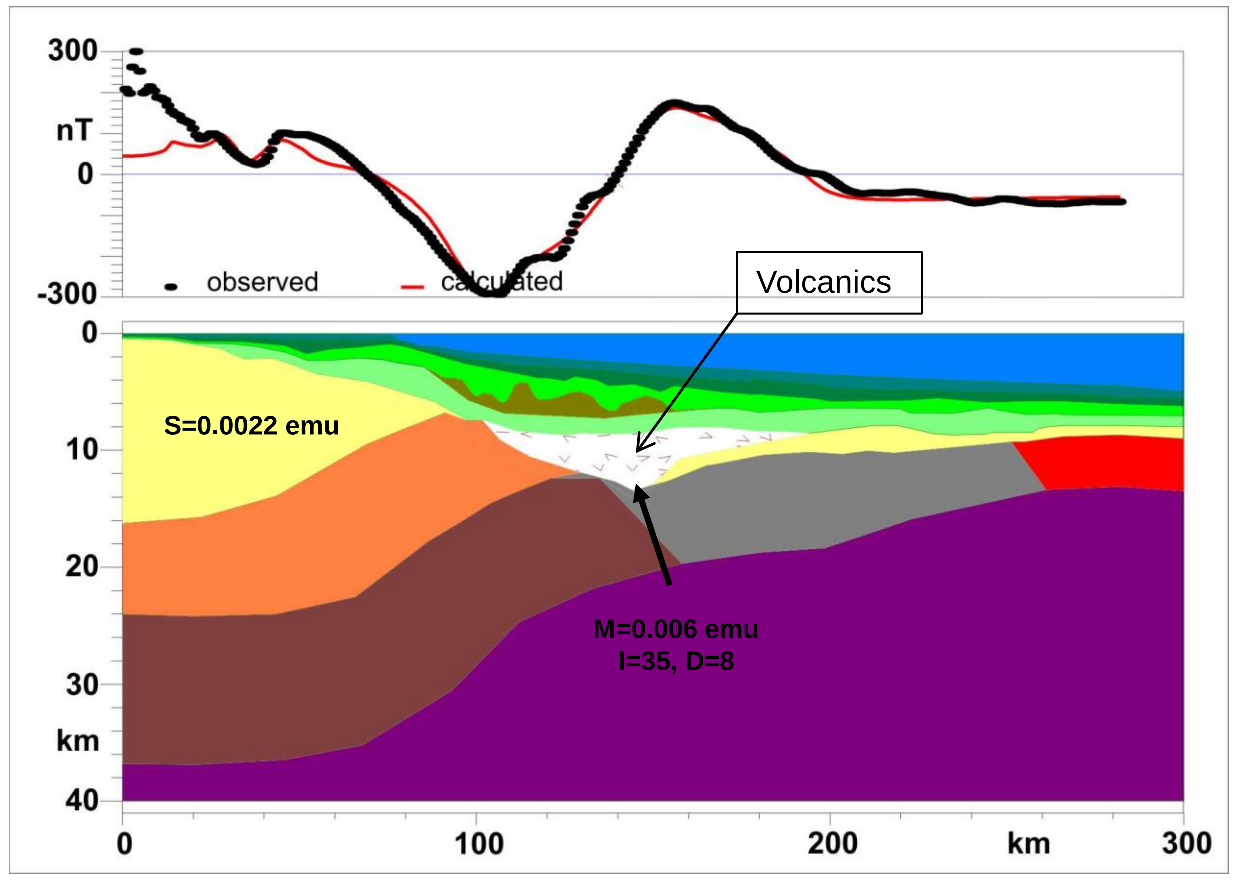
PLATE TECTONICS



Dehler, 2010

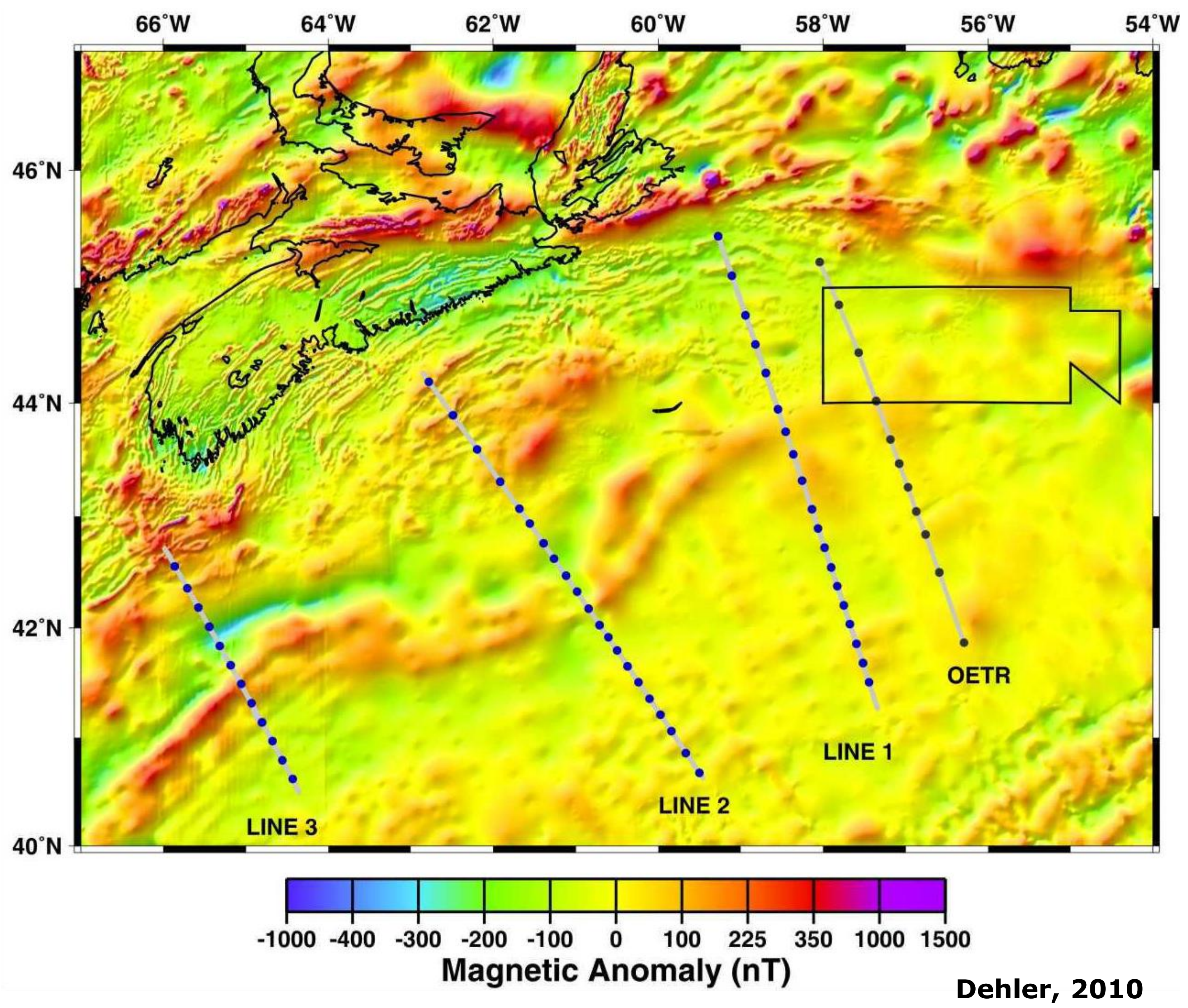
Figure 1: Magnetic anomalies along the U.S. and Canadian (Nova Scotia) continental margins and adjacent ocean. The ECMA is a prominent positive anomaly along much of the margin.

LINE 3 – SW Margin



Dehler, 2010

Figure 4: Seismic refraction line 3 (SMART 3). Observed (black) and calculated (red) magnetic anomalies. ECMA can be fit with volcanic body at the edge of the stretched continental crust.



Dehler, 2010

Figure 2: Magnetic anomalies along the Scotian margin, showing variations in trend and amplitude of the ECMA. Data is from Geological Survey of Canada (Oakey and Dehler, 2004),
except outlined area where data is courtesy of Fugro and OETR Association, Nova Scotia. Lines with labels indicate locations of seismic refraction profiles.

Magnetic Data

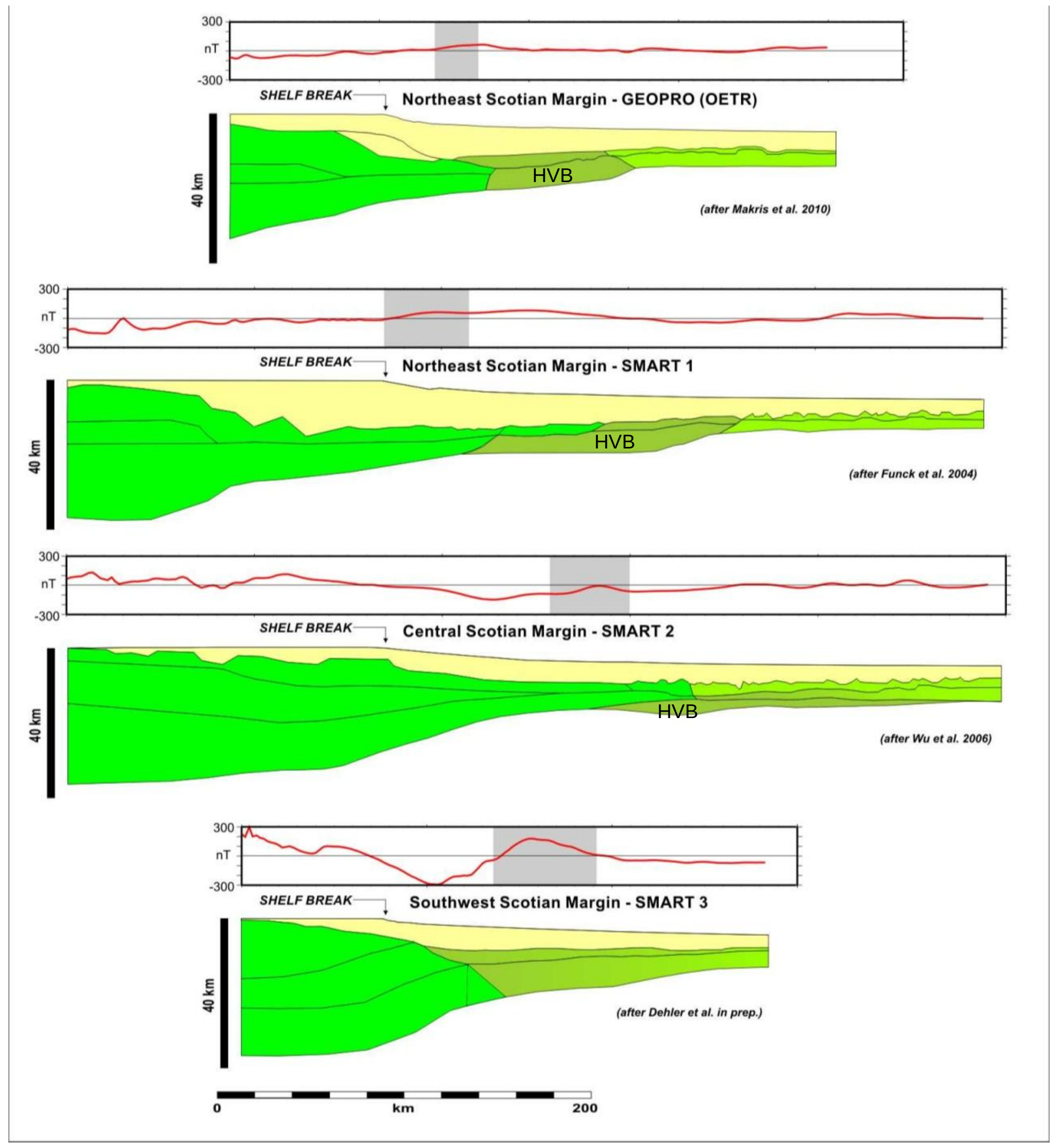
The East Coast Magnetic Anomaly (ECMA) can easily be followed along the U.S. Atlantic margin and much of the Nova Scotia margin. The anomaly varies in character along the margin, with several areas where offsets are noted, such as the vicinity of the New England Seamounts near 40 N (Figure 1). The changes are more notable offshore Nova Scotia, where both the trend and the character of the anomaly change. The anomaly becomes more difficult to follow to the northeast, and appears to break into two parallel components, one of which terminates near Sable Island at 60 W. The outermost branch continues until at least 58 W. It is difficult to determine the trend of the anomaly east of this location on the regional compilation of magnetic data, which was compiled and processed by the Geological Survey of Canada (GSC) from a variety of sources including aeromagnetic grids and marine surveys (Oakey and Dehler, 2004).

A grid of high resolution magnetic data, acquired by Fugro in 1999 through 2001, covers the northeastern end of the margin where GSC coverage is sparse. This grid was processed and merged into the regional GSC grid for this study to allow examination of the eastern end of the ECMA. On the merged map the ECMA appears to continue until at least 57 W (Figure 2).

Modeling Results (Figure 4)

It is clear that at least part of the ECMA is related to the rift-related volcanic extrusives present along the US and southwestern Scotian margin. However, the source of the anomaly along the central and eastern part of the Scotian margin may not be related to this event, or may have been disrupted by additional tectonism during or following rifting (Dehler, 2010).

The SW margin has evidence of voluminous magmatism: SDRs, high velocity body, and strong ECMA-style magnetic anomaly. The NE margin does not show such characteristics and is generally considered as magma-poor margin: complex OCT with possible exhumed mantle, and little evidence of volcanism.



Dehler, 2010

Figure 3: Seismic refraction lines shown in figure 2 and magnetic anomaly profiles .The positive anomaly identified as the ECMA is indicated on the profiles (shaded areas). HVB = High Velocity Body.

Refraction Profiles and ECMA (Figure 3)

The ECMA does not coincide with the shelf break or the edge of thinned continental crust.

On refraction line 3, the ECMA coincides with an interpreted volcanic wedge and SDRs (PL 2-4). Magnetic modeling of the other refraction lines indicates that the lower amplitude ECMA could be explained by thin volcanic layers at the seaward edge of thinned continental crust.

There is good correlation between the ECMA and the edge of the salt basin (PL 8-1-1a).

Magnetic Data (Dehler 2010)

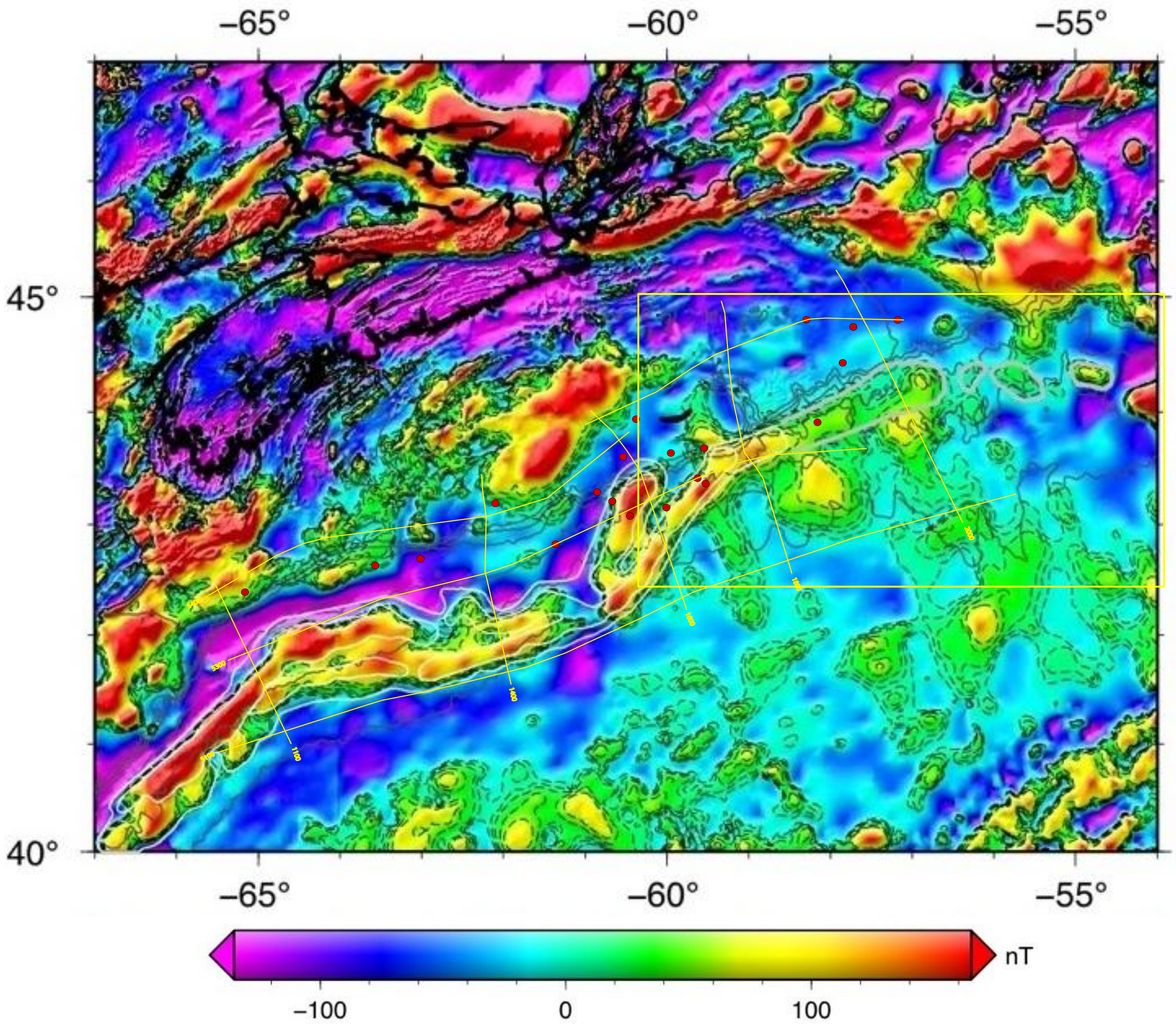
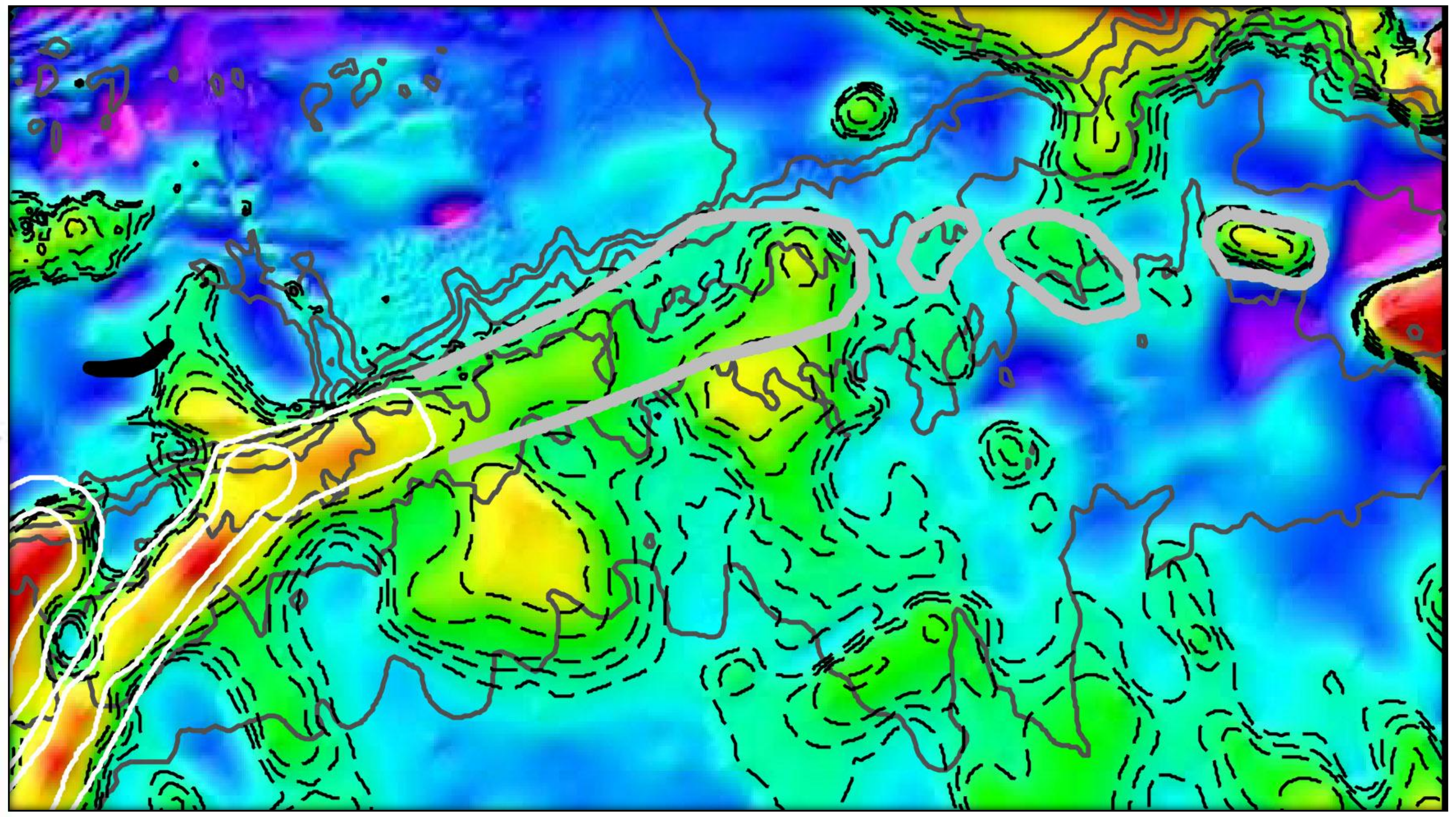


Figure 1: Updated magnetic grid of the northwestern central Atlantic ocean (Dehler, 2010) (top) and detail of the northeastern termination of ECMA (top right). Dashed lines are contoured magnetic anomalies and continuous black lines are bathymetric contours every km. In white, the portion of ECMA already identified by Sahabi et al. (2004) and in gray is what we suggest as a reasonable northern prolongation of ECMA. Seismic reflection lines are shown in yellow. Red dots are key wells of this study.



The magnetic grid of Verhoef et al., (1996) has been updated by introducing the detailed magnetic data acquired by Fugro in the northeastern part of the map (Dehler, 2010). Thin continuous gray lines are bathymetric contours (200 m, 500 m and then every km, extracted from ETOPO1 data set (Amante and Eakins, 2009).

The East Coast Magnetic Anomaly (ECMA) constitutes the prominent positive anomaly (higher than 100 nT) underlined by white contours (ECMA already identified by Sahabi et al., (2004). In gray is the present interpretation of the northern ECMA prolongation. Dashed black lines are a selection of iso-values used to interpret the ECMA prolongation.

ECMA Northeastward Termination

East of 58.5° W, the amplitude of the ECMA is considerably reduced and associated magnetic anomalies broaden. Whereas the ECMA features a single positive anomaly that locally splits in two branches southward, the northward continuation shows a rather different signature. First, the amplitude is two to three times lower. Second, the prolongation mostly appears as a linear borderline between a large negative anomaly to the north (blue in the Figure) and a gently varying positive anomaly to the south (cyan and green in the Figure). Thus, the northeastward prolongation of the ECMA is straightforward for its landward side and, using the magnetic iso-contours up to 56.5°W, could be defined as a stripe not wider than the ECMA southward. Further east, only individualized, shorter extent and discontinuous anomalies could be interpreted as a possible prolongation of the ECMA.

What caused the ECMA?

The East Coast Magnetic Anomaly (ECMA) seems to be directly related with volcanics producing SDR (Plate 2-4) all along the U.S. Atlantic margin (PL 2-10). However, toward the northeast, the magnetic anomaly is much more diffuse and faint even if new reprocessed data acquired by Fugro suggest a more continuous anomaly. On seismic lines, seaward dipping reflectors are impossible to identify in that part of the margin.

Dehler (2010) suggested, by forward modeling, that the ECMA can be related to a very thin layer of volcanics located above the eastern part of the high velocity body, slightly extending to the northwest of the high velocity body. The ECMA may also be partly caused by the edge effect due to the juxtaposition of a magnetized serpentinized body and a poorly magnetized thinned continental crust.

Magnetic Anomaly Map (Sibuet et al., 2010)

Forewords

The Scotian margin is located in between the volcanic U.S. Atlantic margin at southwest and the non-volcanic Newfoundland margin at the northeast. This observation, added to the vanishing northward along the Scotian margin of both the East Coast Magnetic Anomaly (ECMA) and the Seaward Dipping Reflector sequence on the seismic reflection (SDRs), tend to designate the Scotianmargin as the transition area from volcanic to non-volcanic rifting.

In order to image the transition from continental to oceanic crust and to assess the lateral variation in crustal structure, three wide-angle refraction seismic lines perpendicular to the coastline were acquired in 2001. These lines, called Scotian Margin Transect refraction lines (SMART lines) were acquired during a joint cruise by the Department of Earth Sciences at Dalhousie University and the Geological Survey of Canada (GSC). Processing and interpretation involved researchers at Dalhousie University, the GSC, and GEUS in Denmark.

A new wide-angle refraction reflection line was acquired in 2009 by GeopPro GmbH. This line, parallel to an existing wide-angle reflection line (GXT NovaSPAN line 2000), was planned to clarify the crustal structure of the ocean continental transition and for the plate reconstruction before oceanization project. The plate reconstruction project, putting together the OETR 2009 line and the conjugate line SISMAR4 located in Morocco, was carried out by Jean-Claude Sibuet et al. in 2010.

The presentation of the lines in the following plates is going northward from SMART3 to OETR2009.

Report from the OETR study used for this Atlas:

- Beaumont, C. 2010. Report on continuation of OETR Nova Scotia margin project: forward dynamical modeling of: 1) Margin development during rifting and 2) Salt Tectonics (Annex 10).
- Sibuet, J.C., Rouzo S., Srivastava S., 2011. Plate tectonic reconstructions and paleo-geographic maps of the central and north Atlantic oceans.
- Louden, K., Lau, H. Wu, Y., Nedimovic, M. 2010. Refraction crustal models and plate reconstruction of the Nova Scotia and Morocco margins.
- Sibuet, J.C., Rouzo S., 2010. Reprocessing of SISMAR refraction lines.
- GeoPro GmbH Hamburg, 2010. Vp/Vs converted waves report central Scotian margin, Canada.

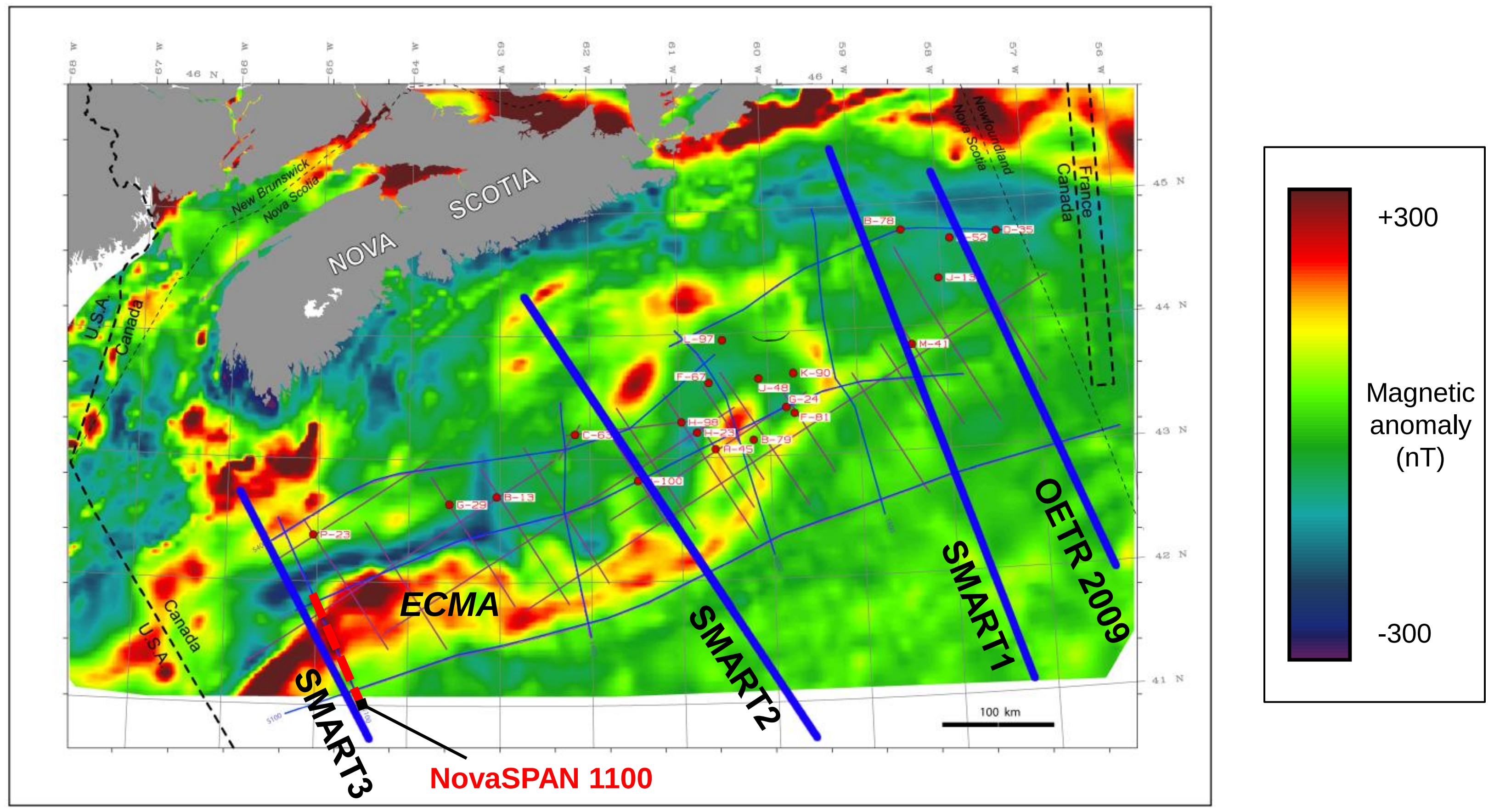


Figure 1: Location of the wide-angle seismic line on the regional magnetic anomaly map.

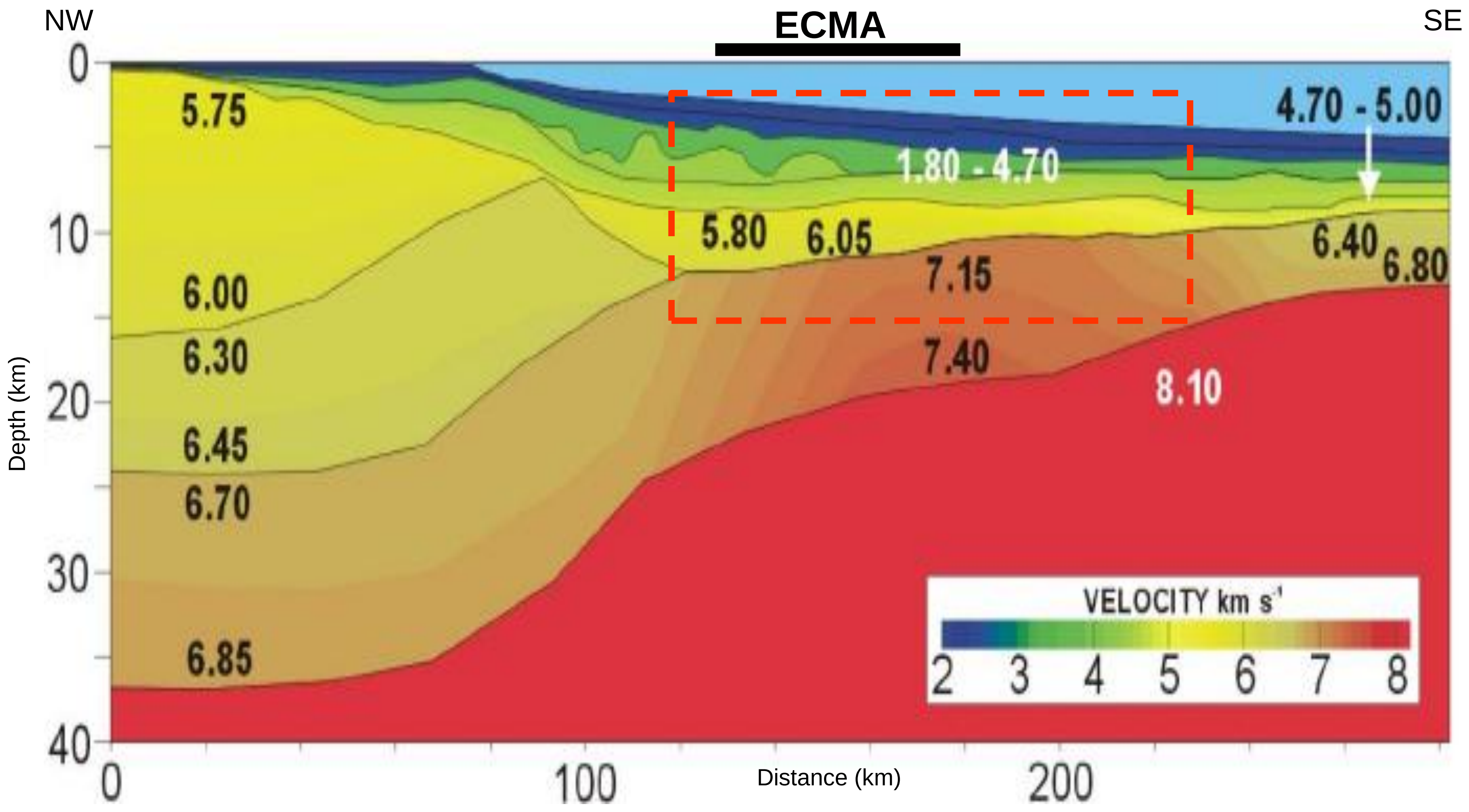


Figure 2: P-Wave velocity model – SMART line 3; Red dashed = Figure 3.

Velocity Modeling Description

The velocity model was developed by Dehler et al., 2004.

The continental crust is divided into 3 layers: the upper, middle and lower crust (Figure 2).

The continental crust thins over a 100 km wide zone. Oceanic crust of at least 5 km thickness lies seaward of 250 km distance.

A high velocity lower crustal (HVLC) layer with Vp > 7.2 km/s has been identified at x = 120 km, coincident with the ECMA. This HVLC layer is interpreted as an underplated or intrusive igneous body. An overlying unit has been interpreted as a layer of volcanic extrusives, a hypothesis supported by the Seaward Dipping Reflector (SDR) sequence observed on the nearby seismic reflection line (Figure 3).

Interpretation

The comparison of various crustal transects from the U.S. 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 has the following set of characteristics:

1. Narrow region (100 km 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;
4. Normal thickness oceanic crust;
5. Thin sedimentary basin; and
6. Wedge of volcanic material above underplated region.

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

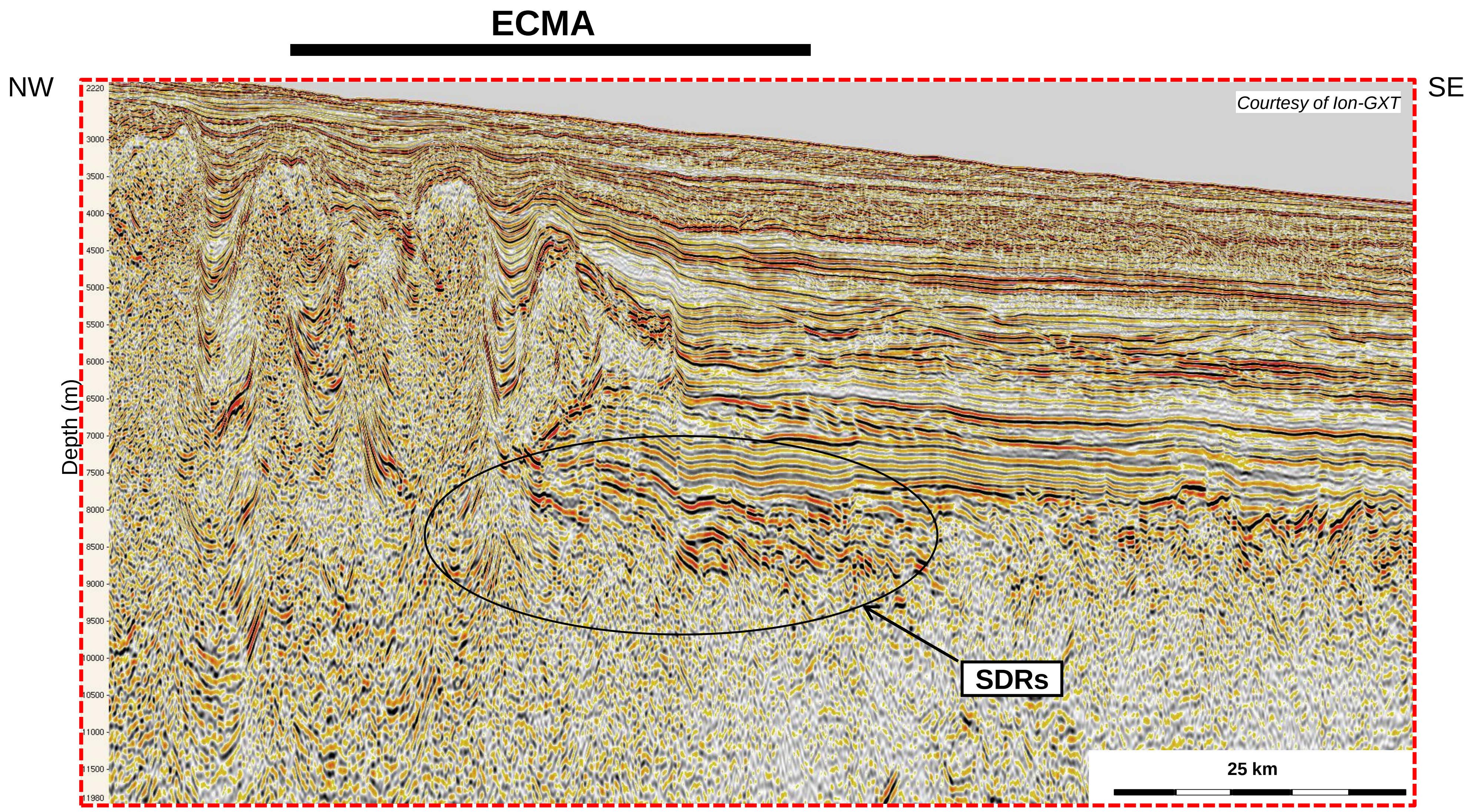


Figure 3: Seismic reflection line – NovaSPAN reprocessed 2010 – line 1100 PSDM.

Crustal Scale Section SMART 3

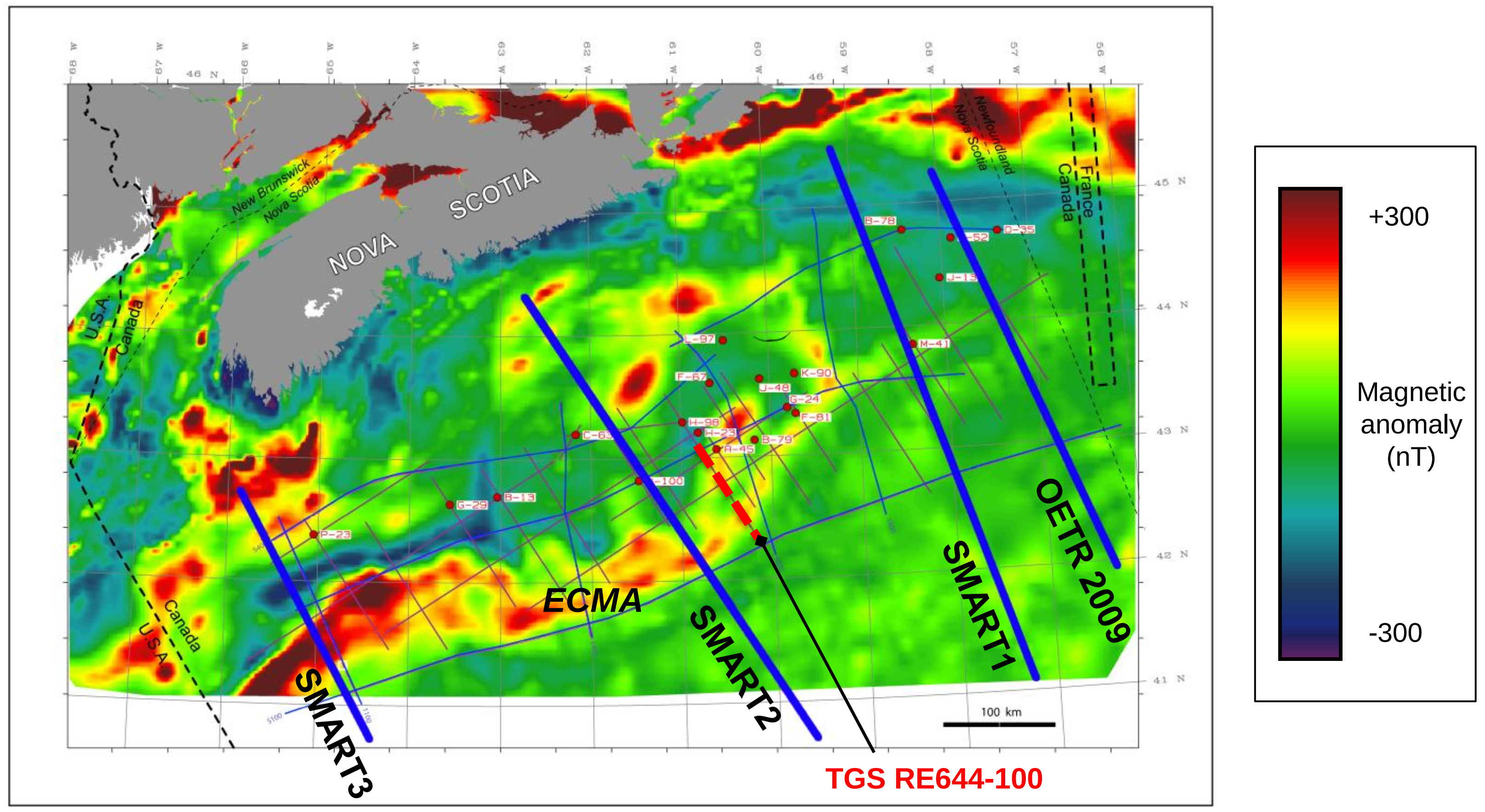


Figure 1: Location of the wide-angle seismic line on the regional magnetic anomaly map.

From Internal OETR Reports

Beaumont, C., 2011. Report on continuation of OETR Nova Scotia margin project: forward dynamical modeling of: 1) Margin development during rifting and 2) Salt Tectonics.

Louden, K., Lau, H. Wu, Y., Nedimovic, M. 2010. Refraction crustal models and plate reconstruction of the Nova Scotia and Morocco margins

Velocity Modeling Description

The velocity model has been done by Wu et al. in 2006 (Figure 2).

The continental crust is divided in three layers: the upper, middle and lower crust. The upper crust thins from 4 to 2 km over a distance of 285 km with Vp ranging from 5.5 to 5.7 km/s. The unstretched middle crust is 12 km thick and thins over a distance of 245 km till complete absence. Thus, beyond x = 260 km, the upper crust directly overlies the lower crust within a 60 km wide zone. The body, which velocity ranges between 5.2 and 5.6 km/s from 180 to 300 km distance, could be attributed to sediments. The lower crust thins from 18 to 2 km over a distance of 300 km with P-Wave velocity ranging between 6.8 and 6.9 km/s.

Immediately following continental break-up, a relative thin (4 km) oceanic crust forms with a distinct continent-ocean boundary (COB). The oceanic crust is composed by two layers, the lower unit of Vp ranging between 6.95 and 7.4 km/s an upper unit with Vp ranging between 5.5 and 6 km/s. A constant sedimentary sequence is overlying these two layers. The oceanic continental transition (OCT) zone also encompasses an anomalously High Velocity Lower Crust (HVLC) with Vp between 7.6 to 7.95 km/s of 200 km wide with a maximum of 4 km thick.

The maximum sedimentary thickness is 6 km, with Vp ranging between 1.8 to 5 km/s but as shown by seismic line (Figure 3), part of what is attributed to the upper crust between km 160 and 300 (Vp = 5.2 -56) is probably of sedimentary origin.

Interpretation

SMART2 is representative of the central margin. Its velocity model reveals an OCT zone consisting of a HVLC.
This High Velocity Body has been interpreted as partially serpentinized mantle (PSM) or as underplated magmatic body .

However, along these profiles there are four differences that are noteworthy:

1. The lateral extent of the middle crust;
2. The total width of the crustal thinning zone that defines the margin;
3. The location and extent of the HV body; and
4. The thickness of the overlying sedimentary basin.

On this part of the margin, no SDRs have been observed at the location of the ECMA on the seismic reflection but it may be obscured by the prominent diapiric salt structures (Figure 3). Also note that SDR's are observed at the conjugate location offshore Morocco in a zone that intersects the West Africa Continental Magnetic Anomaly (WACMA).

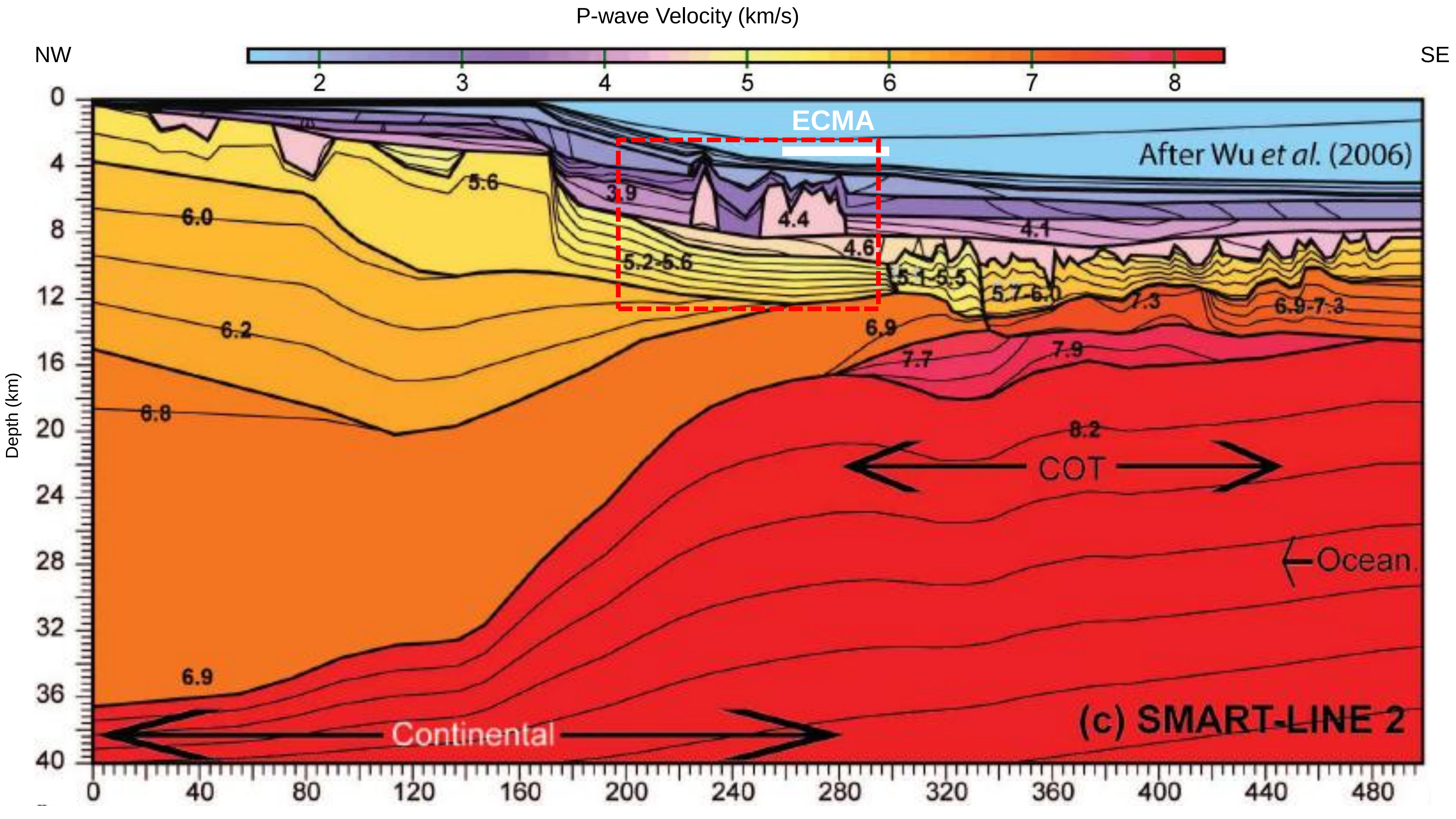


Figure 2: P-Wave velocity model – SMART line 2.

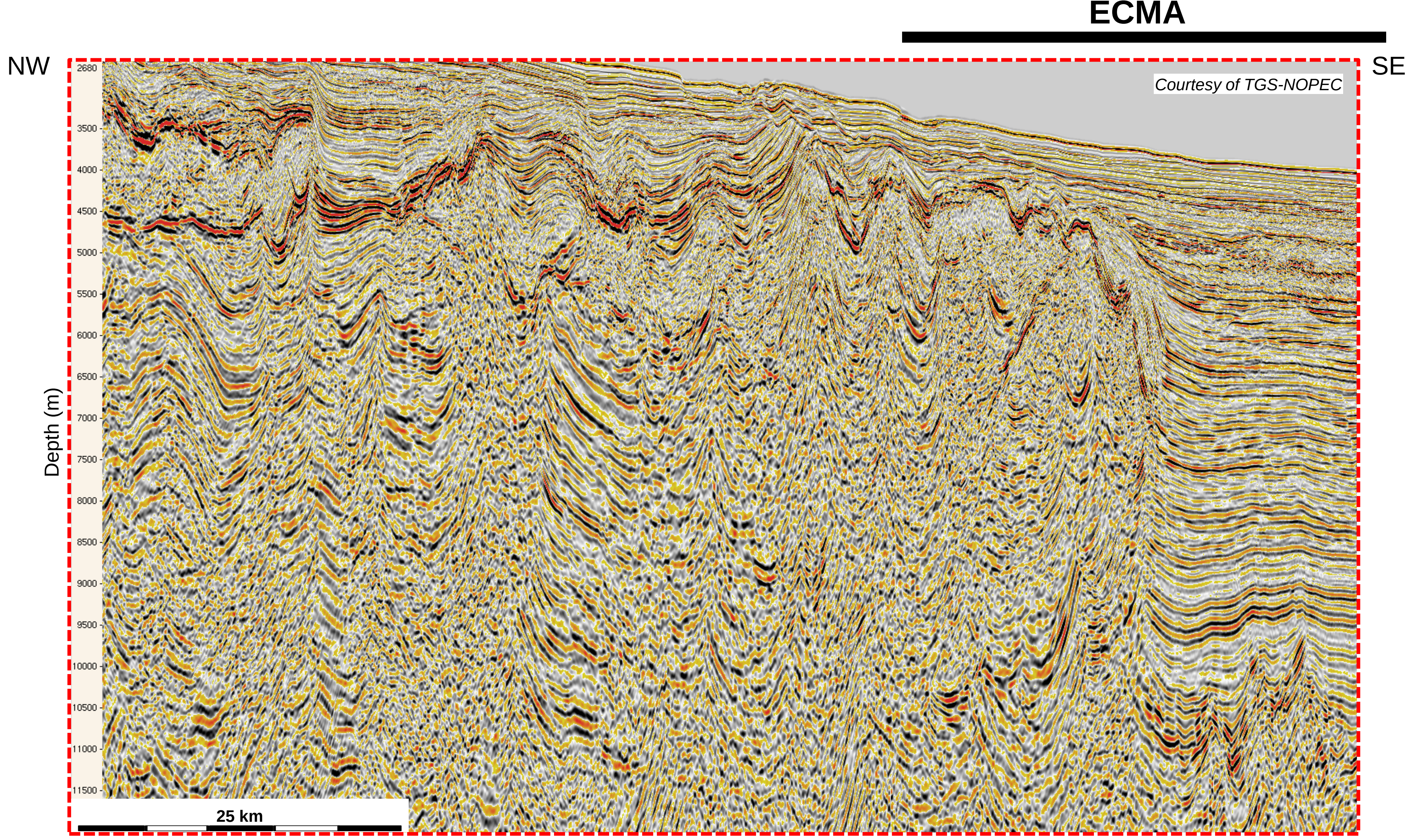


Figure 3: Seismic reflection line – TGS reprocessed 2010 – line 644-100 PSDM.

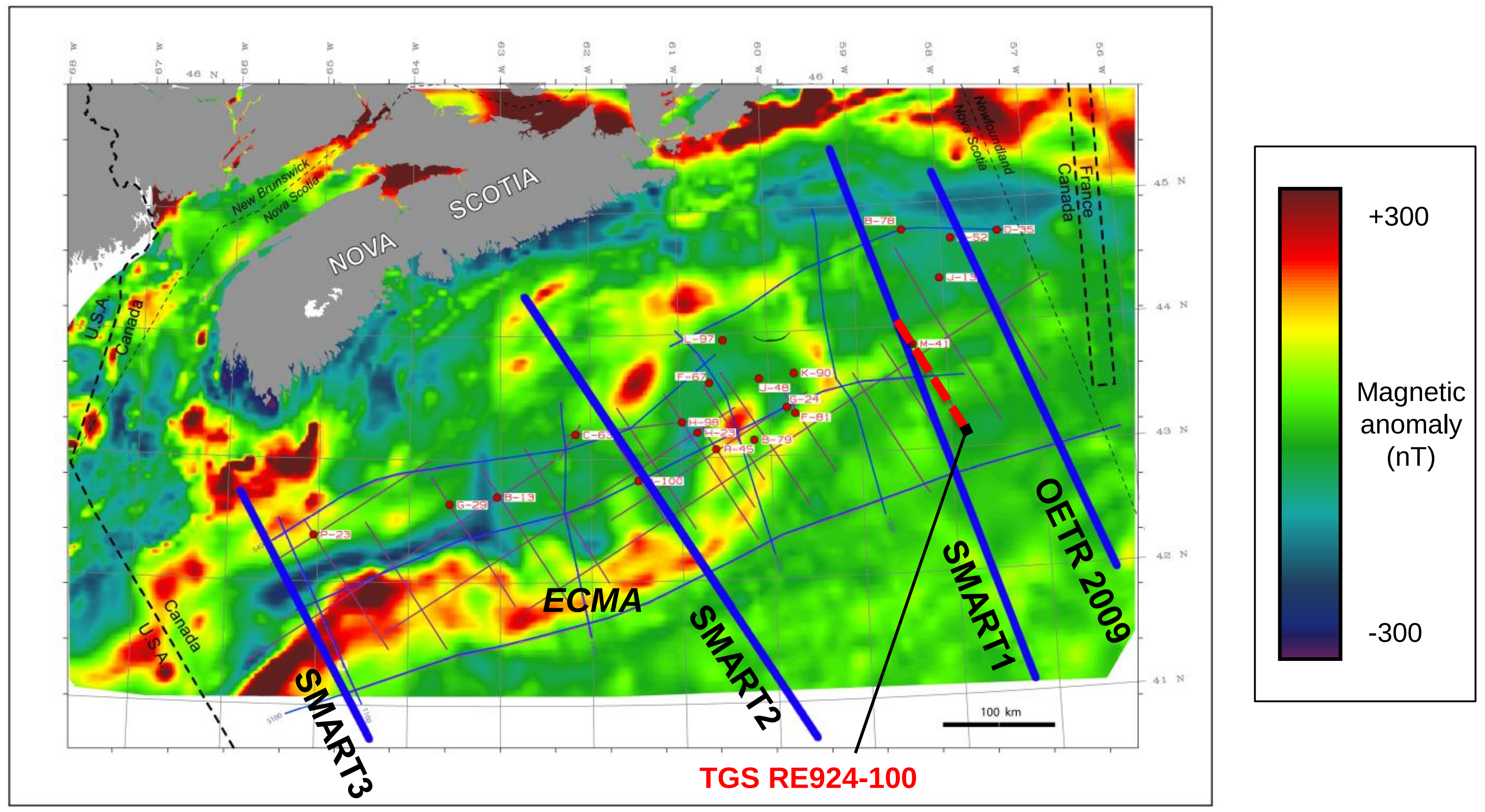


Figure 1: Location of the wide-angle seismic line on the regional magnetic anomaly map.

From internal OETR Reports

Beaumont, C. 2011. Report on continuation of OETR Nova Scotia margin project: forward dynamical modeling of: 1) Margin development during rifting and 2) Salt Tectonics.

Louden, K., Lau, H. Wu, Y., Nedimovic, M. 2010. Refraction crustal models and plate reconstruction of the Nova Scotia and Morocco margins.

Velocity Modeling Description of SMART1

The velocity model has been developed and interpreted by Funck et al., in 2004 (Figure 2).

The continental crust is divided in three layers: the upper, middle and lower crust. The upper crust thins from 10 to 3 km over a distance of 230 km with Vp ranging from 5.7 to 6 km/s. The unstretched middle crust is 6.5 km thick and thins over a distance of 25 km till complete absence. Thus, beyond x = 80 km, the upper crust directly overlies the lower crust within an approximate 160 km wide zone. The lower crust thins from 20 to 5 km over a distance of 180 km with P-Wave velocity ranging between 6.7 and 6.9 km/s.

The oceanic crust is 4 km thick containing 2 layers with a lower unit of Vp ranging between 6.4 and 6.6 km/s an upper unit with Vp ranging between 4.7 and 5 km/s. A constant sedimentary sequence is overlying these two layers. The upper crust and the oceanic crust are separated by a relatively low velocity domain (5.2-5.4 km/s) which has been interpreted as an exhumed and highly serpentinized mantle of 70 km wide (Louden et al., 2010). The continental oceanic transition encompasses a high velocity lower crust body of 130 km wide and a maximum of 6 km thick, which separates the lower continental crust and the lower unit of the oceanic crust.

The sedimentary basin can reach up to 14 km of thickness with Vp ranging between 1.8 to 5 km/s.

Interpretation

SMART1 is representative of the northern margin. In contrast to SMART2, the upper continental and the oceanic crust of SMART1 are separated by a wide Low Velocity Body (Vp =5.2 km/s) overlying a High Velocity one (7.6-7.3 km/s). The Low Velocity body has been interpreted as exhumed and highly serpentinized mantle meanwhile the High velocity body is considered as partially serpentinized mantle (Louden et al., 2010). The same alternate interpretation with under plated magmatic body has been proposed (Luheshi et al., 2010).

On this part of the margin, the ECMA has almost disappeared and no SDRs have been recognized on the seismic reflection. However, as noted above for SMART2, evidence of SDR's at the offshore Morocco conjugate location has been reported by Maillard et al. (2006) and Roeser et al., 2002.

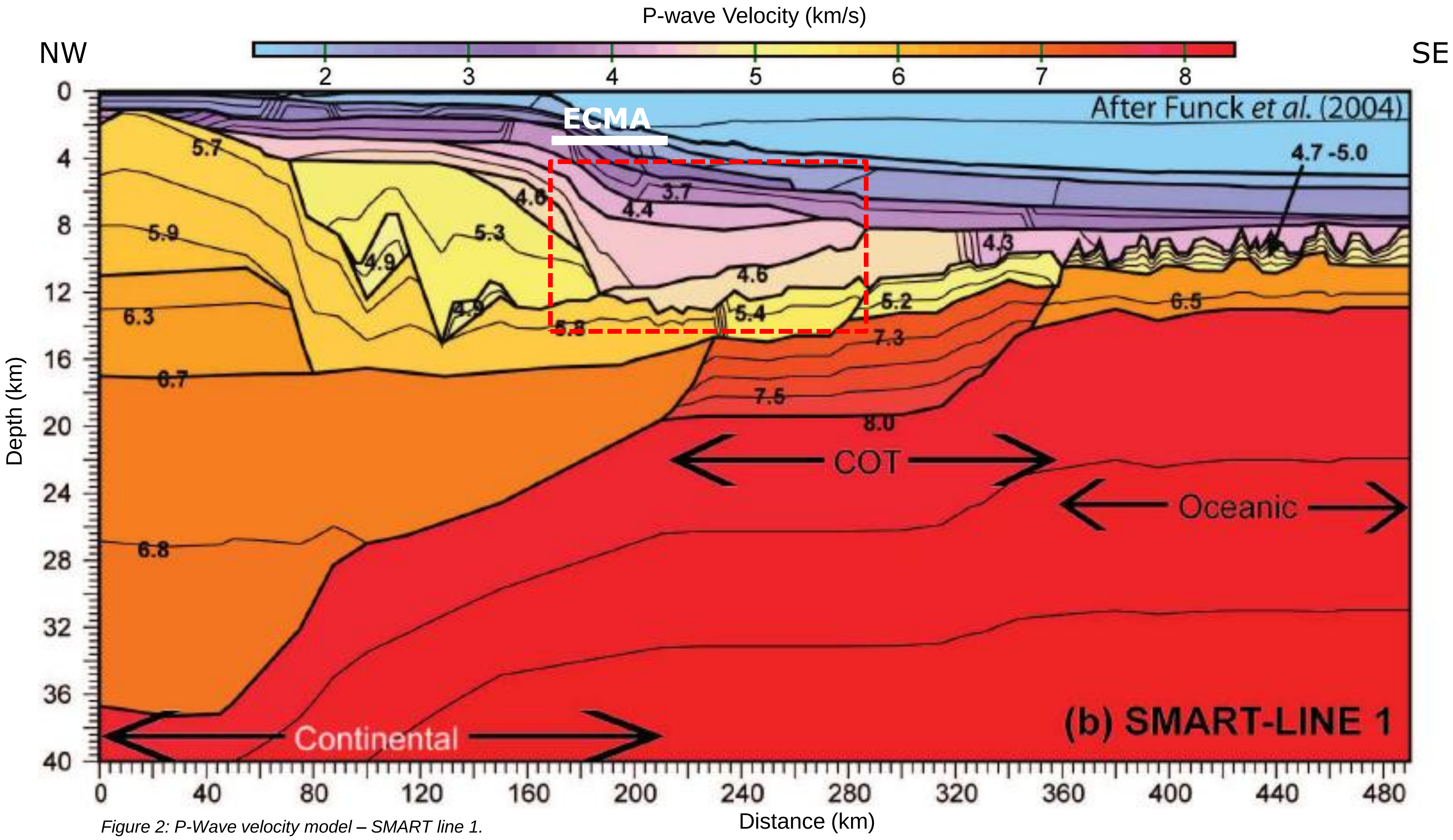


Figure 2: P-Wave velocity model – SMART line 1.

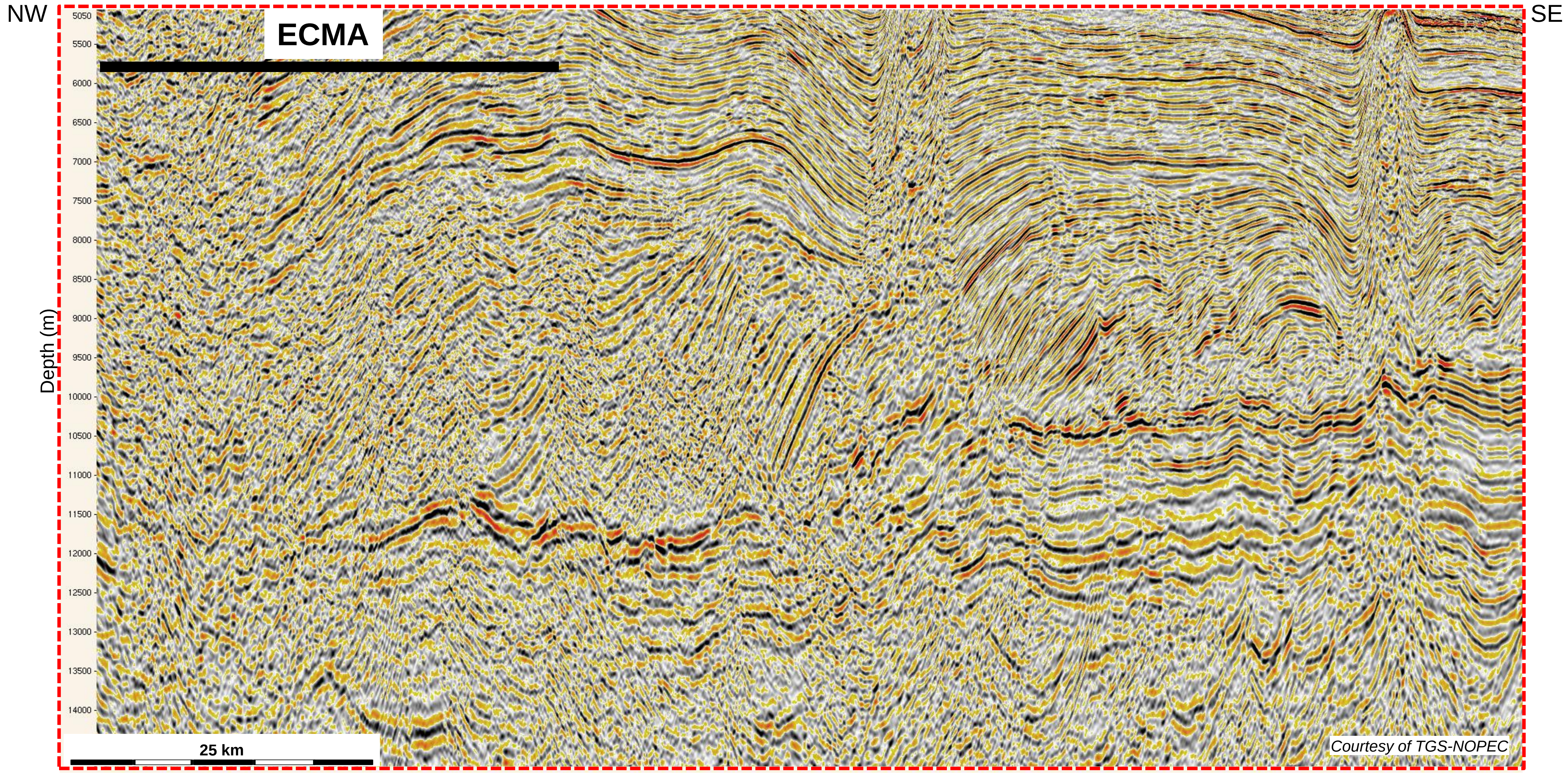


Figure 3: Seismic reflection line – TGS reprocessed 2010 – line 924-100 PSDM.

Crustal Scale Section SMART 1

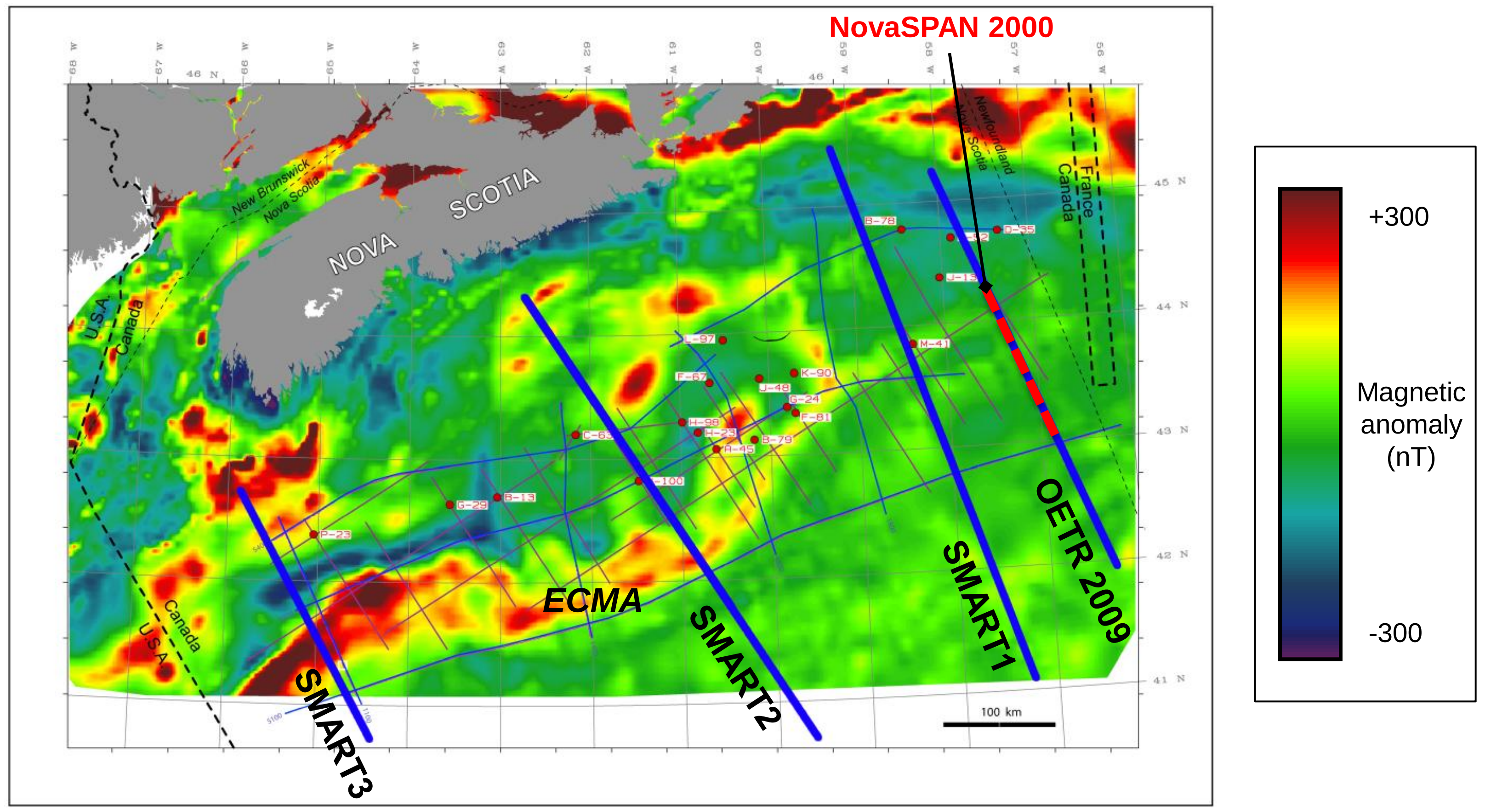


Figure 1: Location of the wide-angle seismic line on the regional magnetic anomaly map.

The 400 km long OETR 2009 OBS survey was acquired by GEOPRO from November 2nd to 28th, 2009. The survey used 100 OBS. The details of the processing an analysis are reported in the two following annexed reports:

- Refraction Seismic Survey Central Nova Scotia Margin- Canada Final Evaluation Report, (GEOPRO, May 2010); and
- VP/VS converted waves Report Central Nova Scotia Margin- Canada Evaluation and Interpretation of Converted Waves (GEOPRO, September 2010).

OETR 2009 and Smart1 are very similar and general structure and velocity units are the same in both profiles. In OETR 2009 the middle crust (Vp = 6.4) thin and is no more present at km 80. Between km 80 and km 160 the upper crust rests directly on top of lower crust. In the SE, oceanic crust is interpreted between 255-405 km distance, consisting of crustal layers 2 and 3 with a total thickness of 4-5 km. Between these two zones, there is a transitional zone (COT; 180-255 km distance) that cannot be explained by either a standard continental or oceanic crustal model.

Interpretation

The Vp model confirmed the presence of a high velocity body, with velocities in the range of ~7.2–7.5 km/s, as observed on SMART lines 1-2. The main interpreted results from Geopro are shown in Figure 4 and the underplated magmatic body was preferred to the serpentinized mantle mainly on the basis of:

1) A Vp/Vs ratio ~1.7, not in the range of generally admitted values for serpentinized mantle; and
2) A strong reflectivity and a sharp transition at the base of this layer not expected in the case of the progressive process of serpentinization .

However, interpretation of the Vp/Vs values in the anomalous bodies as implying an underplated body needs further review.

No SDRs have been observed along the reflection profile (Figure 3).

Maximum sedimentary thickness of 12 km has probably been underestimated if compared to Smart 1 and Novaspan 2000 (Figure 3) with values generally higher than 14 km.

As shown by the analysis of this profile, interpretation of the High Velocity body (Vp = 7.4) found in the transition zone is still a matter of debate and further acquisitions and analyses would be necessary to properly characterize the deep structure of the Nova Scotia margin. In this study the HVL is interpreted as being of magmatic origin as the balance of evidence supports this view.

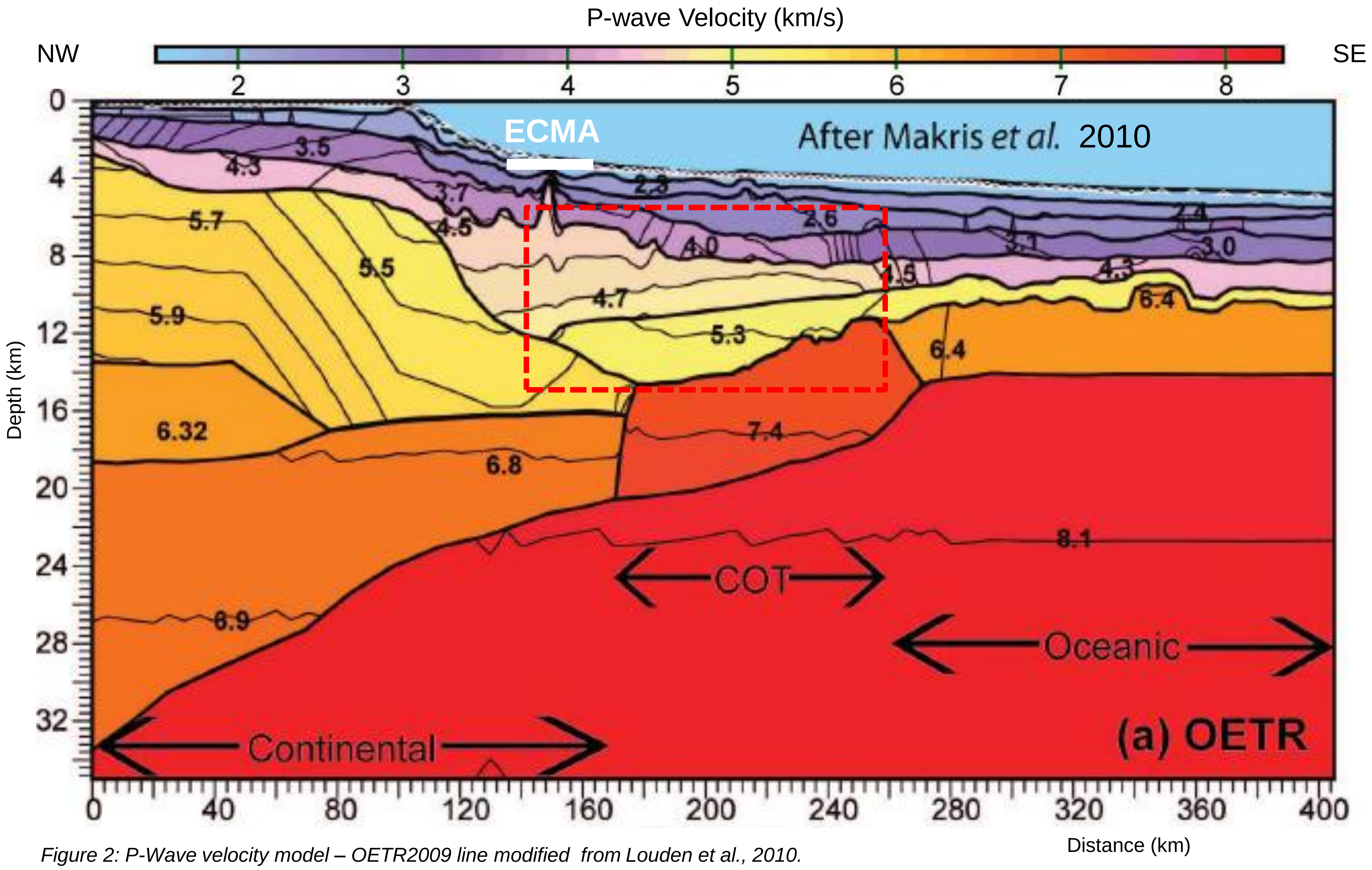


Figure 2: P-Wave velocity model – OETR2009 line modified from Louden et al., 2010.

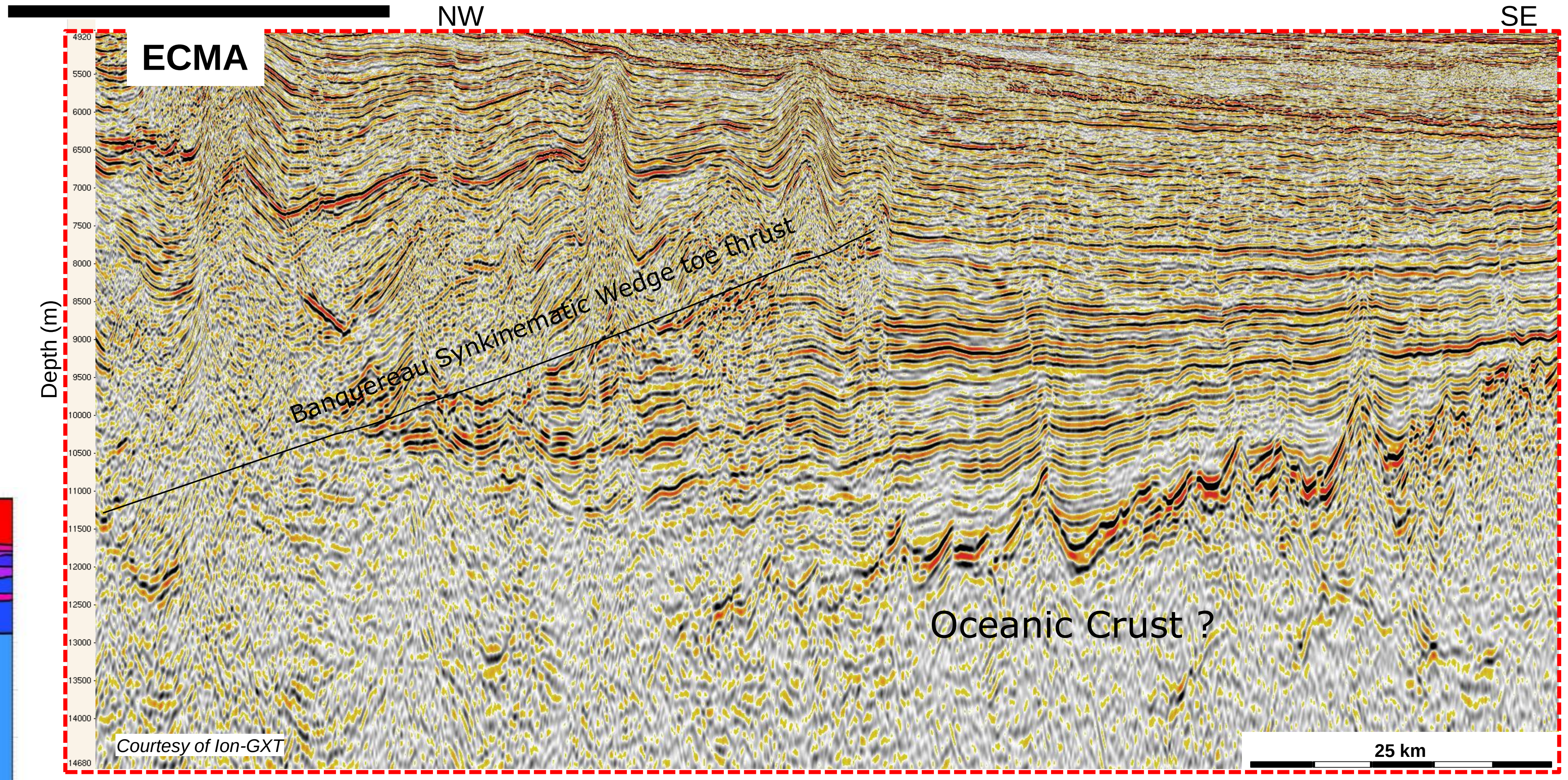


Figure 3: Seismic reflection line – NovaSPAN reprocessed 2010 – line 2000 PSDM.

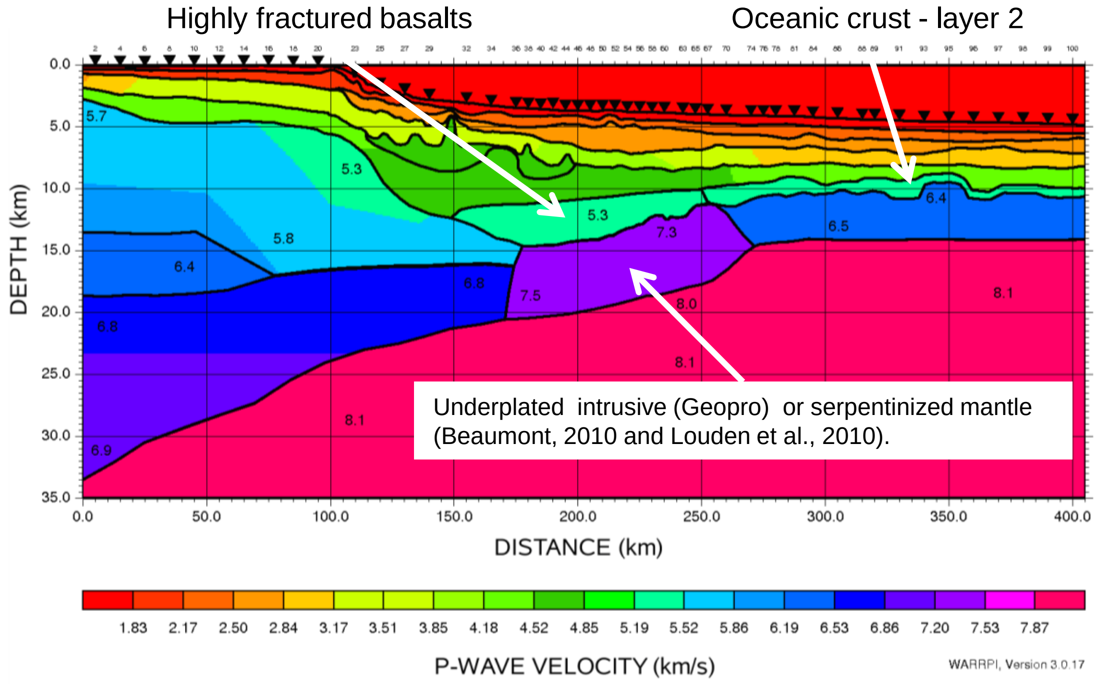


Figure 4 : P wave velocity model – OETR2009 line and main interpretative results (from Makris et al., 2010).

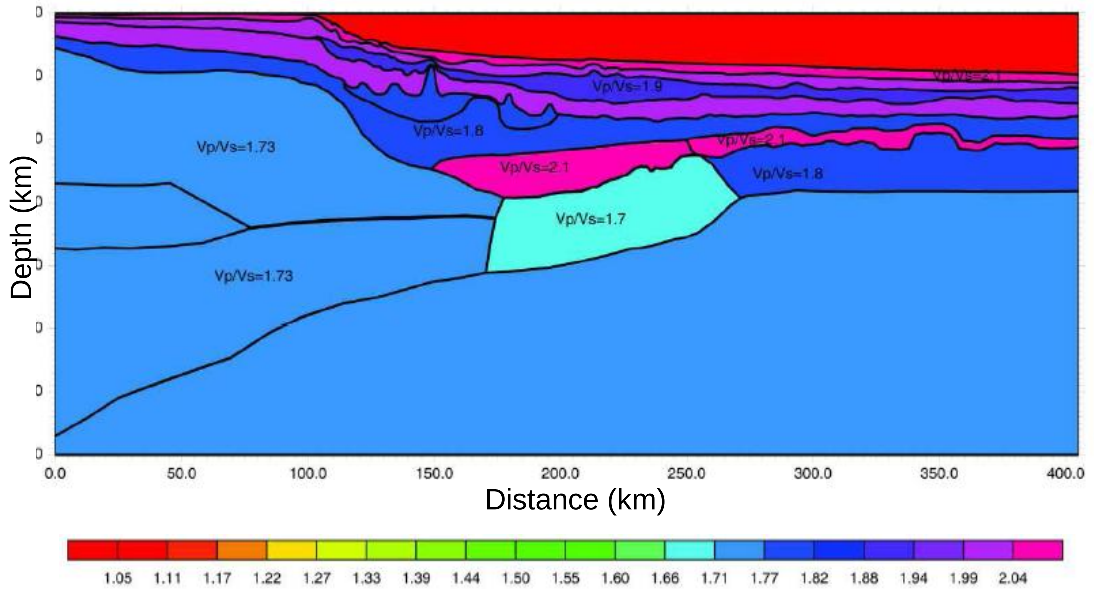


Figure 5: Vp/Vs model – OETR2009 line.

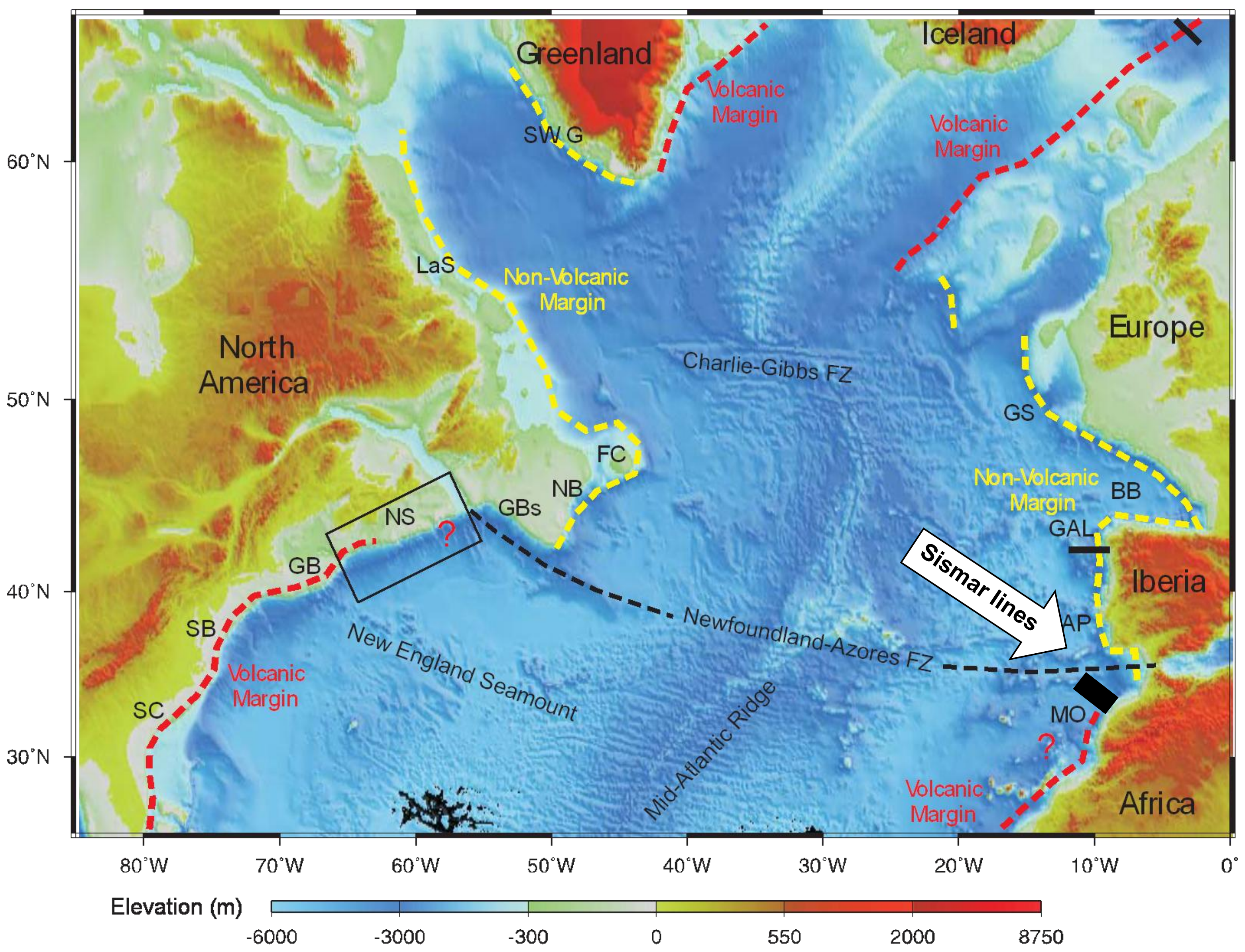


Figure 1: Central Atlantic map (modified from Louden, et al., 2010) showing Sismar lines location.

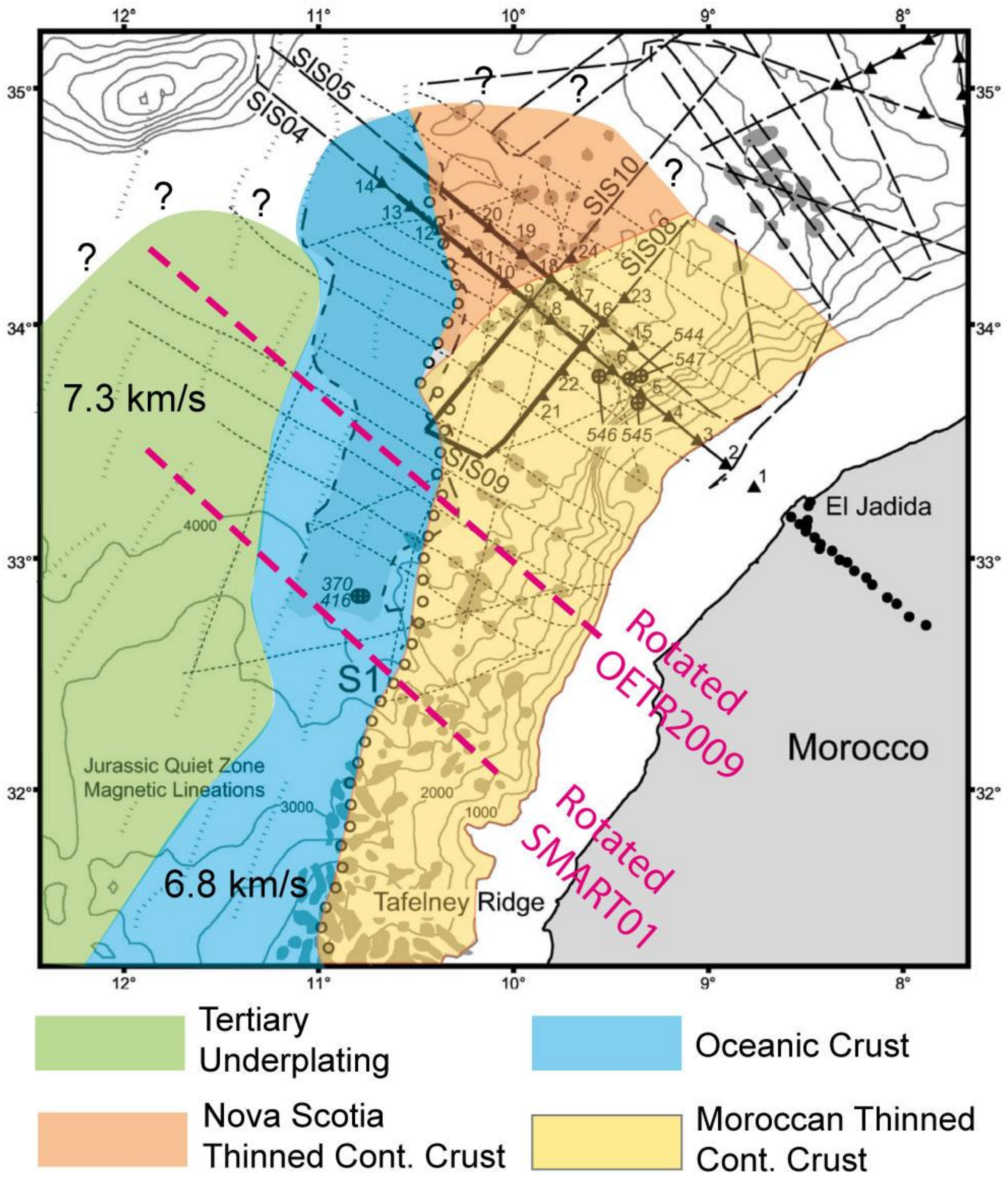


Figure 2 (from Sibuet et al., 2010): Location of Multi Channel Seismic (MCS) and wide-angle reflection and refraction SISMAR lines. Open dots underline the S1 magnetic lineation. Salt diapirs (small gray polygons) are mostly located landward of S1 (Maillard et al., 2006). DSDP holes are indicated. In light green, the extent of unusually high 7 km/s + underplated crust emplaced during Tertiary and in light blue, the oceanic crust determined from sonobuoy data (Holik et al., 1991). In light yellow, the Moroccan thinned continental crust and in light orange, the portion of transferred Nova Scotia thinned continental crust. The limit between the light orange and yellow thinned continental crusts is the western extent of the Moroccan thinned continental crust; it is constrained by the SISMAR MCS and refraction data.

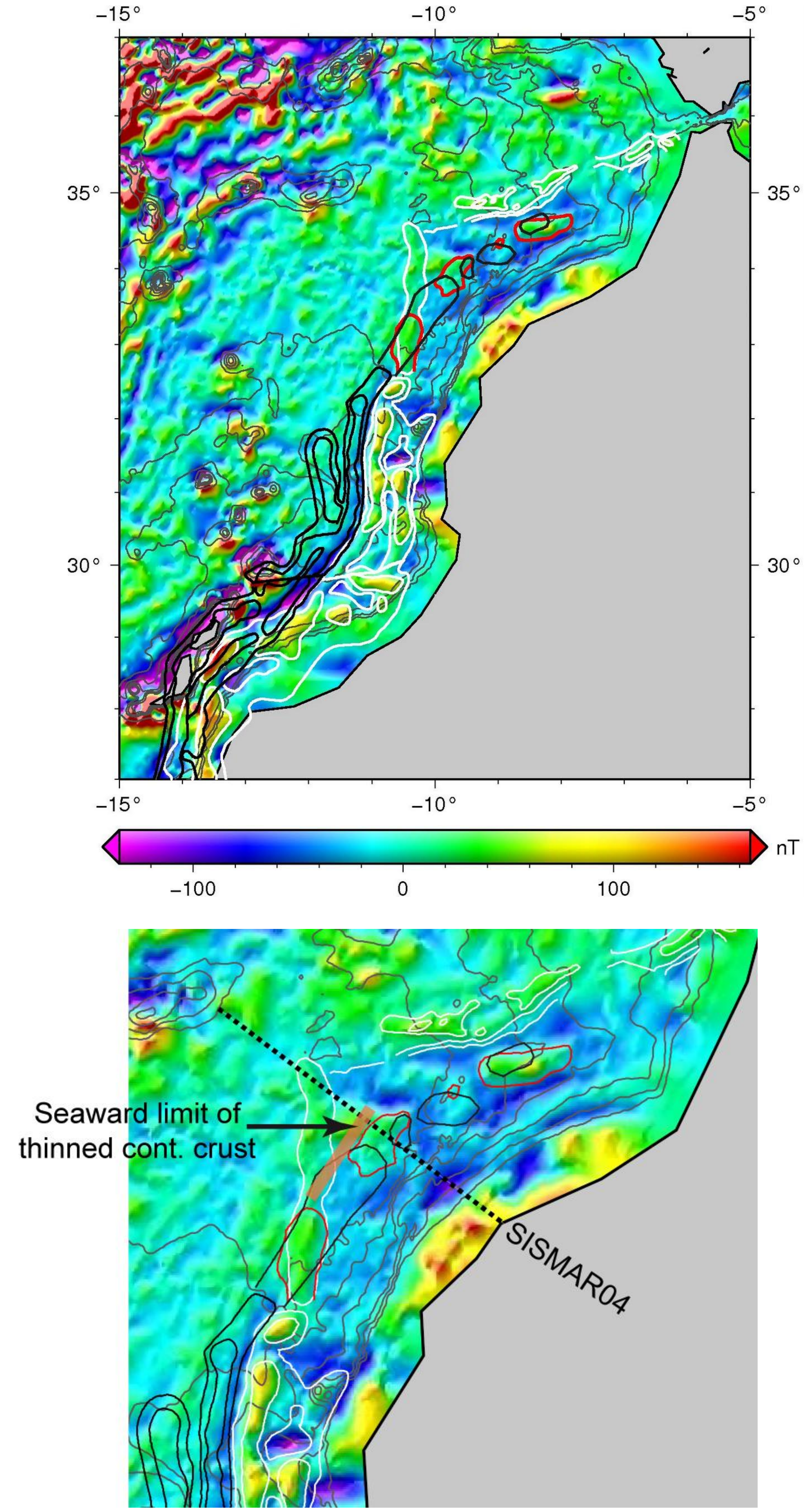


Figure 4 (from Sibuet et al., 2010): Northeastern central Atlantic magnetic anomaly map based on Verhoef (1996) data set updated by S. Dehler (personal communication, 2010) (top) and detail of the northern portion of the WACMA (bottom). In gray, bathymetric contours every km. Continuous white lines are the WACMA contoured magnetic anomalies of Sahabi et al. (2004) and Labails et al. (2010) and continuous black lines are the rotated ECMA contoured magnetic anomalies (rotations parameters of Labails et al., 2010). In white the portion of ECMA already identified by Sahabi et al. (2004) and in red what we suggest as a possible northern prolongation of the WACMA. In brown, the seaward limit of the thinned continental crust based on the results of SISMAR04 refraction line and further southwest on the emergence of a crustal detachment fault on MCS SISMAR10 line.

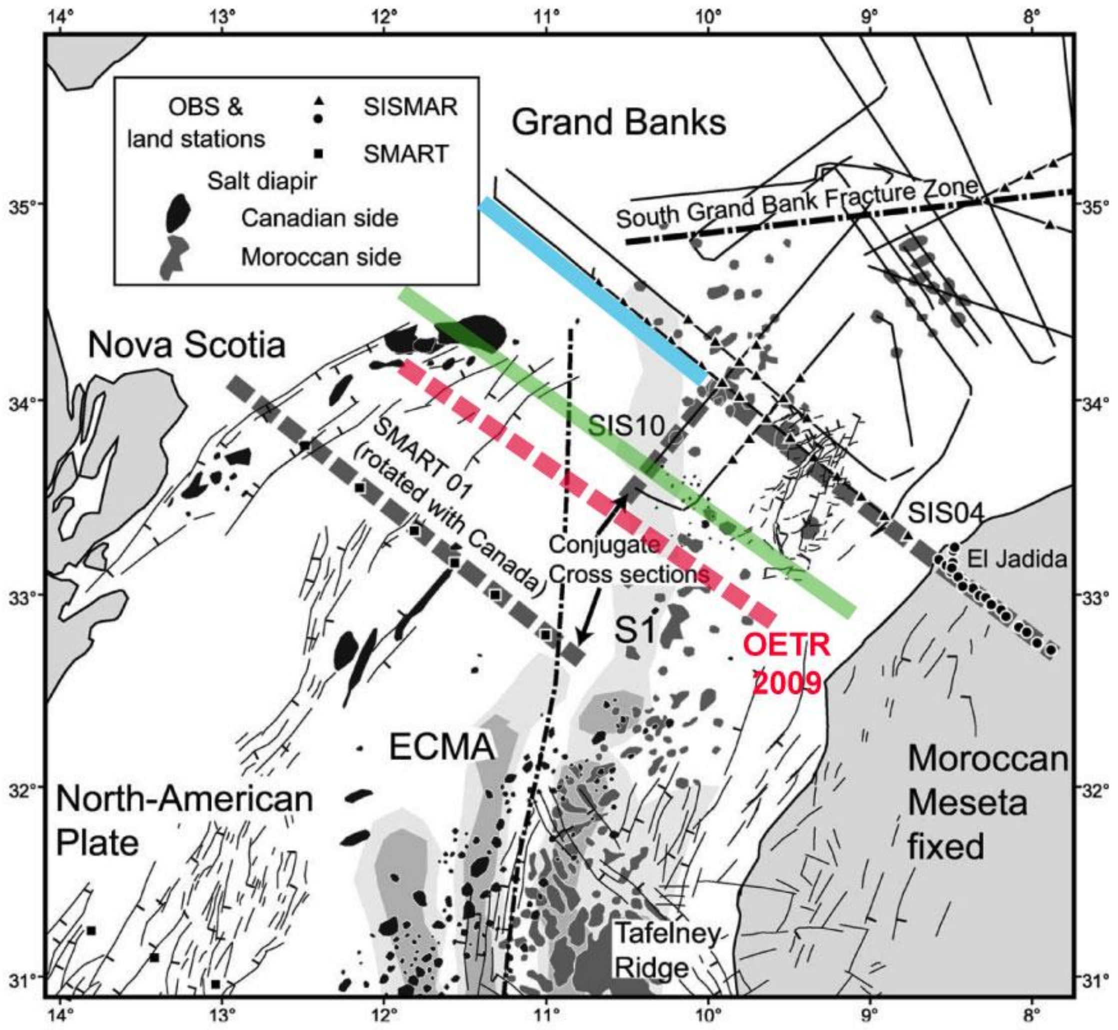


Figure 3 (from Maillard et al., 2006) in Sibuet et al., 2010: Reconstruction at the time of juxtaposition of the magnetic anomalies S1 and ECMA. The line of breakup is shown as a stippled-dashed line. SISMAR04 and SMART01 lines (black squares) and OETR2009 line (red squares) are shown. The composite profile shown in Figure 4 is built on SISMAR10. Thin continuous lines represent faults on each margin.

The re-interpretation of SISMAR04 wide-angle reflection and refraction line located in Figures 1 and 2 was presented in the SISMAR final report (July 31, 2009). The proposed interpretation of the velocity structure, which was determined by using the Korenaga code, was influenced both by the Contrucci et al. (2004) interpretation (Plate 2-9) and by the Maillard et al. (2006) interpretation of SISMAR MCS lines (Figure 3). d 09, but not on profiles SISMAR04 and 05, where only faint landward dipping crustal reflections are identified. Maillard et al., (2006) interpret the landward dipping reflectors as a detachment surface which was active during the rifting period (Figure 3). Figure 4 shows the SISMAR04-SMART01 2-D model of Maillard et al. (2006), which does not consist of true conjugate profiles, as the two conjugate sections are ~170 km apart. Assuming the lack of conjugacy is overcome by the 2 dimensionality of the conjugate margins, they proposed a rifting episode in two stages: a widespread crustal extensional stage followed by the exhumation of the lower continental crust and mantle through the play of a large detachment surface as suggested on other margins by Whitmarsh et al., (2001). However, the crucial ingredient of the model (the detachment fault) is not representative of the two conjugate sections, as it is located in between and does not correspond to what is observed on the SISMAR04 profile. We will look in detail at both the interpretation of the SISMAR MCS lines and the new interpretation of the SISMAR04 velocity structure to demonstrate that the detachment model cannot apply to the SISMAR04 profile.

Conjugate Moroccan Margin (Sibuet et al., 2010)

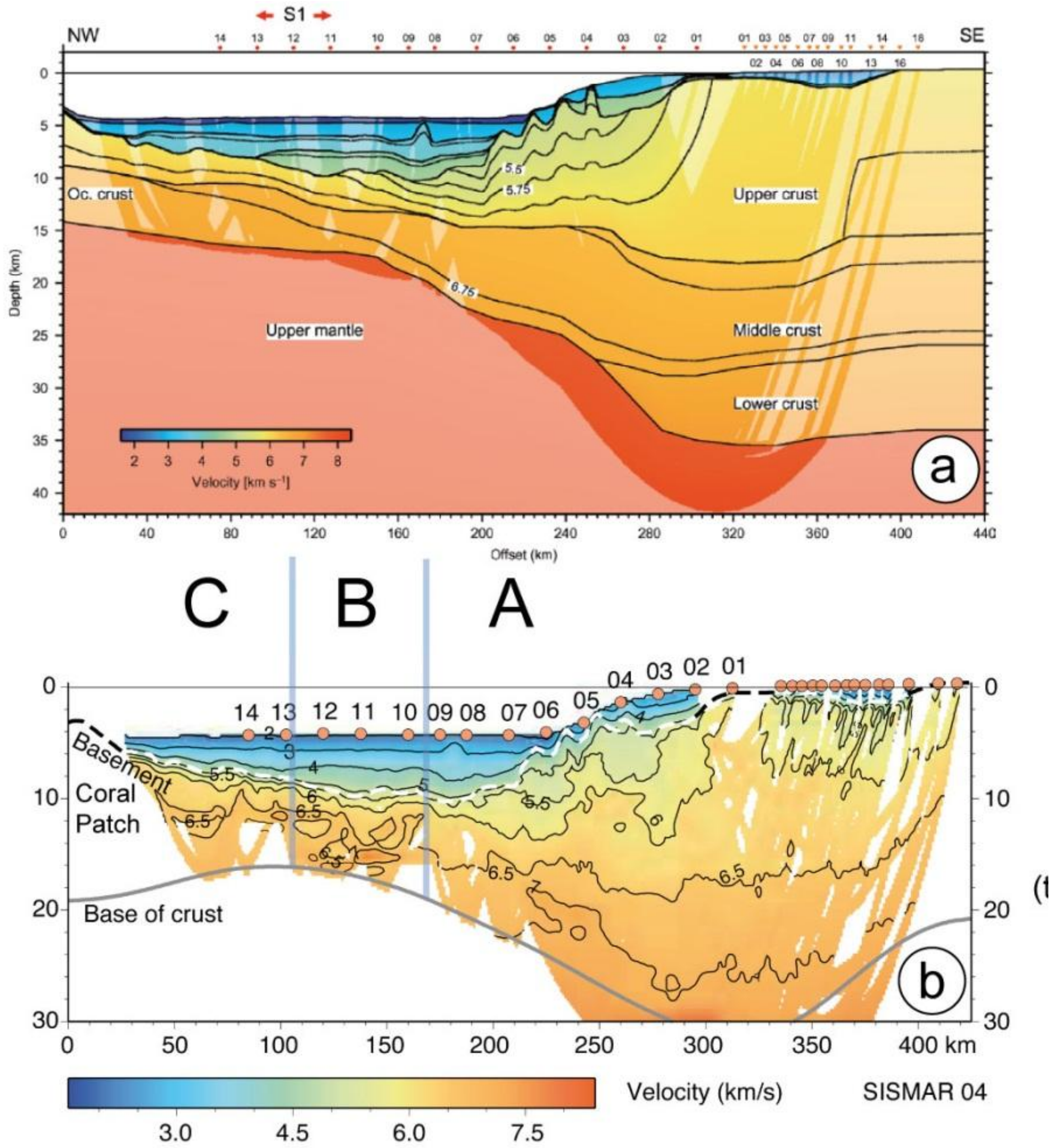
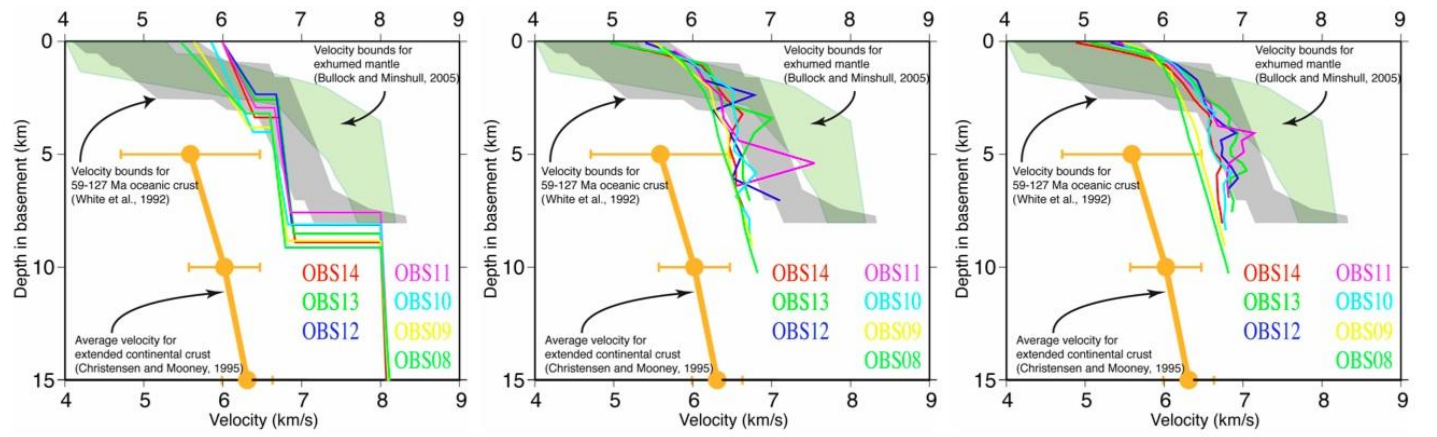


Figure 1: Comparison between the Contrucci et al. (2004) velocity model (a) and the tomographic model (b)(Korenaga code), with similar color scale and iso-value contours for proper comparison. Note that between OBH09 and OBH10, there is a sharp boundary between the Moroccan thinned continental crust and a thinned continental crust intruded by volcanics that we interpret as transferred from the Nova Scotia margin.



a) SISMAR velocity model for the transitional crust (Zelt code)

b) SISMAR velocity model for the transitional crust (Korenaga code)

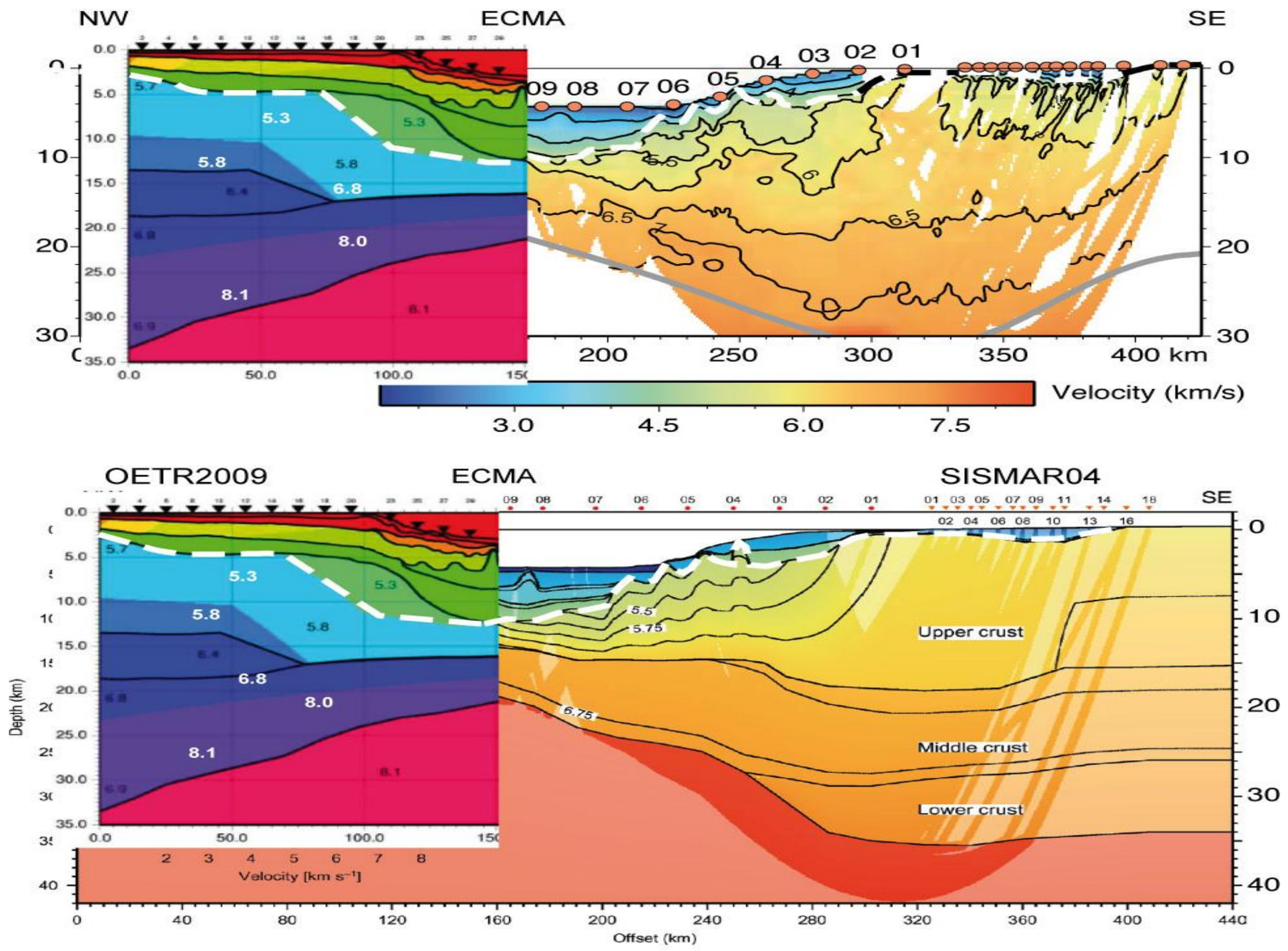
c) SISMAR velocity model for the transitional crust (Korenaga code) (detailed model)

Figure 2: 1-D vertical velocity profiles below each OBH (continuous curves of various colors) when using the Zelt and Korenaga codes: close-up for vertical profiles OBH08 to OBH14. The vertical axis indicates the depth below the top-basement, defined on the coincident MCS profile. The thick orange line with error bars is the average velocity profile in extended continental crust (Christensen and Mooney, 1995). The gray and green shaded areas are the envelops of 1-D velocity profiles in 60-to-130 Ma oceanic crust (White et al., 1992) and in exhumed mantle (Bullock and Minshull, 2005), respectively.

The SISMAR04 line can be considered as representative of the Moroccan margin only for the portion of margin located east of OBH09-10, comprising the Moroccan continental and thinned continental crusts. The OBH10-12 portion of the profile (Domain B) probably consists of a portion of Nova Scotia thinned continental crust intruded by volcanics and transferred to the Moroccan side at the time of ECMA emplacement (190 Ma) (Figure 1b). The OBH13-14 portion of the profile and westward (Domain C) consists of an abnormally thick oceanic crust.

Figure 3a shows the OETR2009 and SISMAR04 conjugate profiles at the end of the rifting episode (ECMA, 190 Ma). Figure 3b shows the same OETR2009 and SISMAR04 conjugate profiles at 170 Ma (Bajocian). In light blue, we have superposed a 6.5-7 km thick oceanic crust identified further south on Holik et al. (1991) data on top of Domain B of SISMAR04 profile interpreted as Nova Scotia thinned continental crust intruded by volcanics, with possible underplating (OBH10 to 12) and oceanic crust (OBH13 and 14).

A slight asymmetry can be observed in the conjugate crustal profile with a slightly steeper dip of the Moho on the Moroccan margin. However, present day comparison should be taken with caution since the two margins suffered distinct evolution during Tertiary time with a continuous passive evolution on the Canadian side and a compressional event on the Moroccan continent.



OETR2009 and SISMAR04 conjugate profiles at 190 Ma (ECMA): juxtaposition of thinned continental crusts

Figure 3a:

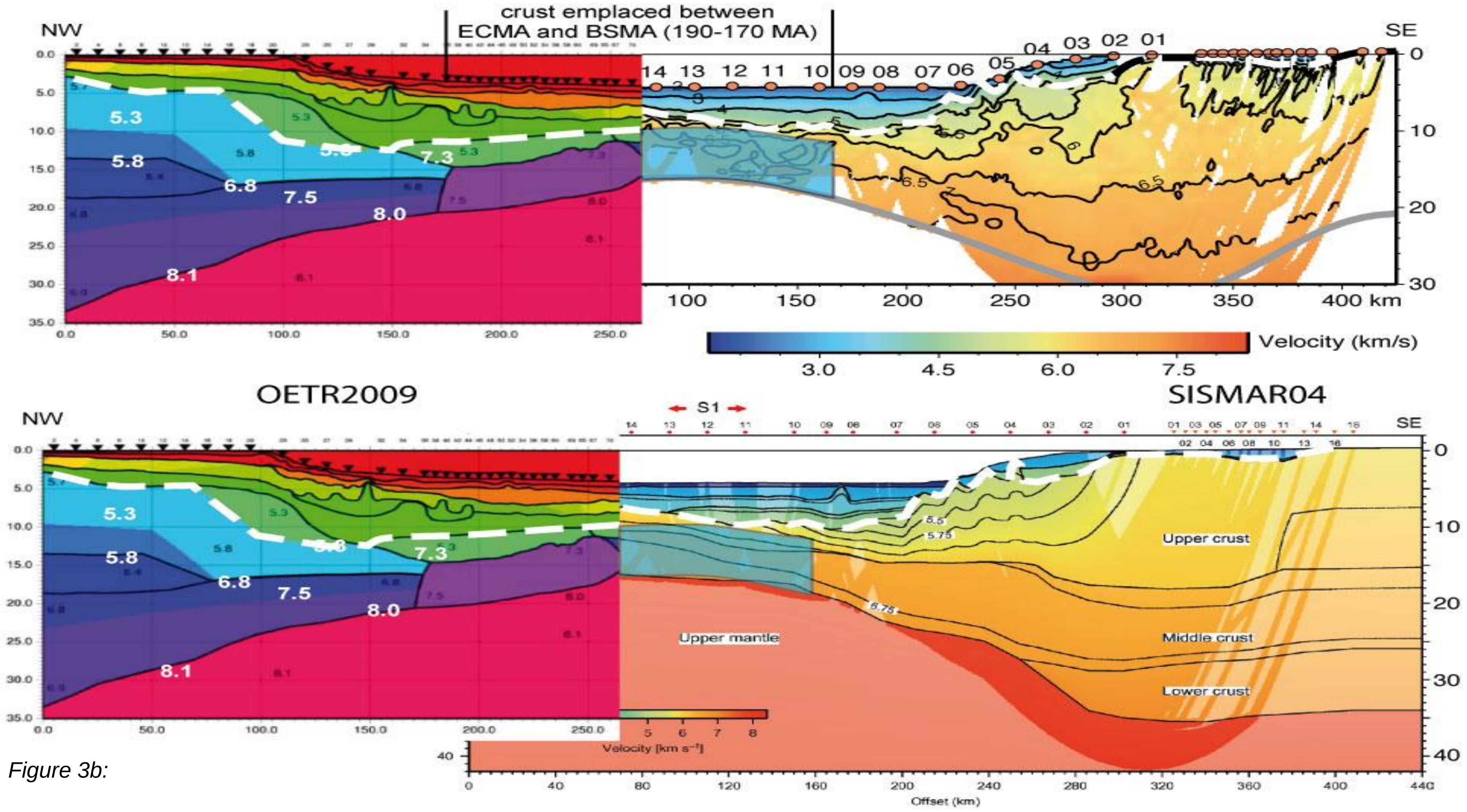


Figure 3b:

OETR2009 and SISMAR04 conjugate profiles (Early Middle Jurassic)

Conjugate Moroccan Margin (Sibuet et al.; 2010)

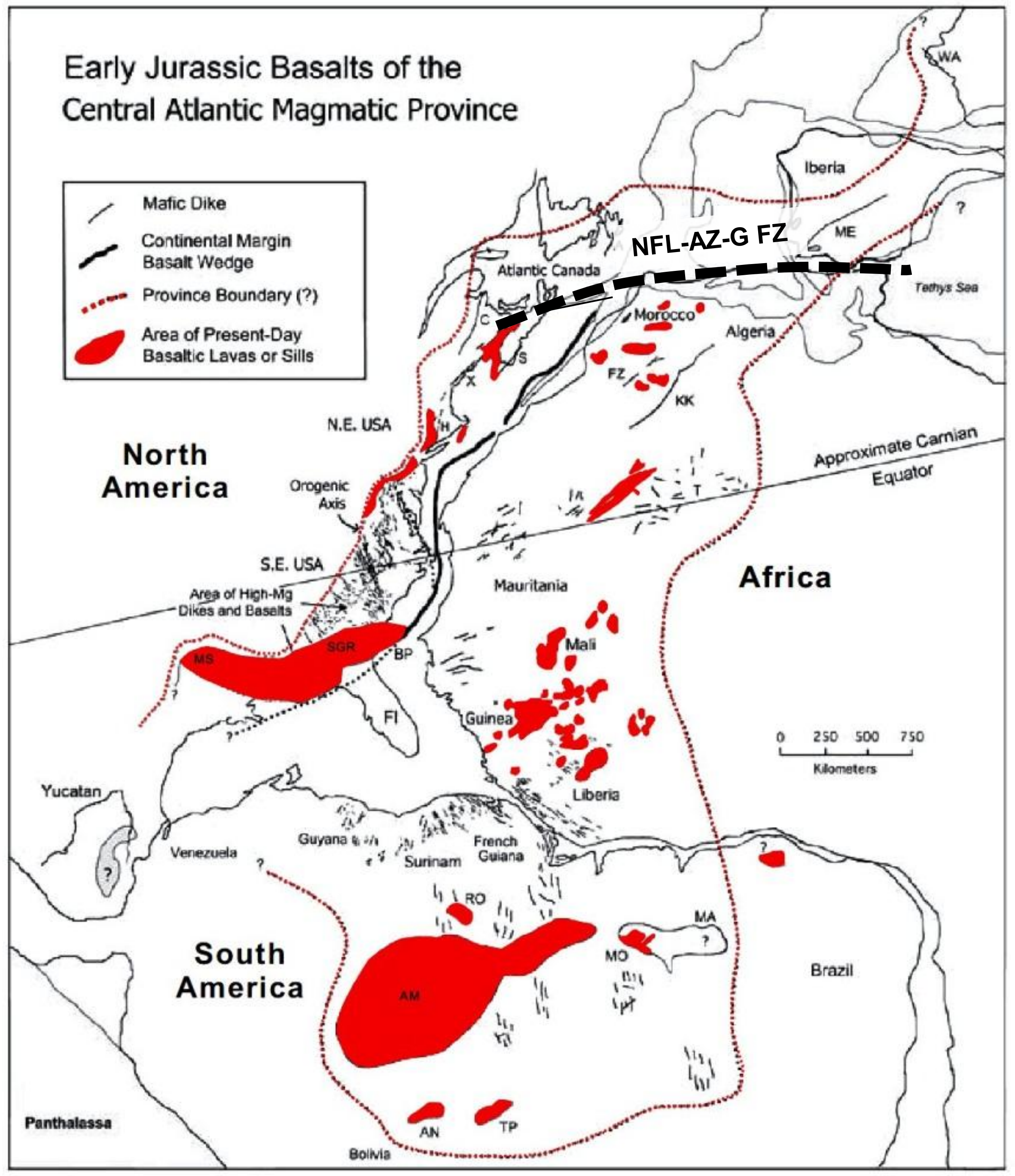


Figure 1 (modified from Louden et al., 2010): Mesozoic volcanism in the Central Atlantic Magmatic Province (CAMP). The base map is the pre-Atlantic reconstruction modified from Klitgord and Schouten (1986). Mesozoic volcanism is mainly developed south of Newfoundland–Azores-Gibraltar fault zone. (See detailed legend in Louden et al., 2010).

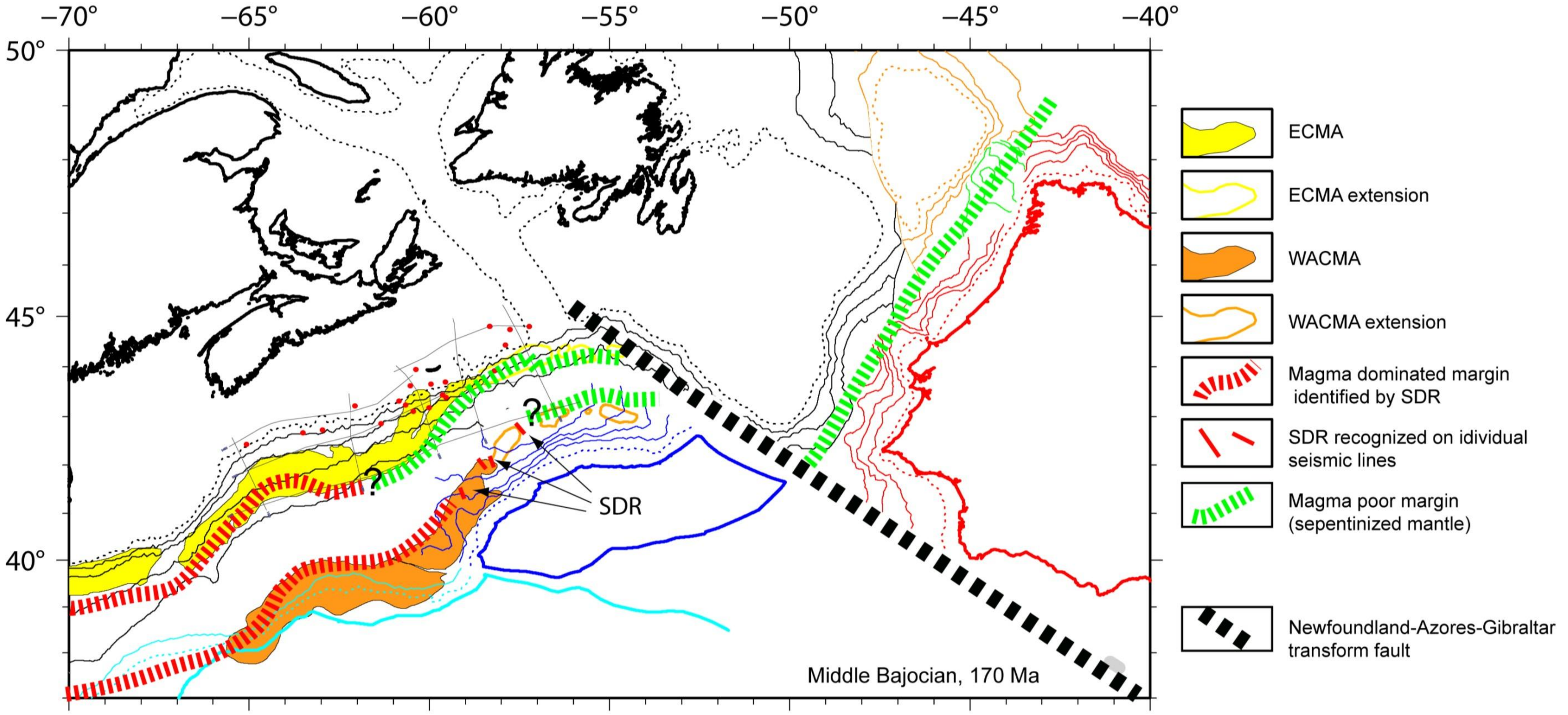


Figure 2: Interpretation 1: Composite type of margin combining magma dominated (red) and magma poor (green) at Middle Bajocian plate reconstruction stage. Such a complex combination implies a longitudinal transition along the Scotian margin. The Newfoundland-Azores-Gibraltar transform fault separate two similar magma poor margins. Reference wells are shown as red dots. Novaspan seismic lines are shown as thin black lines.

Two main interpretations have been proposed for the Scotian Margin deep structure:

Interpretation 1: The Scotian margin is a composite margin with a typical Magma dominated segment in the southwest and a magma poor segment in the northeast. This interpretation is mainly based on lateral changes in character of the East Coast magnetic anomaly (Dehler et al., 2003) and longitudinal variations in crustal scale extension (Louden et al., 2010). In this hypothesis, the high velocity zone observed in most of the refraction lines is interpreted as serpentinized mantle. This hypothesis implies a major change in rifting and drifting mode just south of the Sable Island. It also implies a deep (1000 to 2000 m) rift basin before the onset of drifting.

Interpretation 2 (preferred interpretation): The whole Scotian margin is a magma dominated margin, as along the Atlantic coast of eastern North America. Transition to the magma poor type margin of Newfoundland occurred at the Newfoundland-Azores–Gibraltar transform. In this hypothesis, the high velocity zone observed in most of the refraction lines is interpreted as an underplated body. Changes in character of the East coast magnetic anomaly could be explained by large thickness (14 to 15 km) of sediments in the northeastern part of the margin. This hypothesis suggests strong uplift of the rift shoulders, sub aerial conditions and shallow marine environment at the end of the rifting with deposition of confined water Early Jurassic source rocks (Gammacerane biomarkers).

Distribution of volcanic provinces (Figure 1) strongly suggest a major change in thermal and extensional regime at the Newfoundland–Azores-Gibraltar transform.

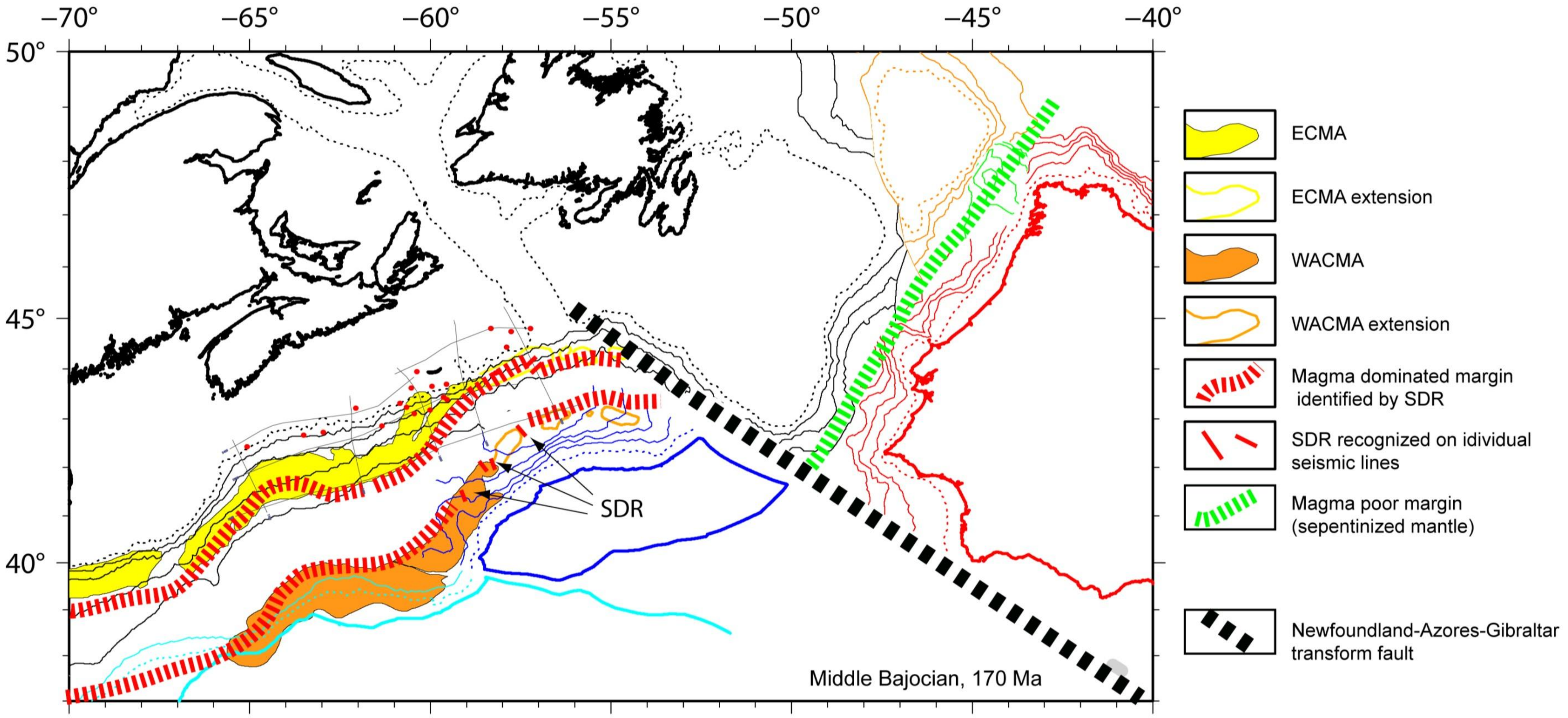


Figure 3: Interpretation 2: magma dominated (red) margin along the Nova Scotia slope (at Middle Bajocian plate reconstruction stage) and magma poor (green) between Newfoundland and Iberia. The Newfoundland-Azores-Gibraltar transform fault constitutes the main limit of the two provinces. Reference wells are shown as red dots. Novaspan seismic lines are shown as thin black lines.

PLATE TECTONICS

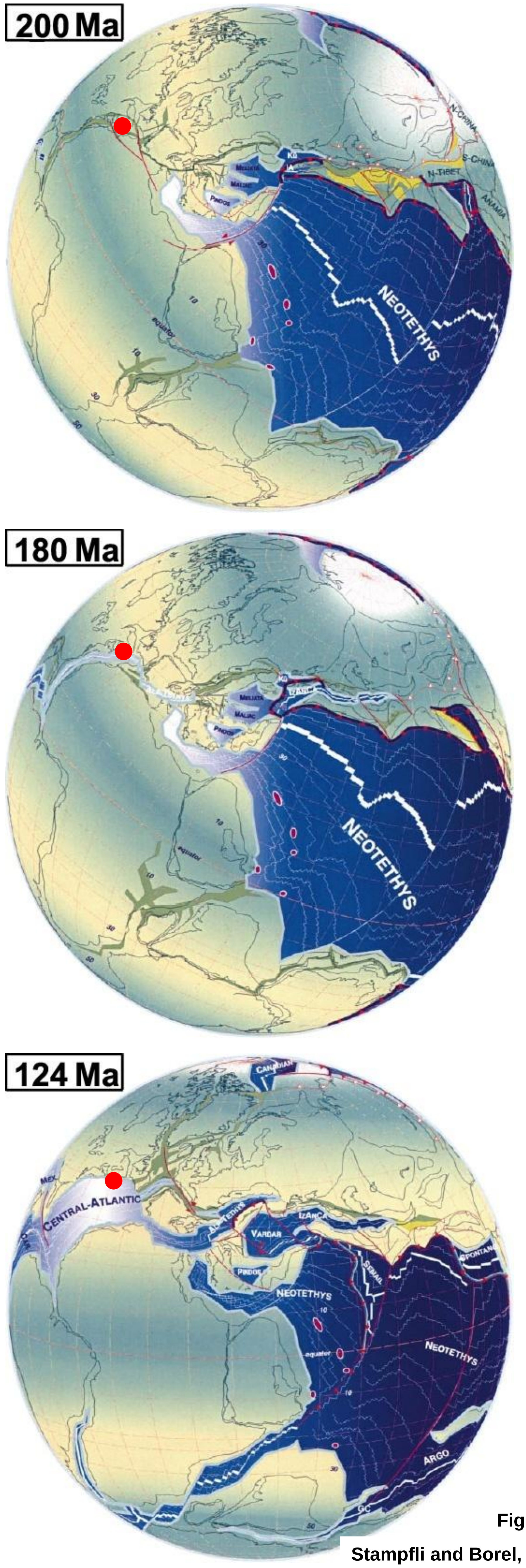


Figure 1

Stampfli and Borel, 2002

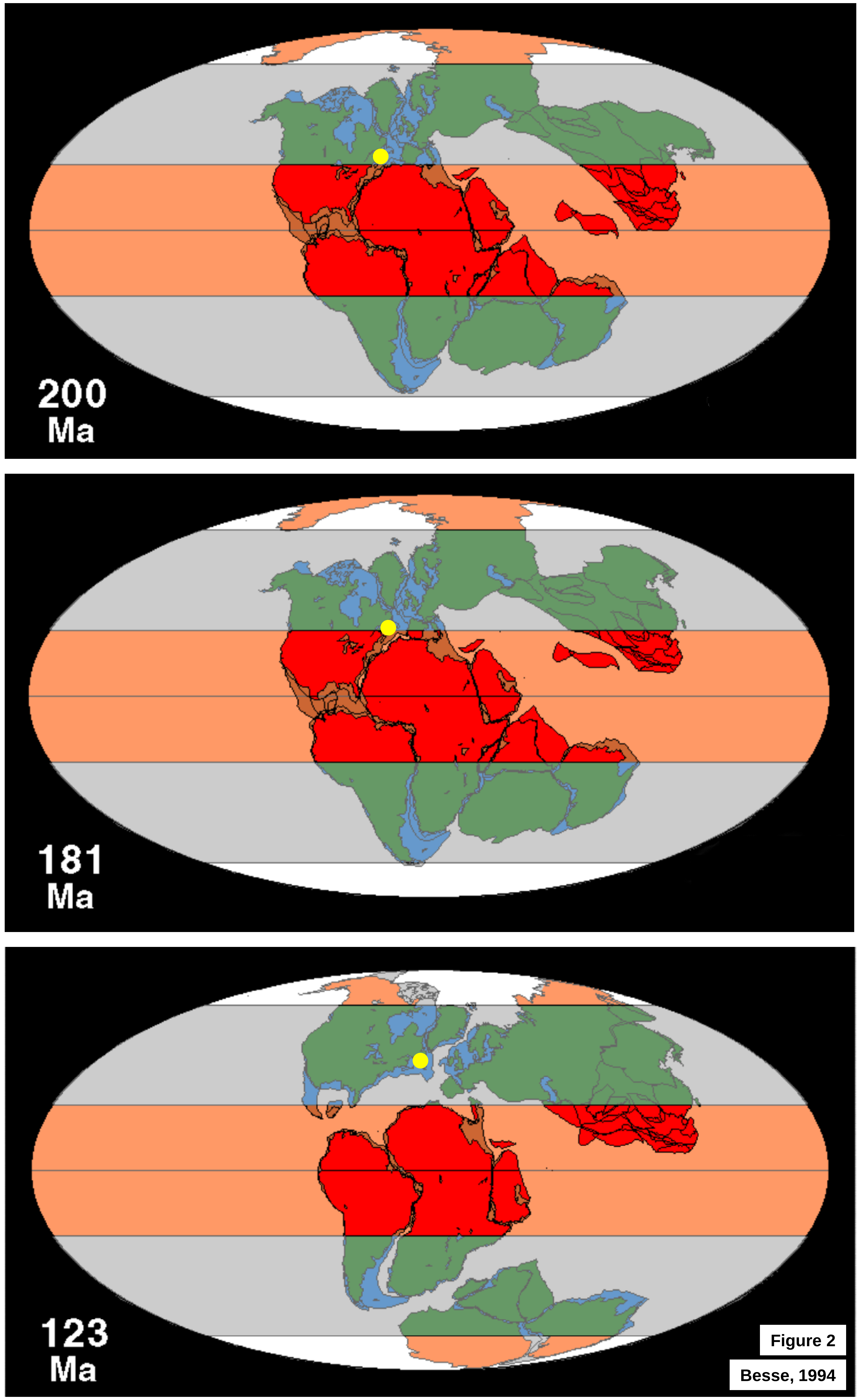


Figure 2

Besse, 1994

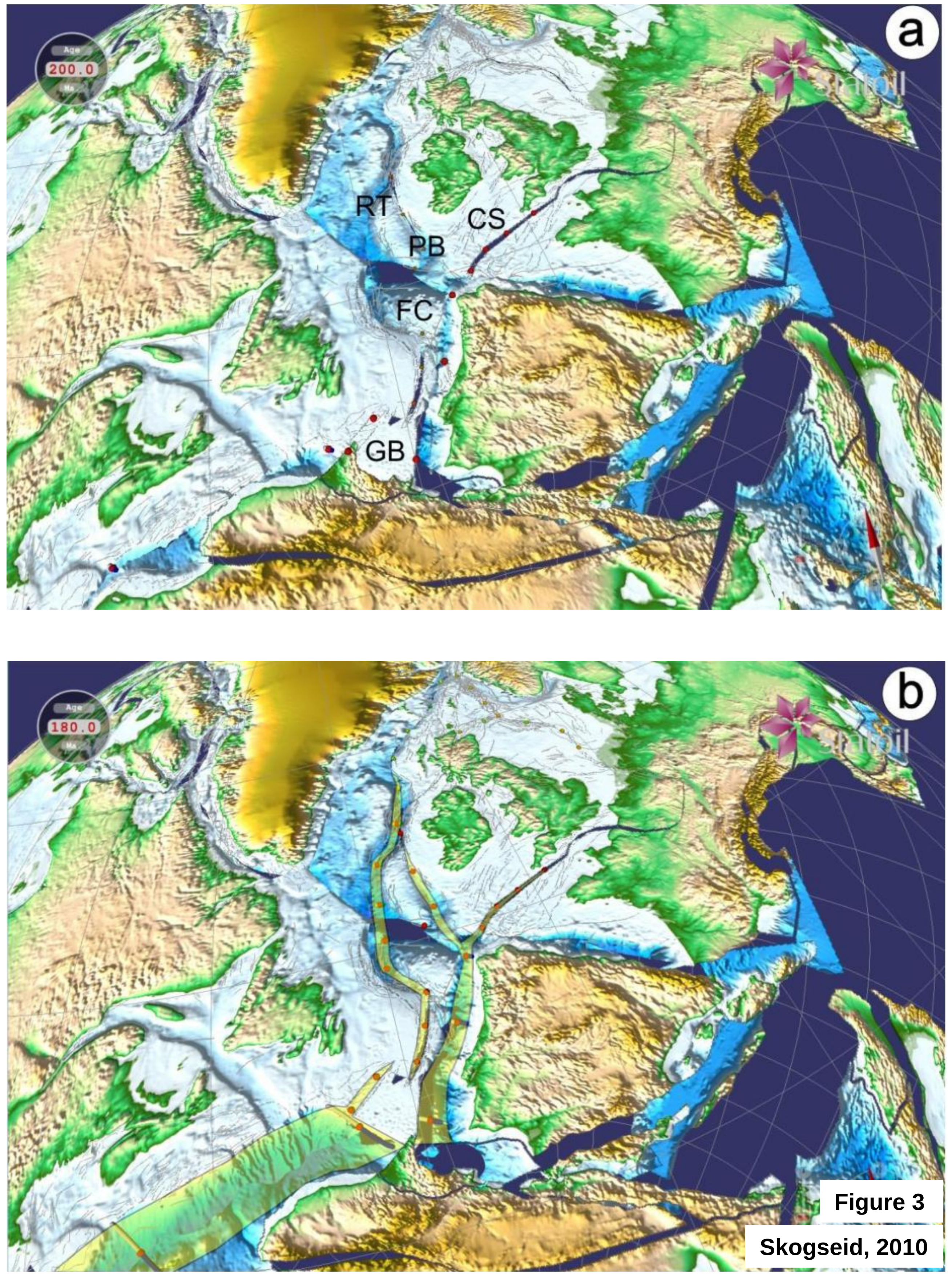


Figure 3

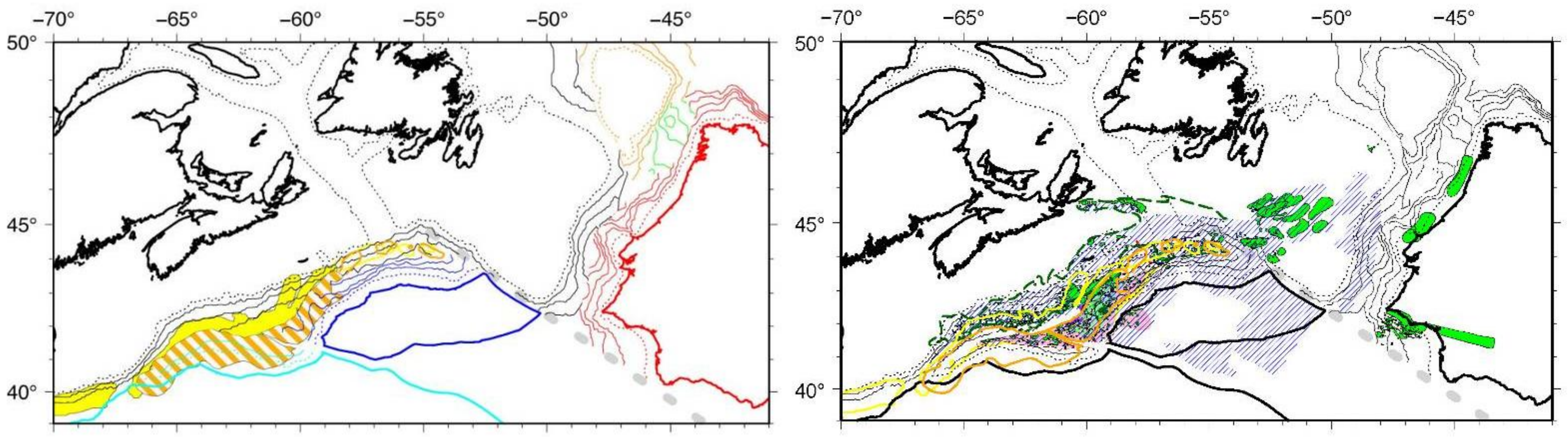
Skogseid, 2010

Figure 3: Plate kinematic model of the North Atlantic a) 200 Ma configuration between North America and Africa/Iberia/Eurasia, and b) 180 Ma early basin formation establishing a system of distributed and overlapping rift zones in the northeastern Atlantic and open marine domain between Morocco and Nova Scotia. Total magnitude of extension along rift zones is shown by yellow shading. GB: Grand Banks; CS: Celtic Sea; FC: Flemish Cap; RT: Rockall Trough; PB: Porcupine Basin (Skogseid, 2010).

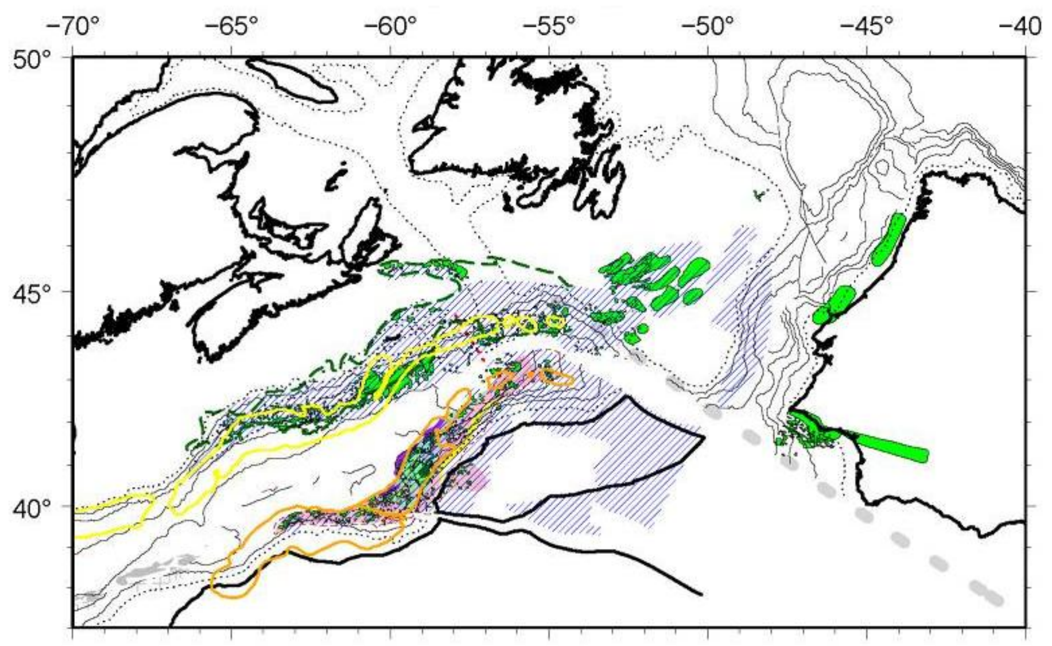
Figure 1: Paleogeographic reconstructions at Triassic-Jurassic boundary ca. 200 Ma, Early Middle Jurassic ca. 180 Ma and Aptian ca. 124 Ma (Stampfli & Borel, 2002).

Figure 2: Paleogeographic reconstructions at Triassic-Jurassic boundary (200 Ma), Early Middle Jurassic (181 Ma) and Aptian (123 Ma) showing the progressive Nova Scotia migration from tropical latitudes during Jurassic times to higher latitudes during Cretaceous times (Besse, 1994).

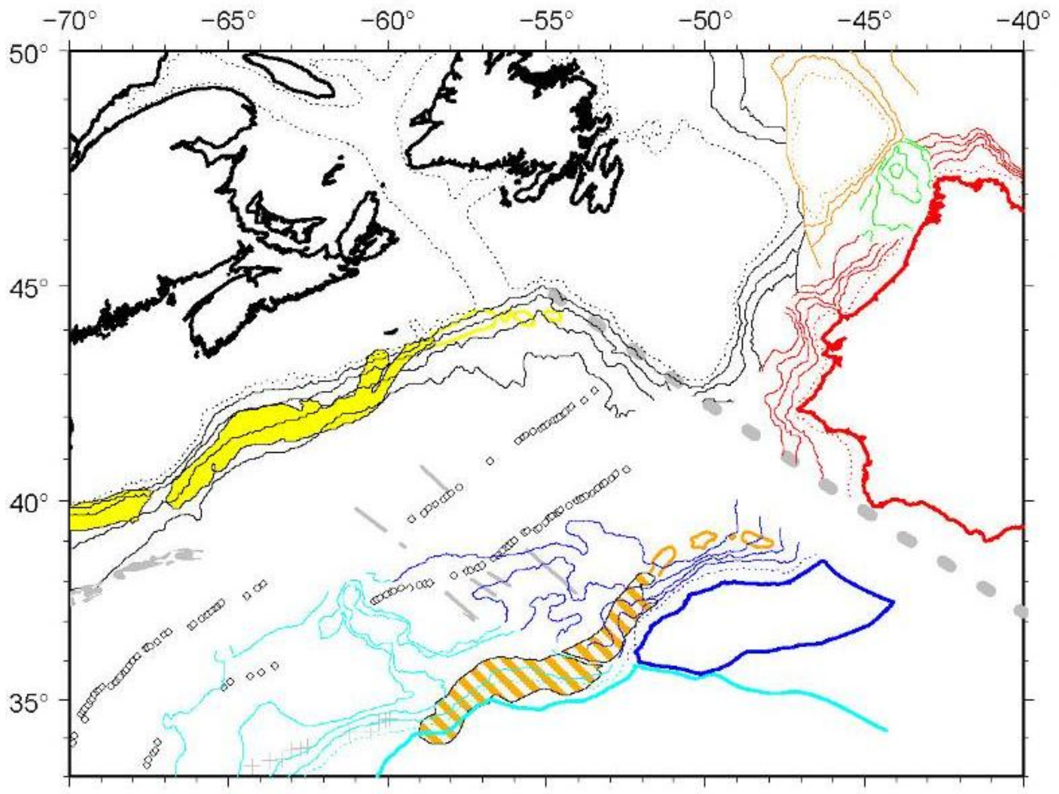
Plate Kinematic Reconstruction between 200 Ma (Triassic-Jurassic) and 124 Ma (Aptian)



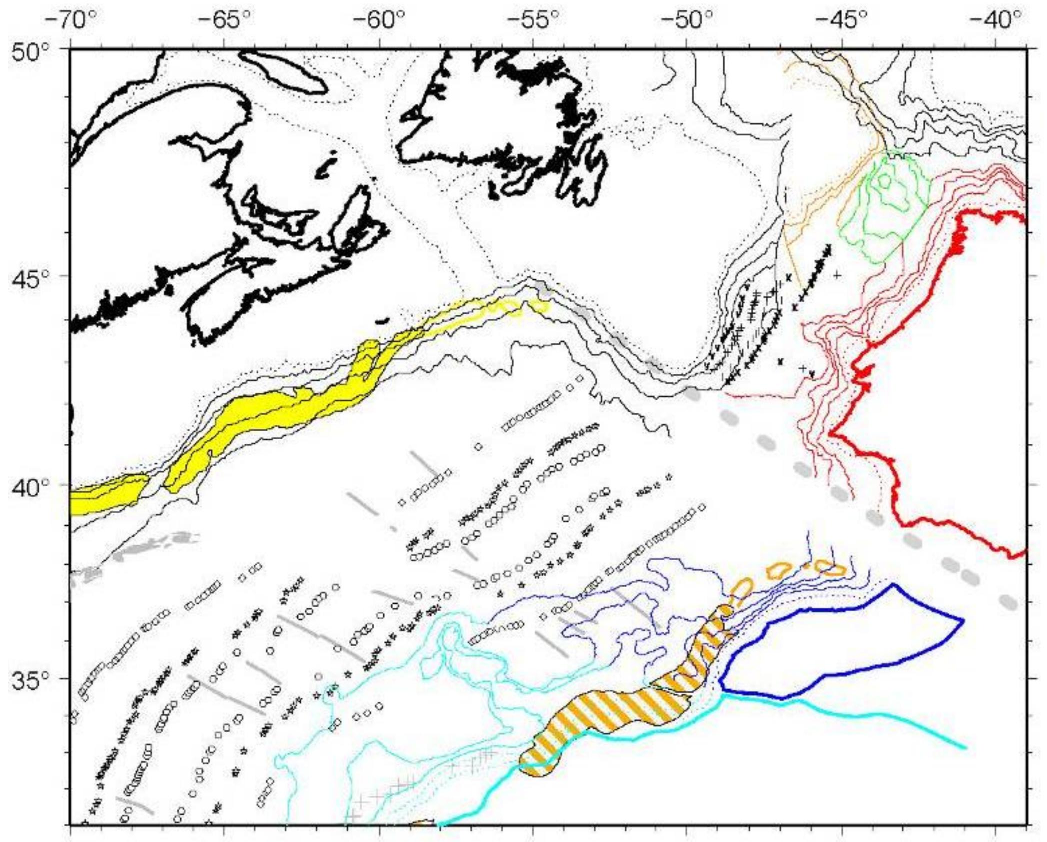
Kinematic reconstruction at chron ECMA (Sinemurian/Pliensbachian limit, 190 Ma).



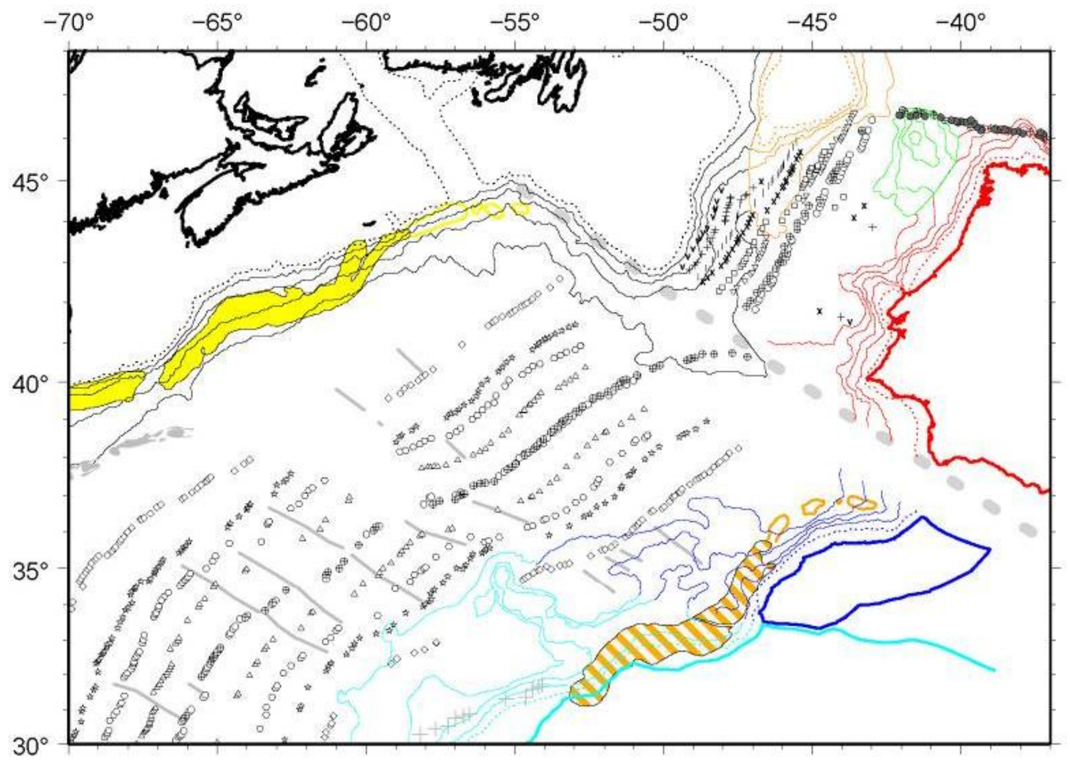
Kinematic reconstruction at chron BSMA (Middle Bajocian, 170 Ma).



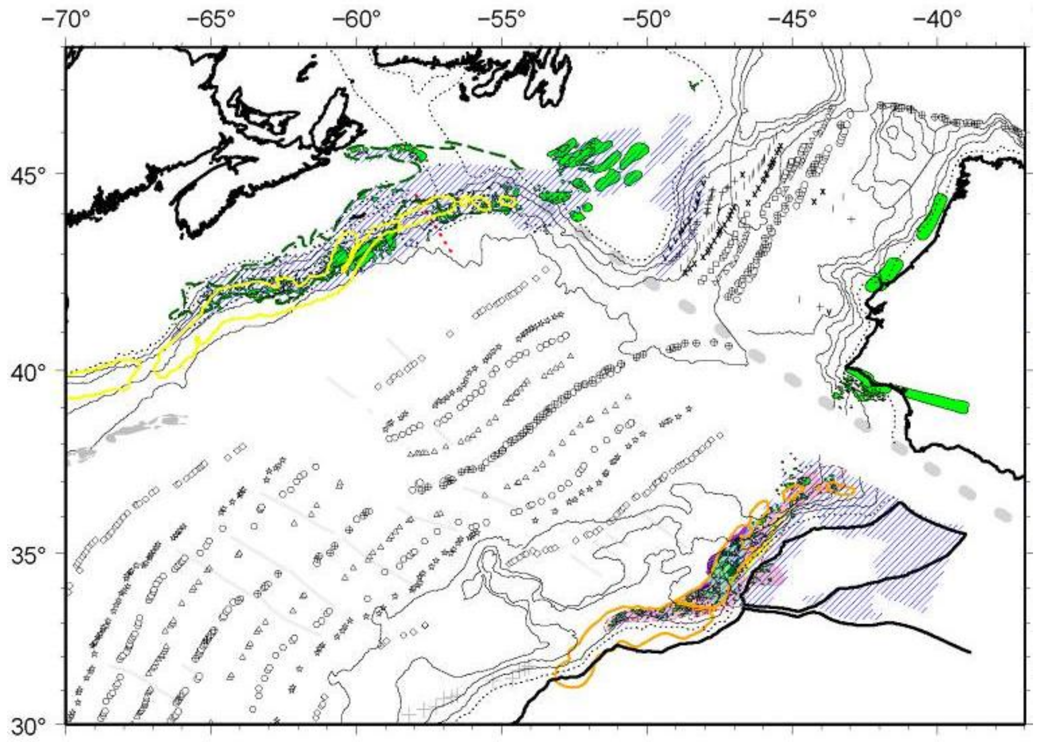
Kinematic reconstruction at chron M22 (Middle Tithonian, 150 Ma).



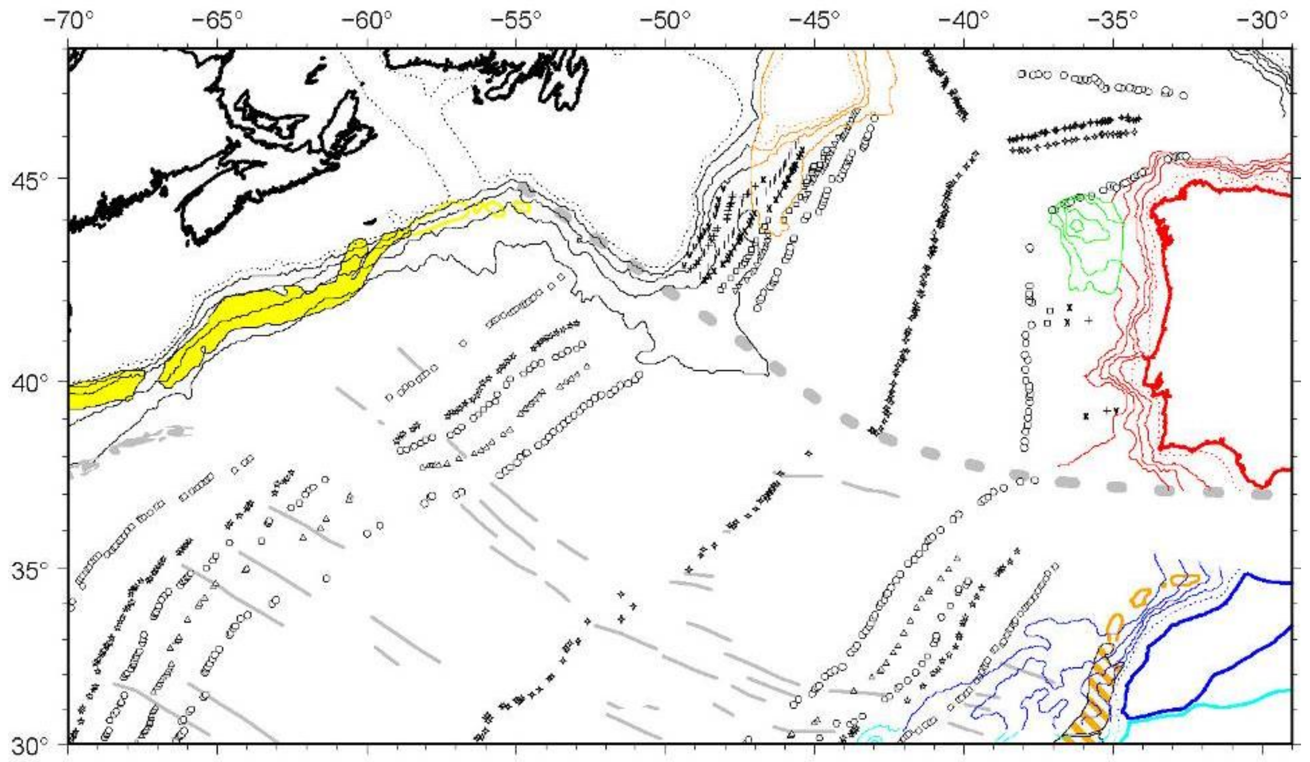
Kinematic reconstruction at chron M11 (Middle Valanginian, 136 Ma).



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).

- 🟨 ECMA
- ☐ ECMA extension
- ▨ WACMA
- ☐ WACMA extension
- ▨ BSMA
- + African equiv. to BSMA
- ○ M25
- ∗ M21
- ▾ M20
- + M17
- ○ M16
- ı M15
- × M11
- △ M10n
- ○ M4
- ▿ M3
- ○ ⊕ ● M0

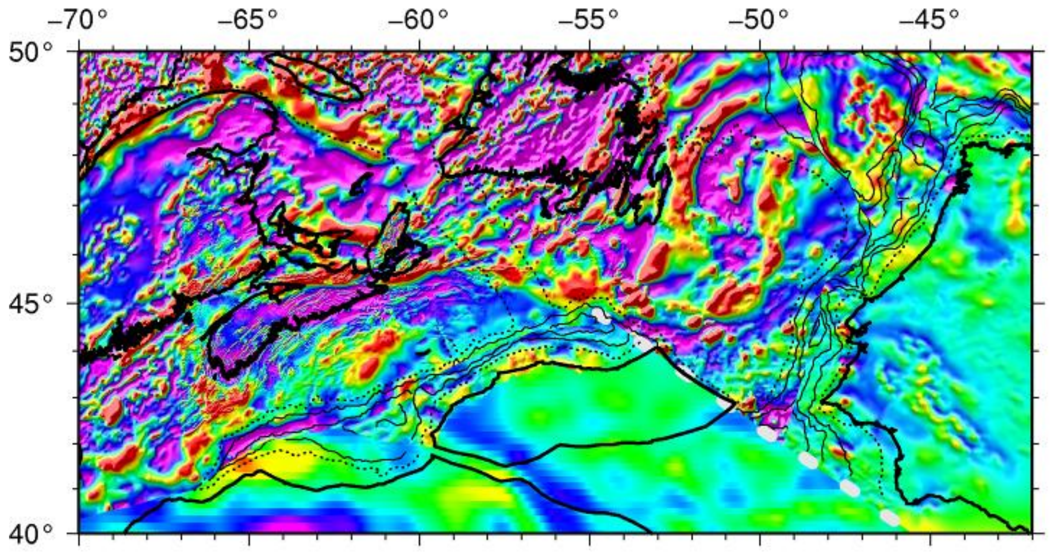
North America

- 🟩 Outlines of salt structures (Beicip, Davison, Edwards, Wade et McLean)
- ▨ Extent of halite (Labails)
- ☐ Autochtonous salt (Albertz)
- ☐ Salt and fault (Beicip, preliminary)

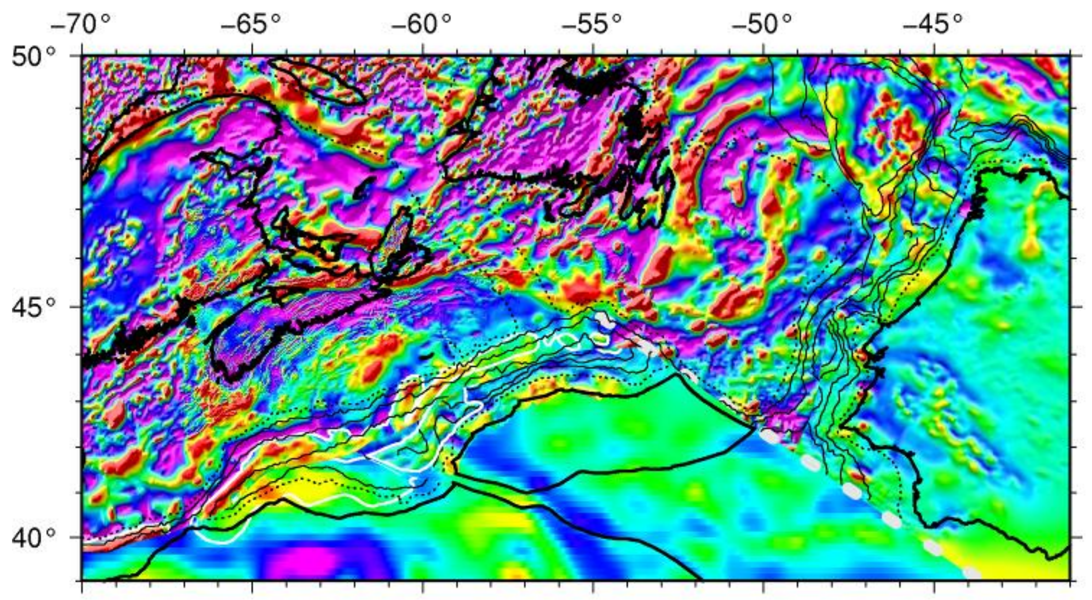
Africa, Meseta and Iberia

- 🟩 Outlines of salt structures (Tari & Molnar, Maillard, Davison, Matias)
- 🟨 Rafts and isolated diapirs (T&M)
- 🟥 Diapiric salt and turtle structures (T&M)
- 🟦 Canopy salt (T&M)
- 🟪 Toe-thrust zone (T&M)
- 🟩 Allochtonous salt (Hafid)
- 🟩 Salt pillow (Hafid)
- ▨ Extent of halite (Labails)
- ☐ Extent of halite (Nemcok)

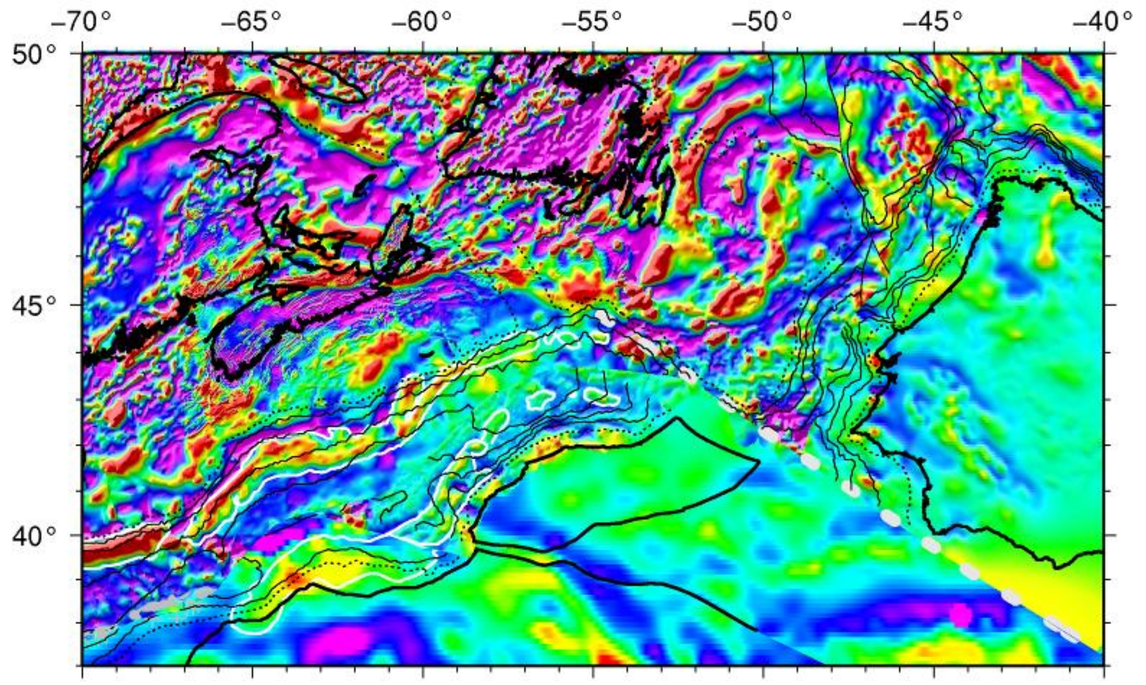
Kinematic reconstruction: Isochron magnetic anomaly maps (Sibuet et al., 2010)



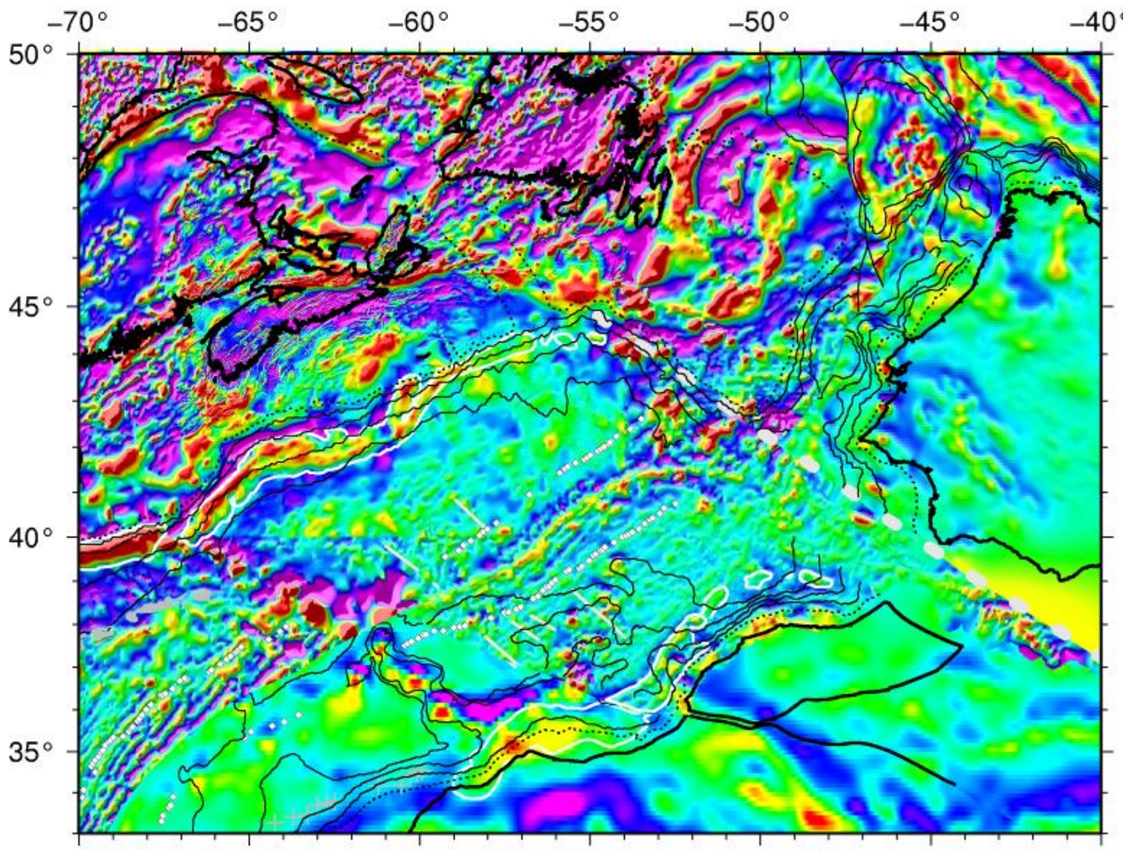
Magnetic anomaly map on kinematic reconstruction at the Norian/Rhaetian limit (203 Ma).



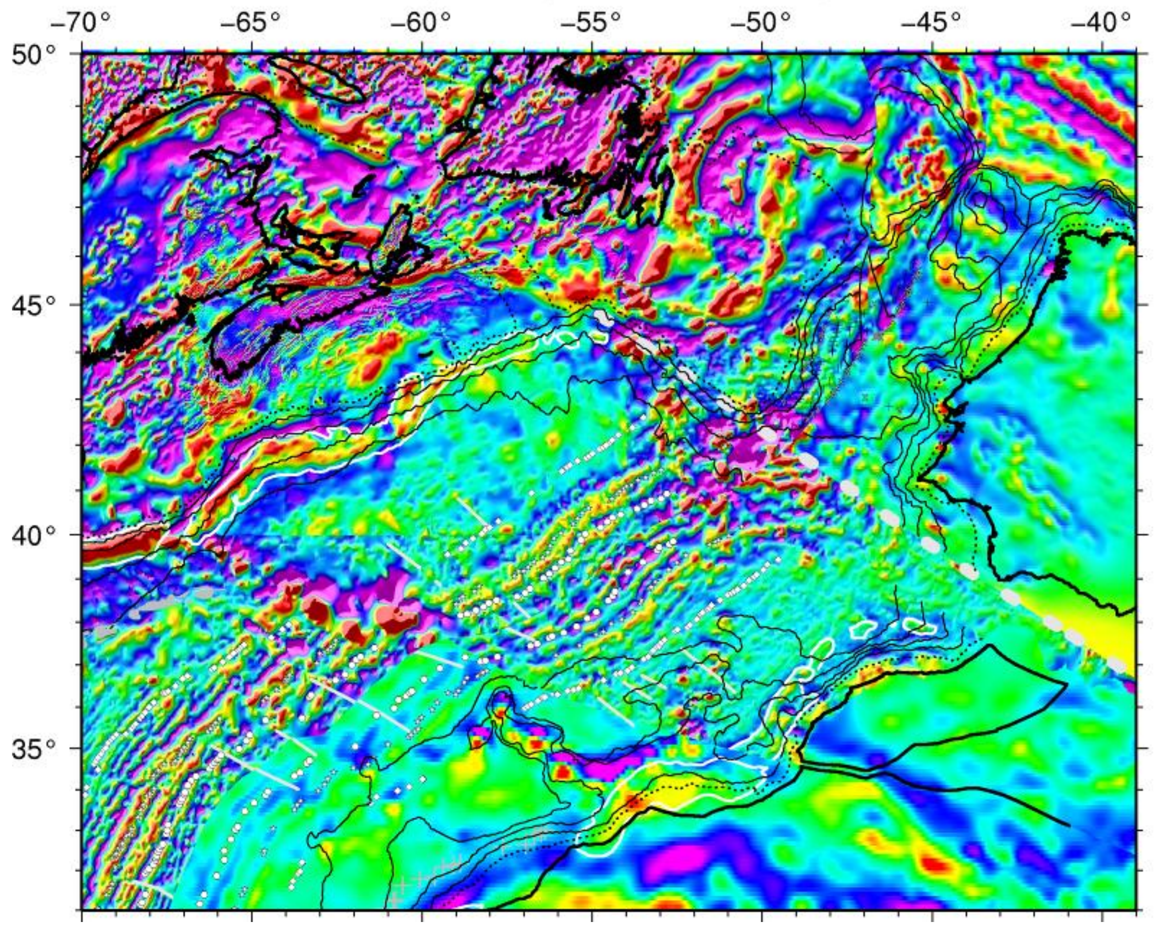
Magnetic anomaly map on kinematic reconstruction at chron ECMA (Sinemurian/Pliensbachian limit,190 Ma).



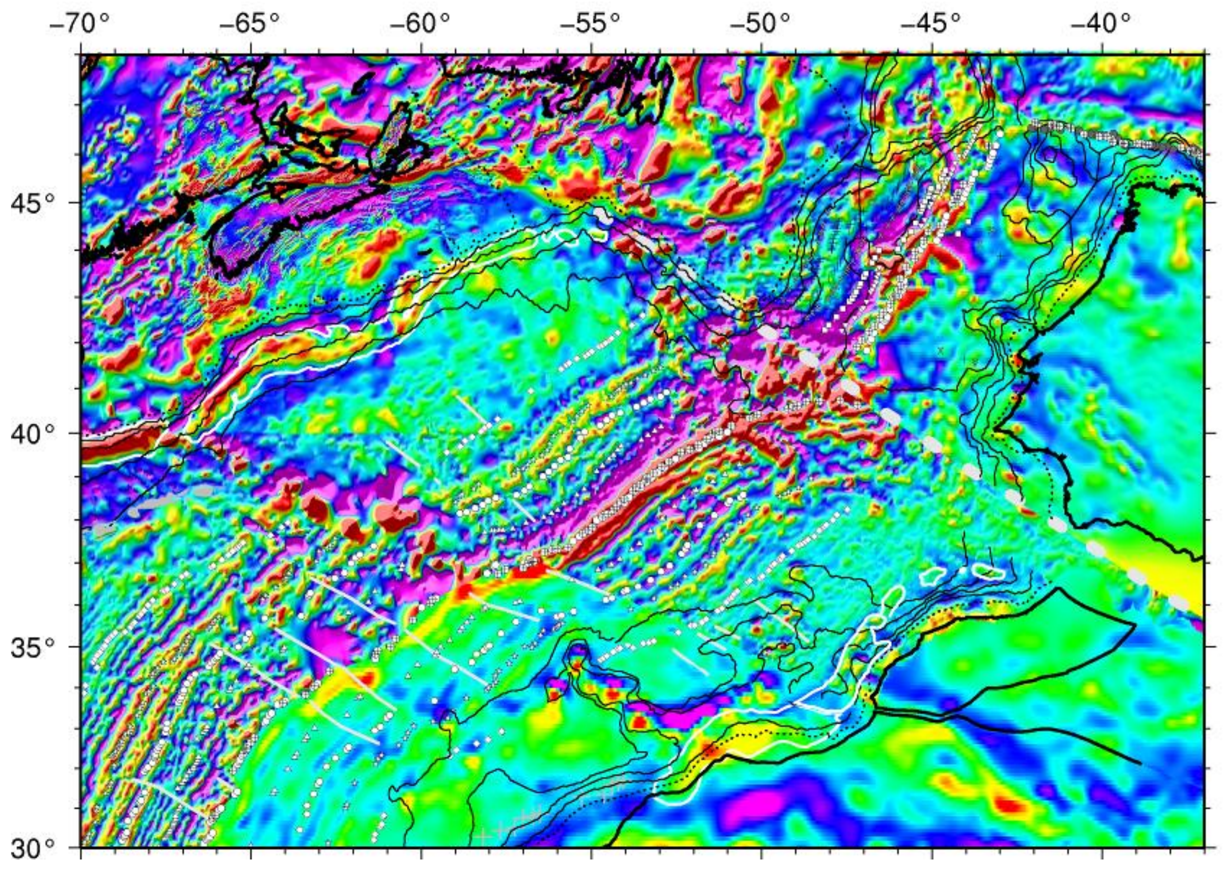
Magnetic anomaly map on kinematic reconstruction at chron BSMA (Middle Bajocian, 170 Ma).



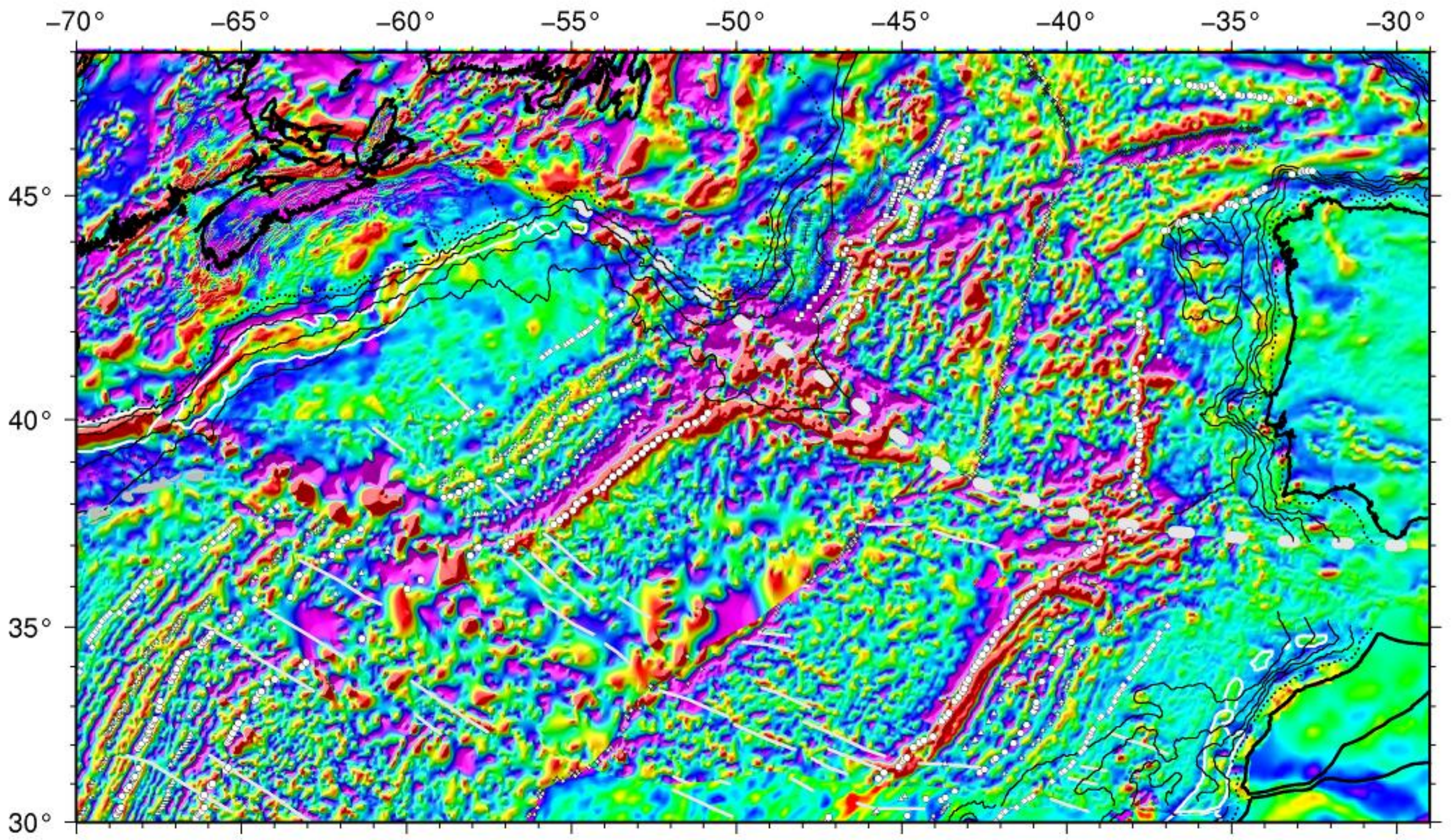
Magnetic anomaly map on kinematic reconstruction at chron M22 (Middle Tithonian, 150 Ma).



Magnetic anomaly map on kinematic reconstruction at chron M11 (Valanginian, 136 Ma).



Magnetic anomaly map on kinematic reconstruction at chron M0 (late Barremian/Early Aptian, 125 Ma).



Magnetic anomaly map on kinematic reconstruction at chron C34 (Santonian, 83.5 Ma).

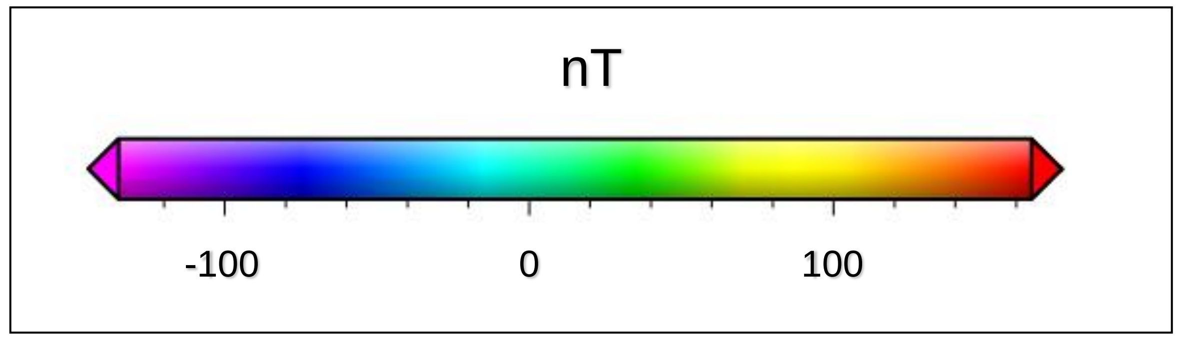
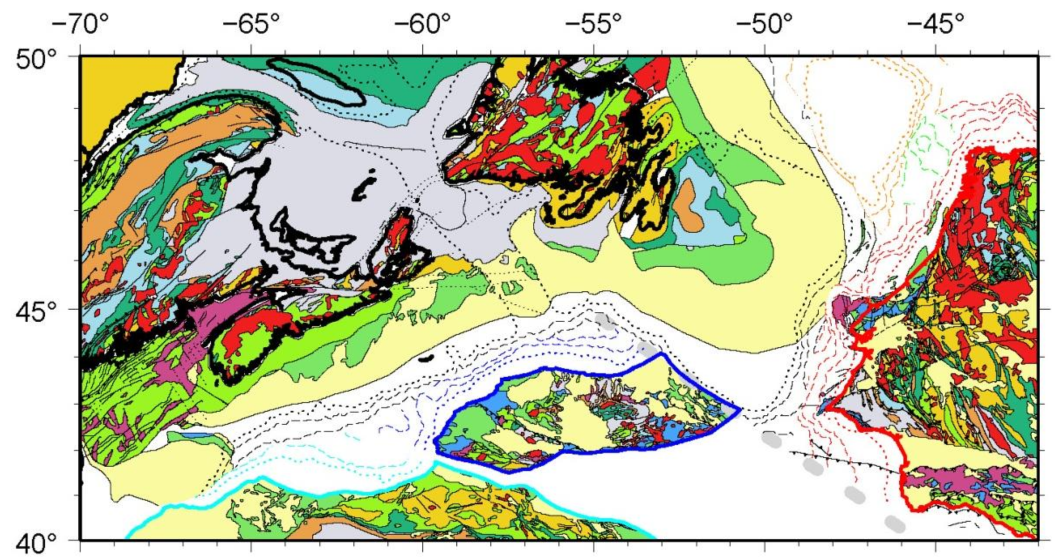
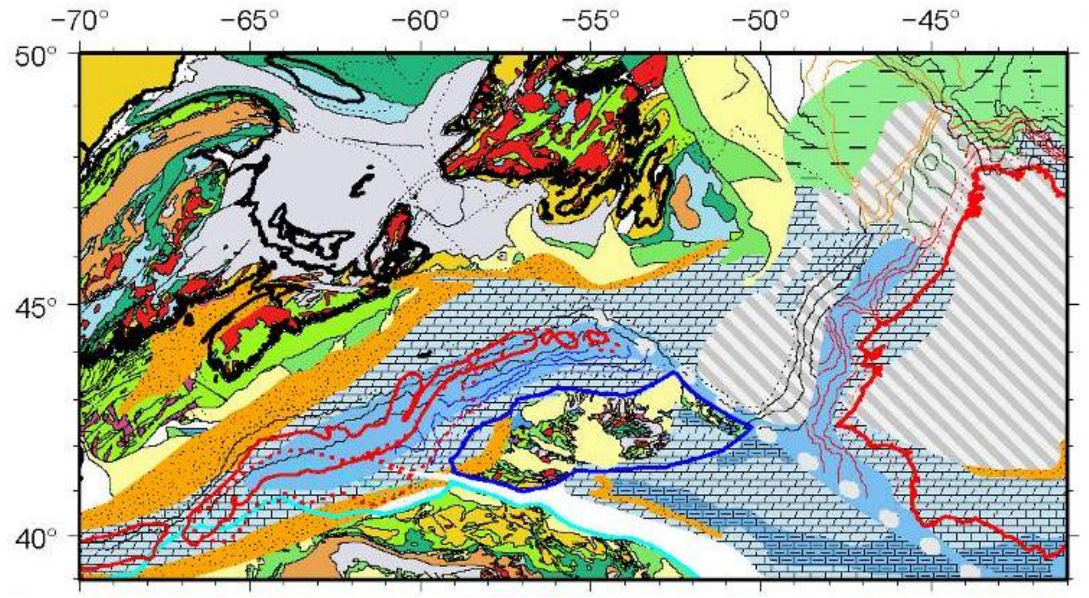


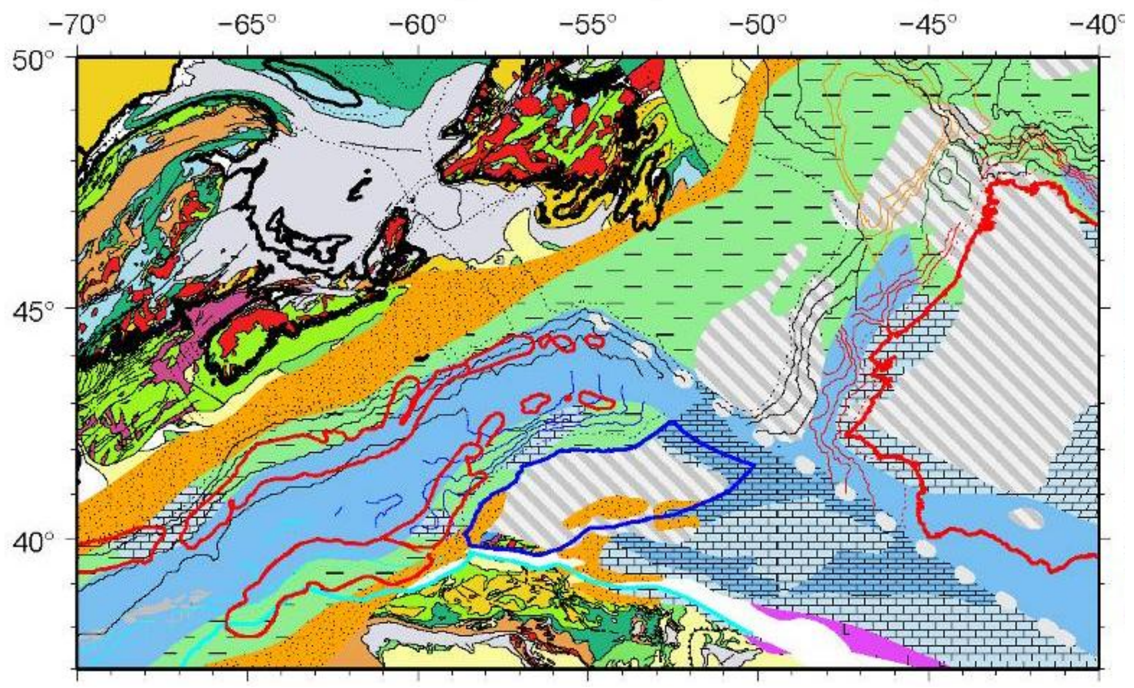
Plate reconstruction: Magnetic anomaly map (Sibuet et al., 2010)



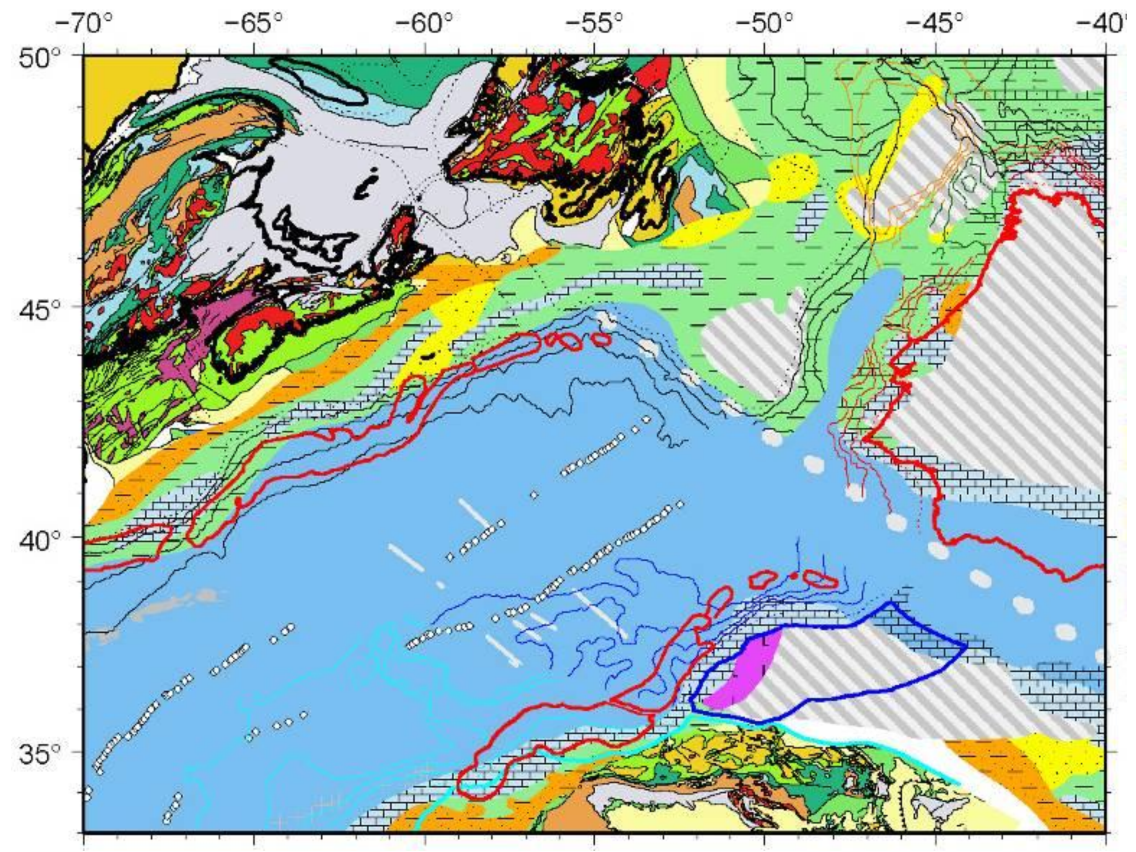
Pre-rift late Triassic geologic map on kinematic reconstruction at the Norian/Rhaetian limit (203 Ma).



Sinemurian-Toarcian paleo-geographic map on kinematic reconstruction at chron ECMA (Sinemurian/Pliensbachian limit, 190 Ma).



Bajocian-Bathonian paleo-geographic map on kinematic reconstruction at chron BSMA (Middle Bajocian, 170 Ma).



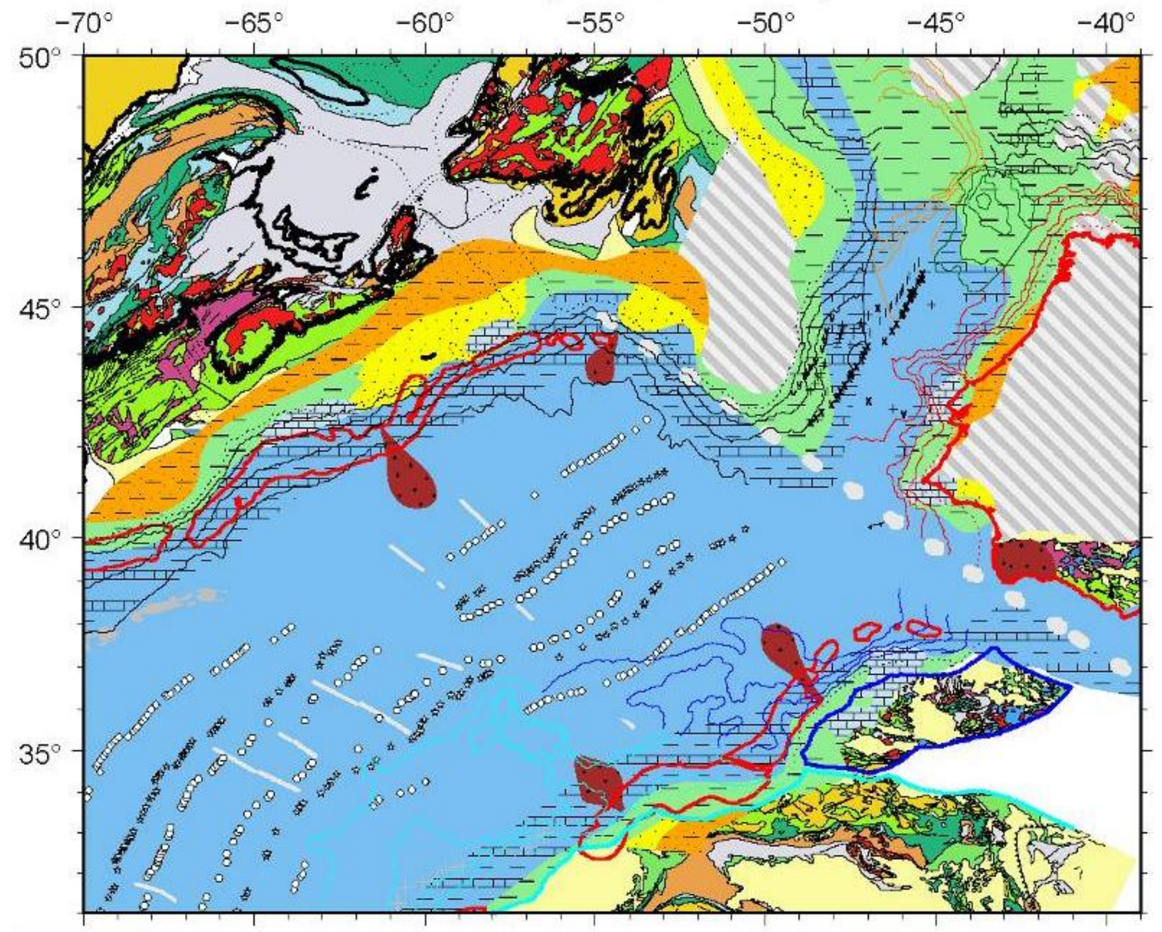
Oxfordian-Portlandian paleo-geographic map on kinematic reconstruction at chron M22 (Middle Tithonian, 150 Ma).

Onshore geology

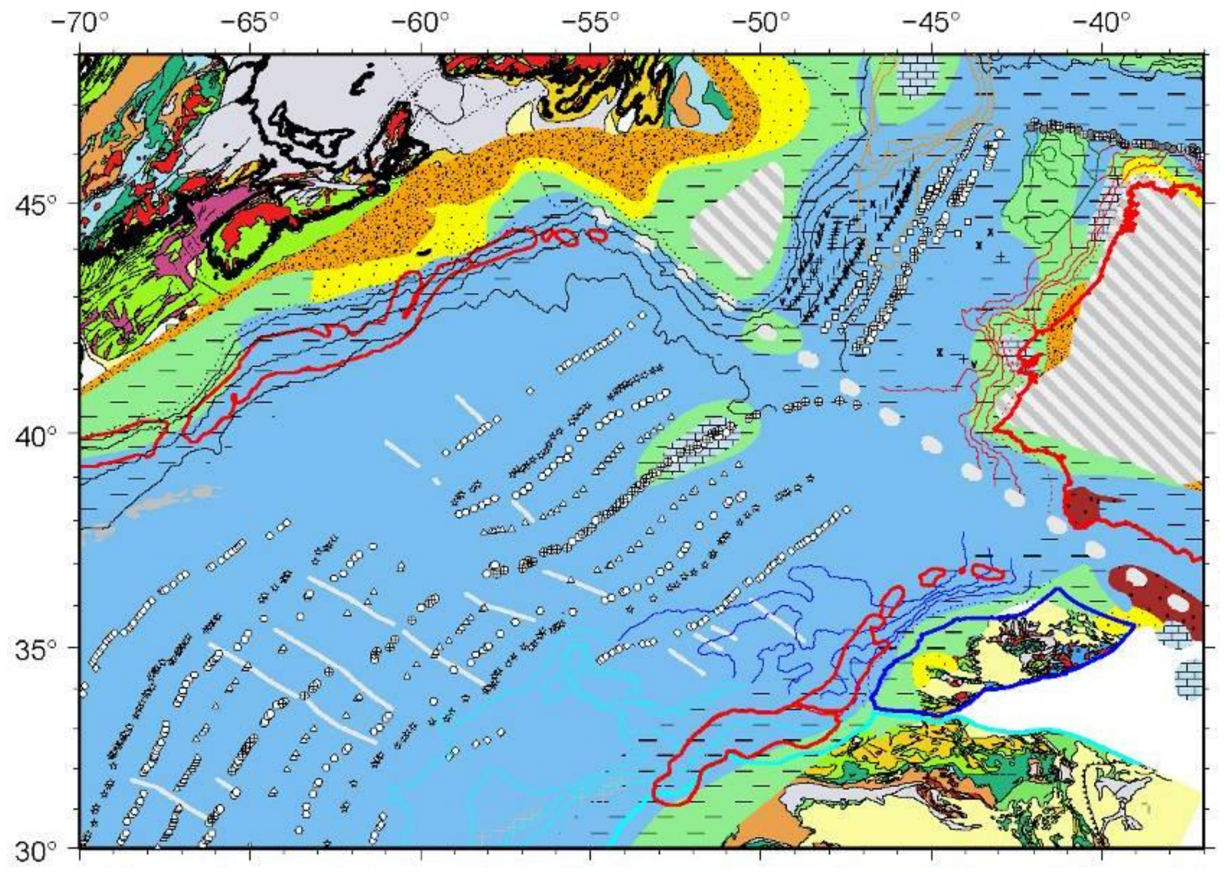
- 🟨 Precambrian
- 🟩 Cambrian
- 🟩 Ordovician
- 🟦 Silurian
- 🟧 Devonian
- ⬜ Carboniferous
- 🟪 Triassic
- 🟦 Jurassic
- 🟩 Cretaceous
- 🟨 Cenozoic
- 🟥 Igneous
- 🟩 Ophiolites

Offshore paleo facies

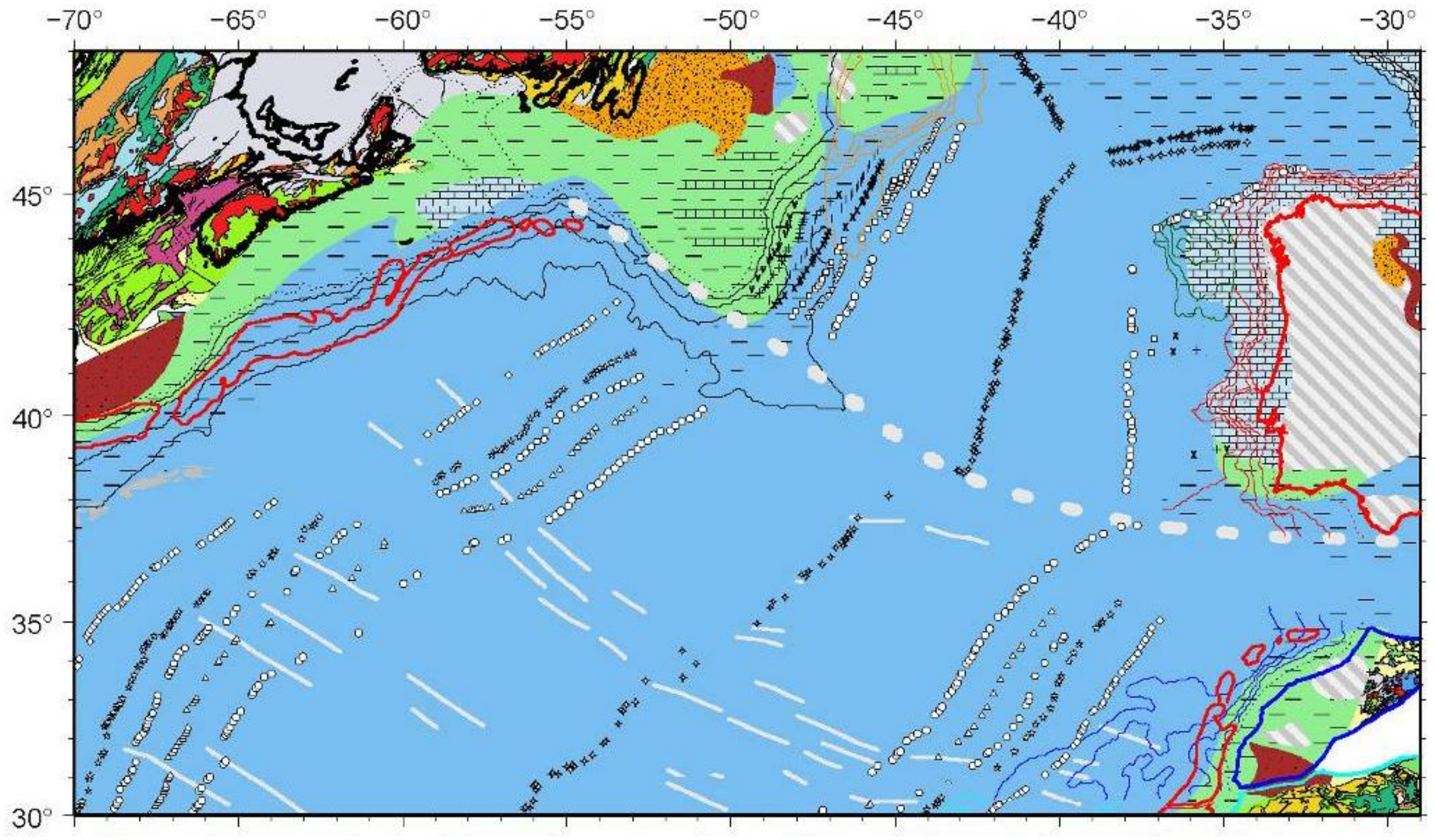
- 🟦 Deep water sediments (organic rich shale (M0), red shale (C34))
- 🟦 Deep water claystone shale
- ▦ Deep water carbonate
- ▤ Deep water calcareous shale
- ▦ Deep water clayey limestone
- 🟩 Shallow water claystone & shale
- ▦ Shallow water carbonate
- ▨ Shallow marine dolomite
- 🟩 Shallow water shale & carbonate
- 🟥 Turbidites
- 🟨 Coastal clastics and sand
- 🟧 Continental conglomerate and sand
- 🟪 Evaporites
- ▨ Area of non−deposition



Berriasian-Barremian paleo-geographic map on kinematic reconstruction at chron M11 (Valanginian, 136 Ma).



Aptian-Albian paleo-geographic map on kinematic reconstruction at chron M0 (late Barremian/Early Aptian, 125 Ma).



Cenomanian-Danian paleo-geographic map on kinematic reconstruction at chron C34 (Santonian, 83.5 Ma).

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