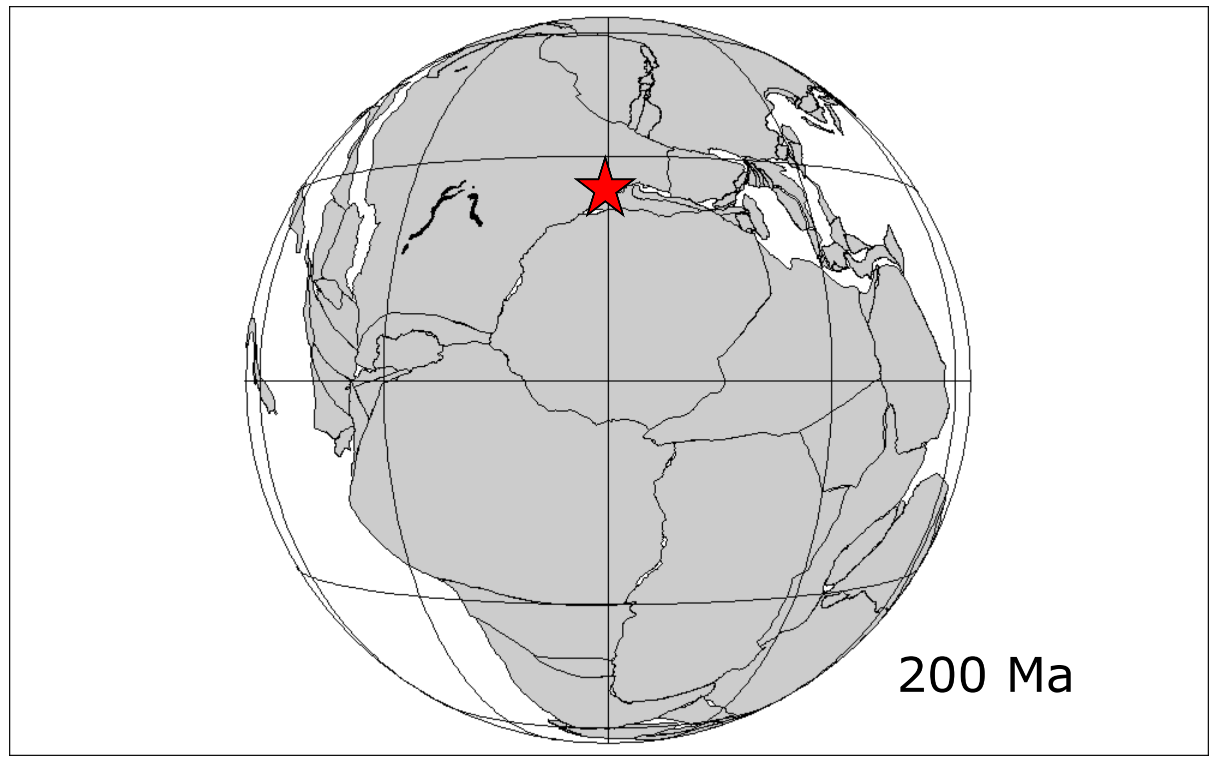
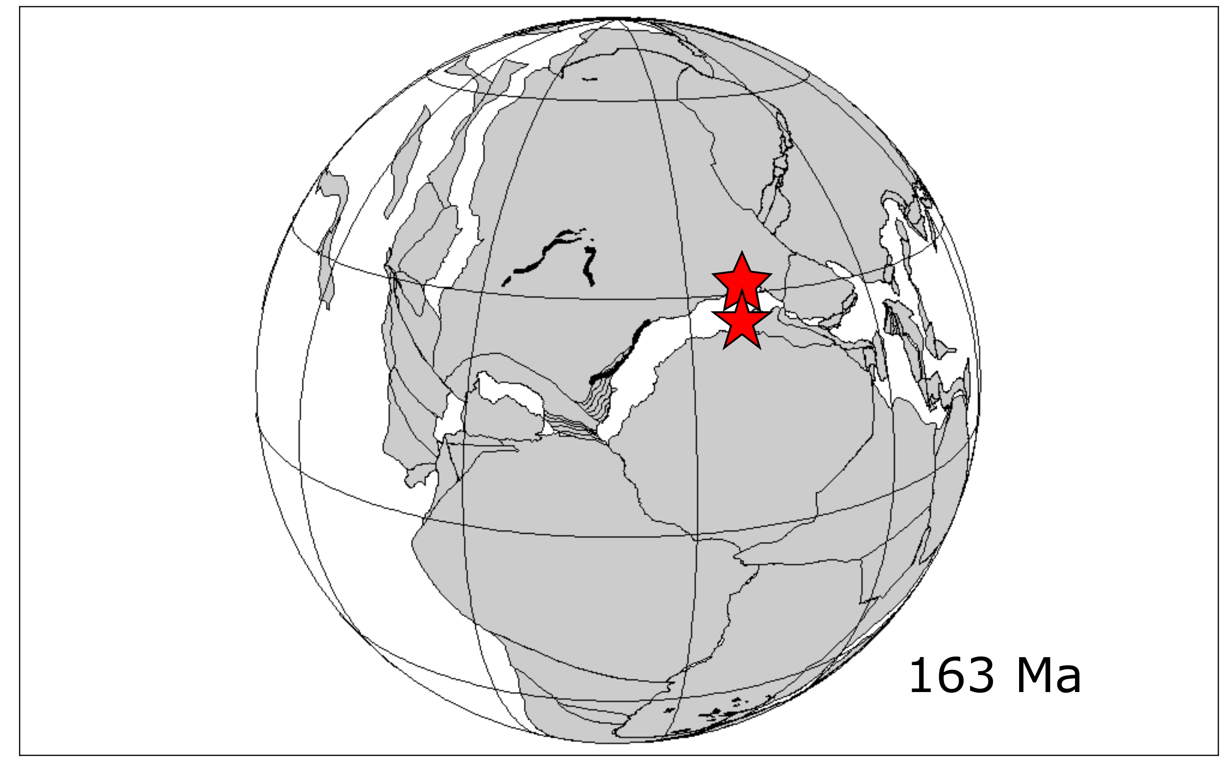
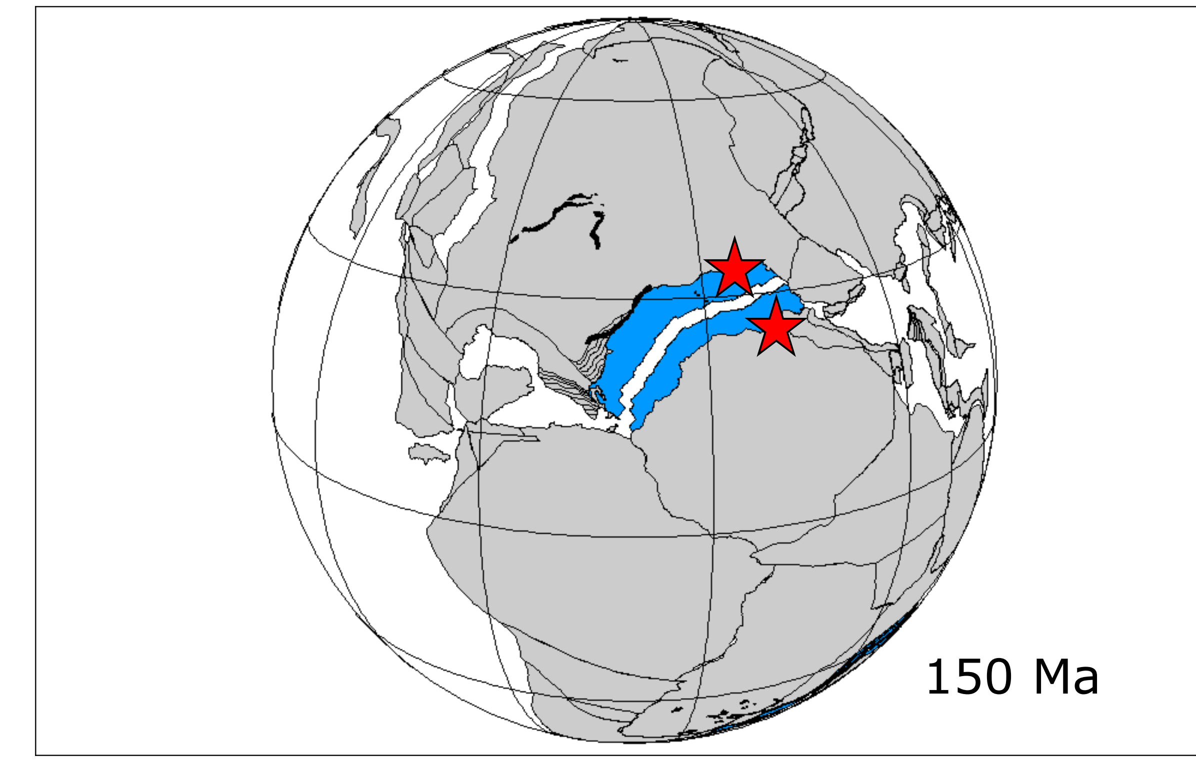
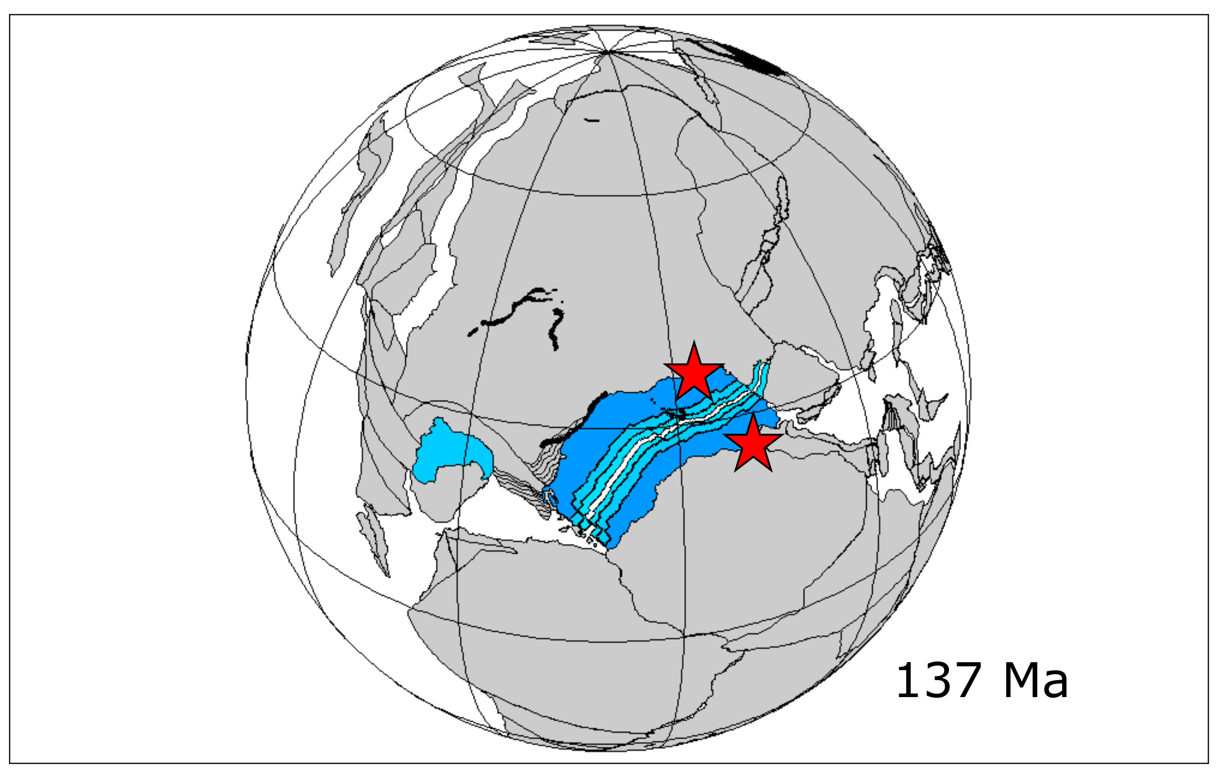
CHAPTER 1

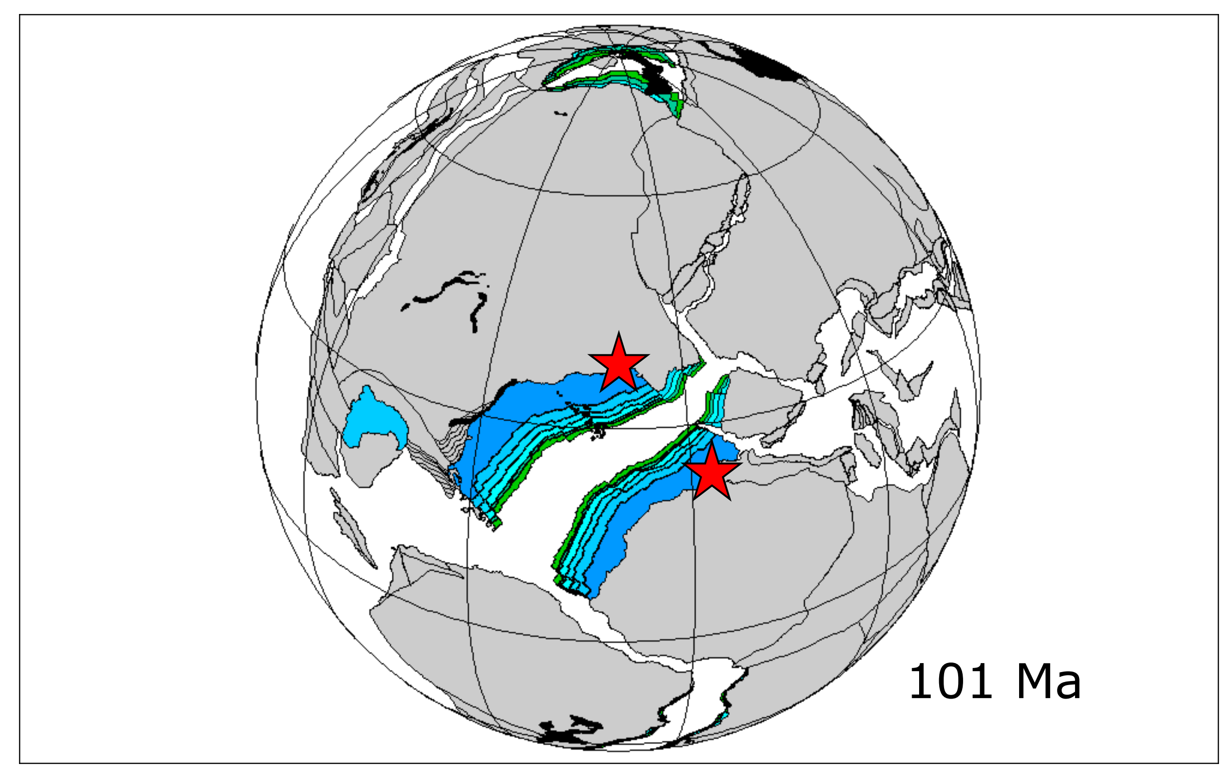
NOVA SCOTIA AND NORTHERN MOROCCO CONJUGATE MARGINS GEODYNAMIC CONTEXT

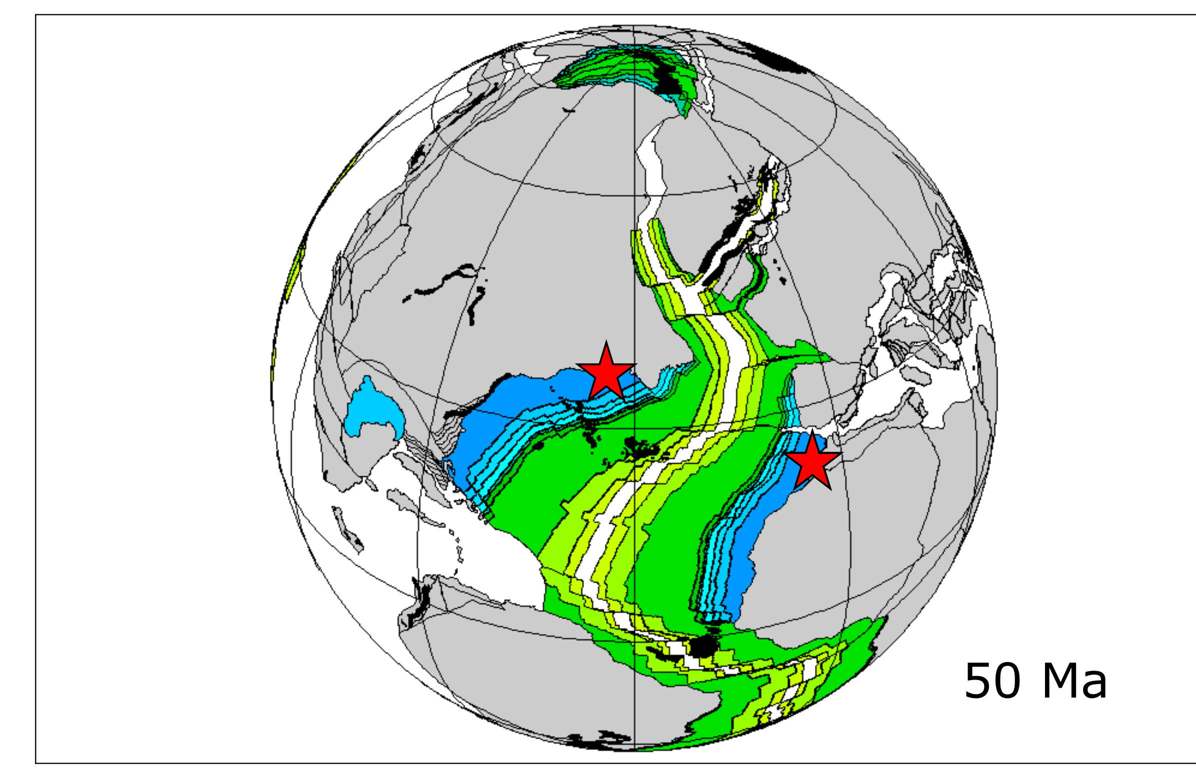


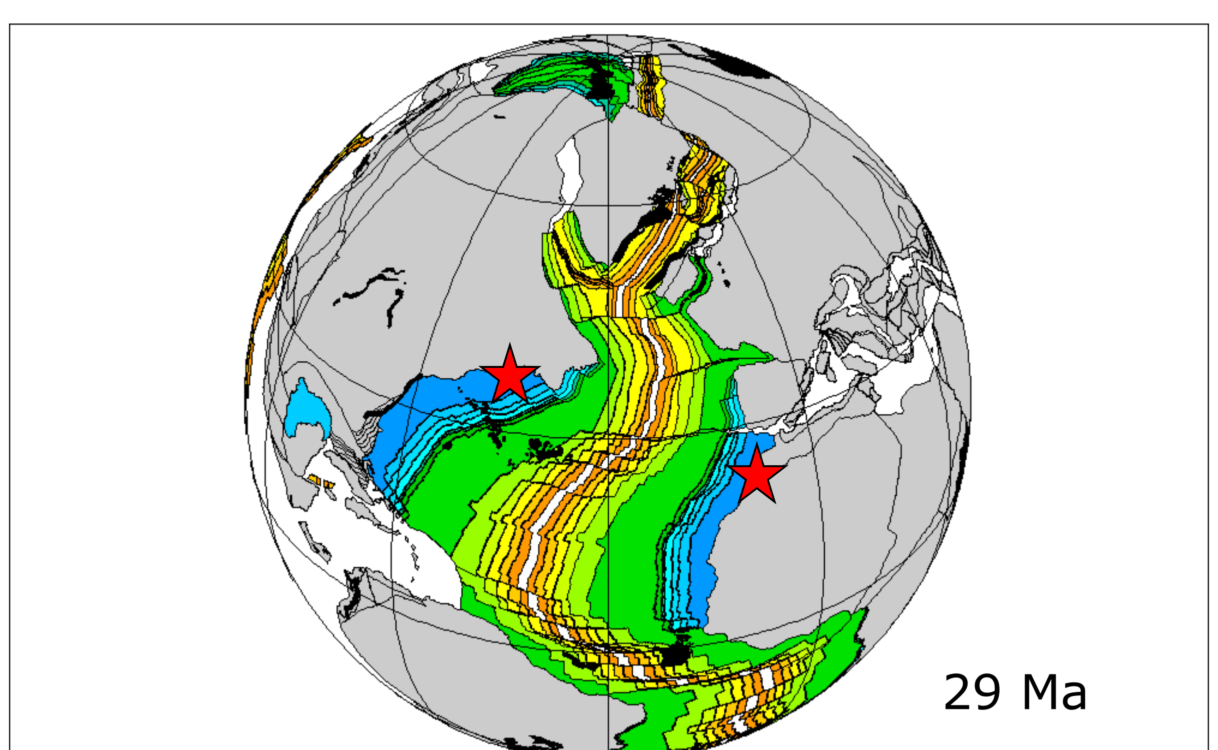












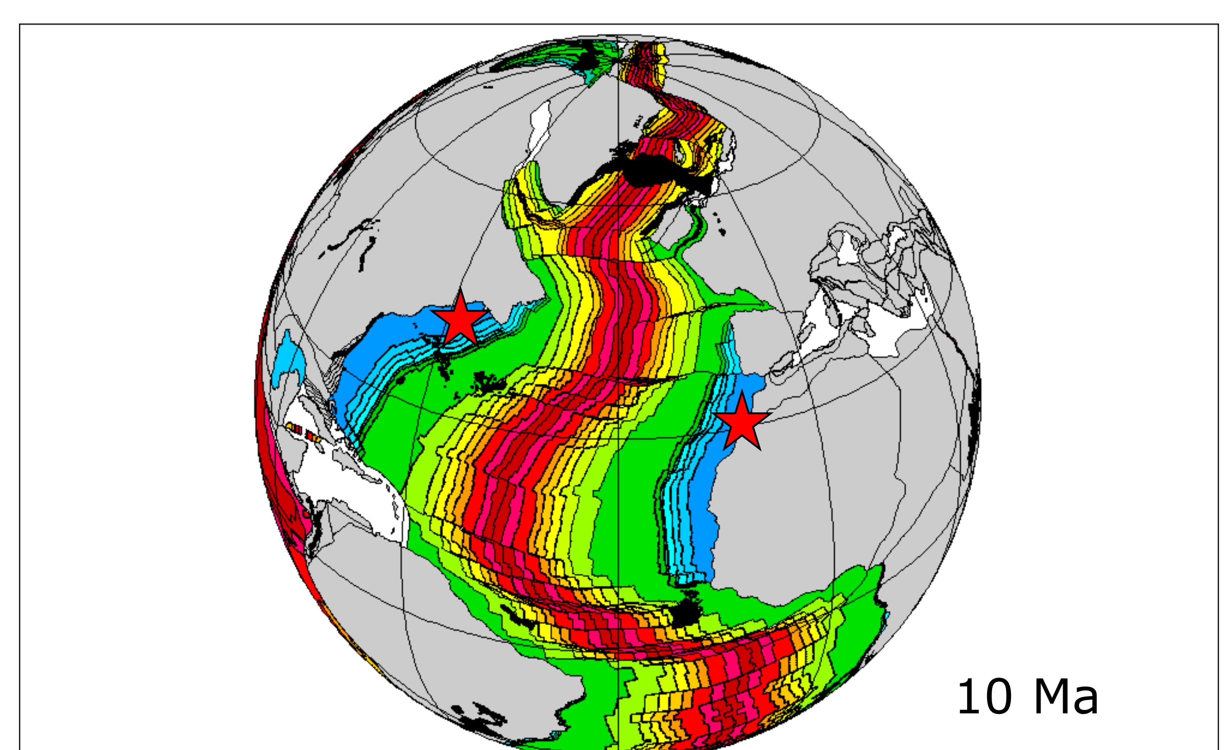


Figure 1.1: Plate kinematic reconstructions for Triassic, Jurassic, Cretaceous and Tertiary ages from Schettino and Scotese (2004) and Schettino and Turco (2009), showing the Atlantic opening. Relative location of Nova Scotia and Morocco conjugate margins are shown by red stars. Both margins pertain to the Central Atlantic segment which started opening during Triassic-Early Jurassic. Latitudes lines corresponds to the Arctic Circle, tropics and the equator.

The reconstruction shows the progressive migration of Nova Scotia from tropical latitudes during Jurassic times to higher latitudes during Cretaceous times. During the Jurassic both margins developed along the Tropic of Cancer. Since Cretaceous times the Morocco margin has remained in the vicinity of the tropical zone while Nova Scotia migrated to higher latitudes. This may explain similarities in sedimentary facies (carbonate platforms) during Jurassic times.

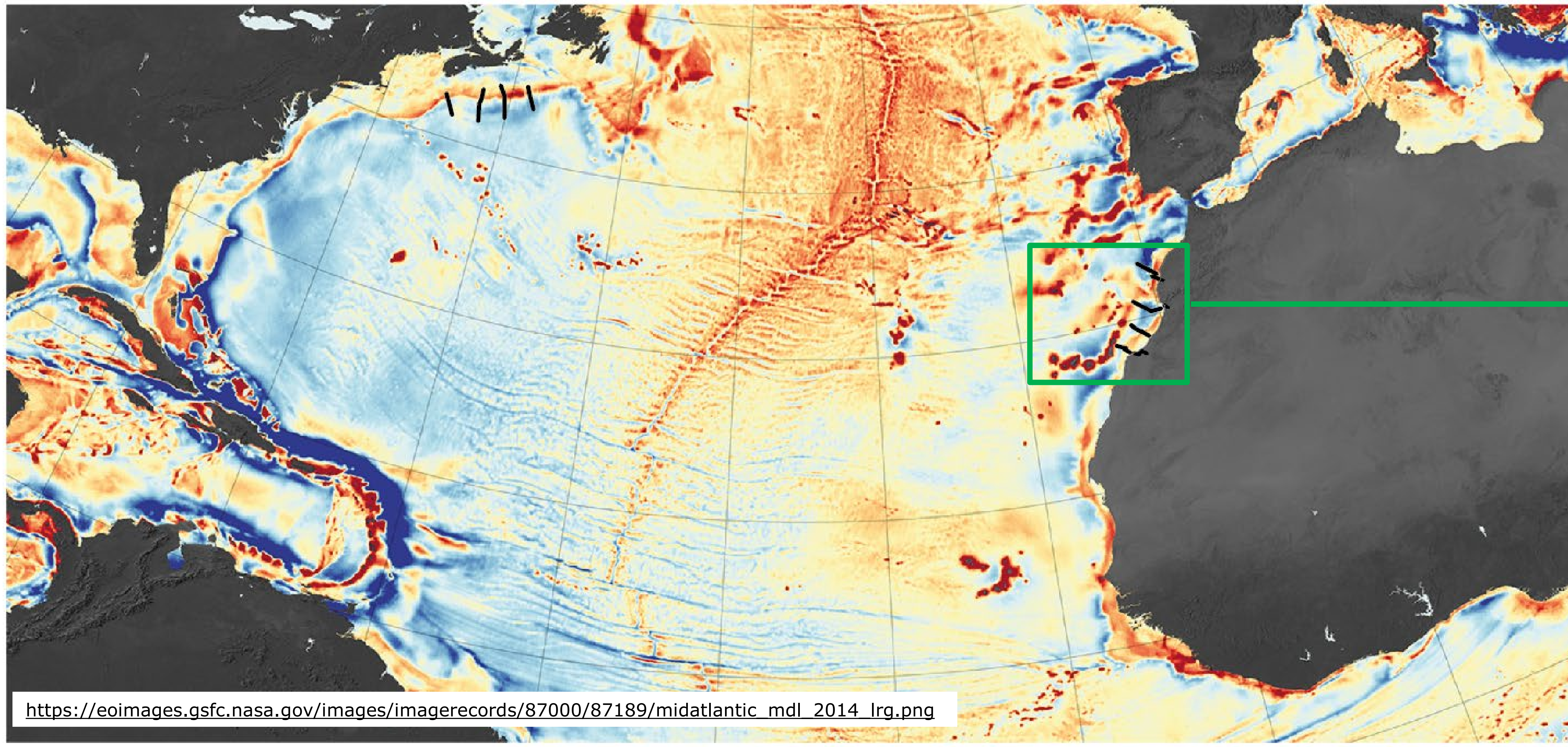


Figure 1.2. Free air gravimetry map of the Central Atlantic, Sandwell et al.,2014.

Analysis of the free air gravity map of Central Atlantic shows obvious differences in the conjugate margins. In Nova Scotia, a single continuous high (dark brown color) corresponding approximatively to the present-day shelf break separates the La Have platform from the relatively continuous slope and abyssal domain. In contrast basin along the Moroccan margin (darks blue) are separated by a complex set of reliefs (see enlarged Figure 1.3). s

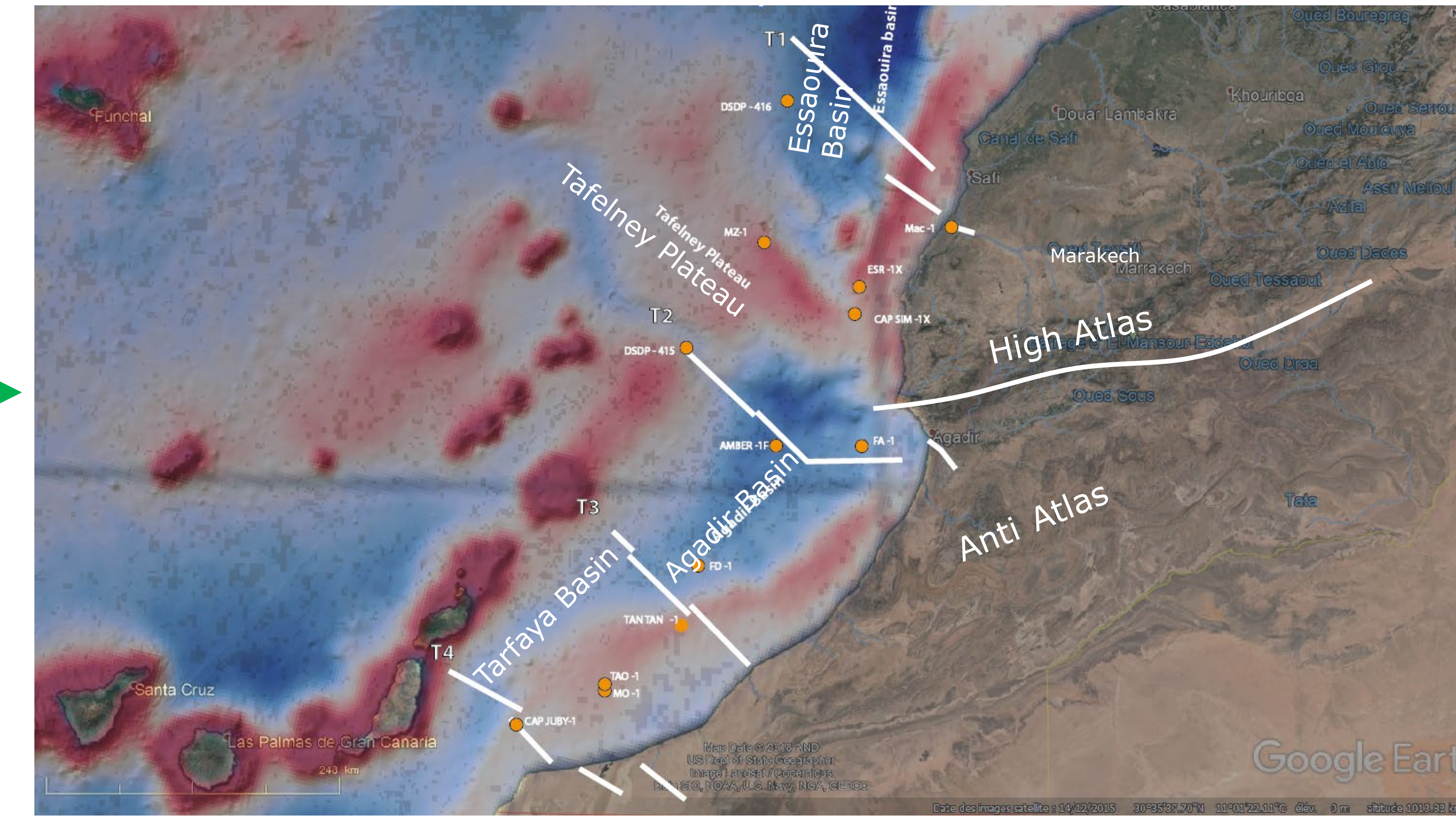


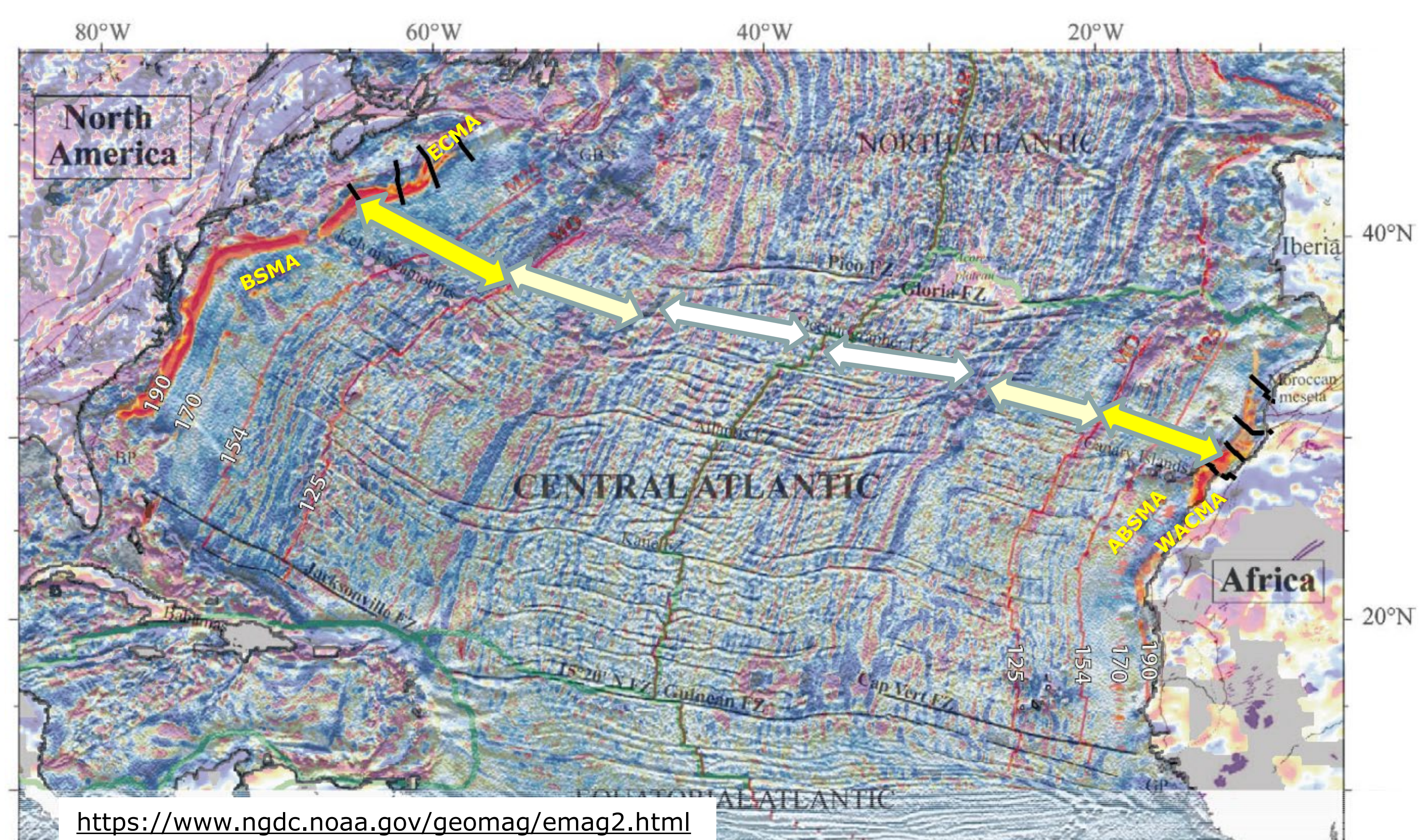
Figure 1.3. Details of the free air gravity map along the Moroccan margin showing the location of transects T1-T4 (modified from Google Earth image and superimposed Sandwell et al., 2014 gravity data.

Along the Moroccan margin the shelf break is also underlined by a clear positive dark brown anomaly but the platform domain is narrower and much more irregular. Moreover volcanic activity related to the Canary and Madeira hot spots active since 60 Ma created volcanic highs which isolated the Tarfaya and Agadir basins from the abyssal domain.

Figure 1.4: Central Atlantic Magnetic anomalies modified from Labails et al. 2010.

ECMA : East Coast Magnetic Anomaly
WACMA: West Africa Magnetic Anomaly

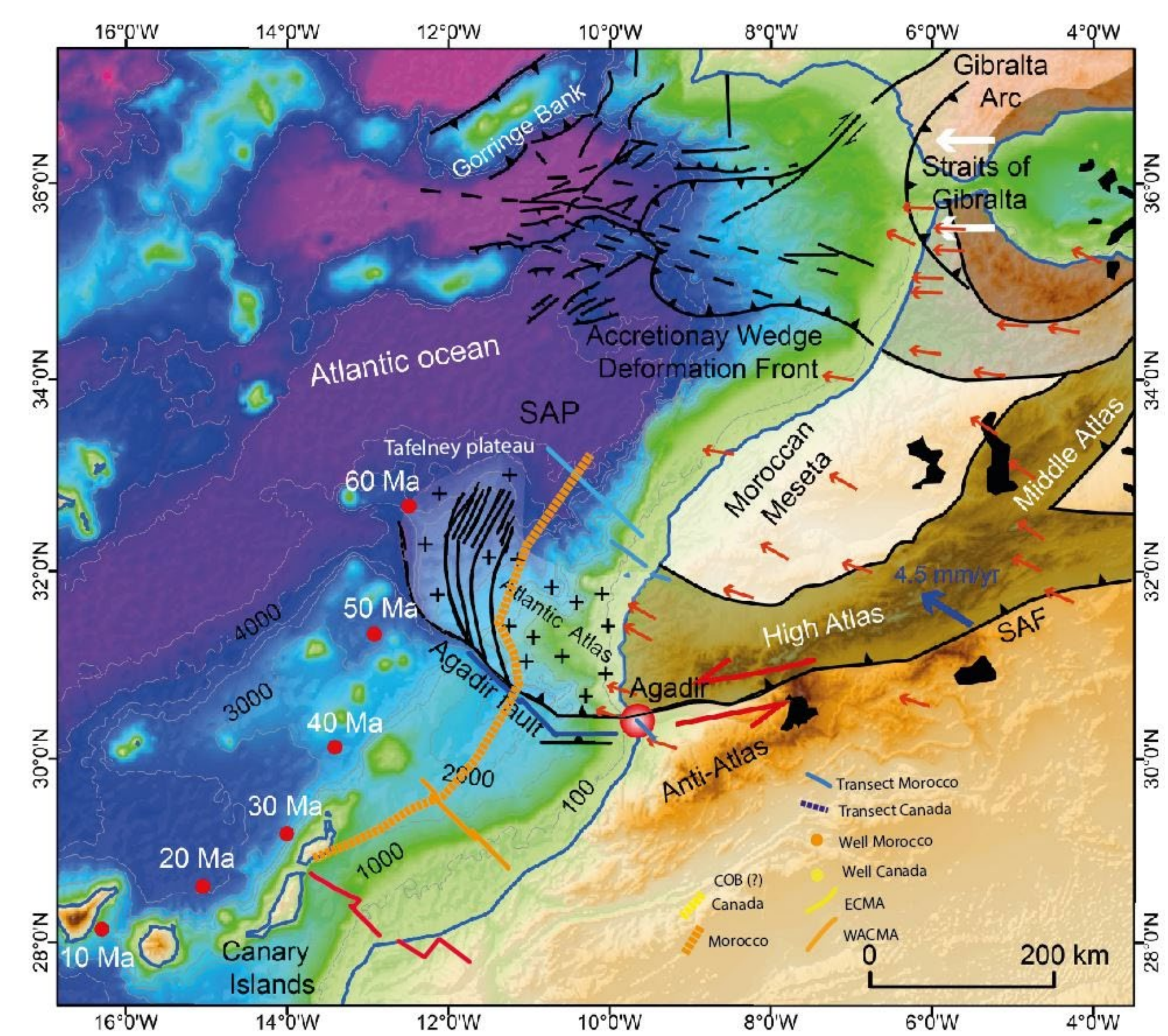
BSMA: Blake Spur Magnetic Anomaly
ABSMA: African coeval to Blake Spur Magnetic Anomaly



Red (positive) and blue (negative) colored anomalies are from EMAG2v3. M0 and M25 anomalies are also shown. Ages attributed to these anomalies by Labails et al., 2010 are respectively ECMA / WACMA = 190 Ma; BSMA / ABSMA = 170 Ma; M25 = 154 Ma; M0 = 125 Ma. The four chosen transects are displayed in black lines on each margin.

Double arrows indicate variation in opening orientations and slight asymmetry in the velocity of opening mainly during Jurassic times. Average velocity of opening of the Central Atlantic is around 2.25 cm/y but could have been much slower (1.5 cm/y) during Early Jurassic times.

Figure 1.5: Schematic structural map of the Moroccan offshore and onshore domains modified from Benabdellouahed et al., 2017. Transects are indicated in red (T4), orange (T3), dark blue (T2), and light blue (T1). Orange dotted line indicates the possible location of Continent Ocean Boundary. Red dots indicate the progressive position of the Canary hot spot.



The Tafelney Plateau has been interpreted by Benabdellouahed et al. (2017) as the oceanic extension of the High Atlas developed during Neogene Quaternary. It separates the Essaouira Basin from the Agadir Basin.
Notice that T2 is located just south of the Atlassic front.

Plate reconstruction: differences and similarities of Canadian and Moroccan margins

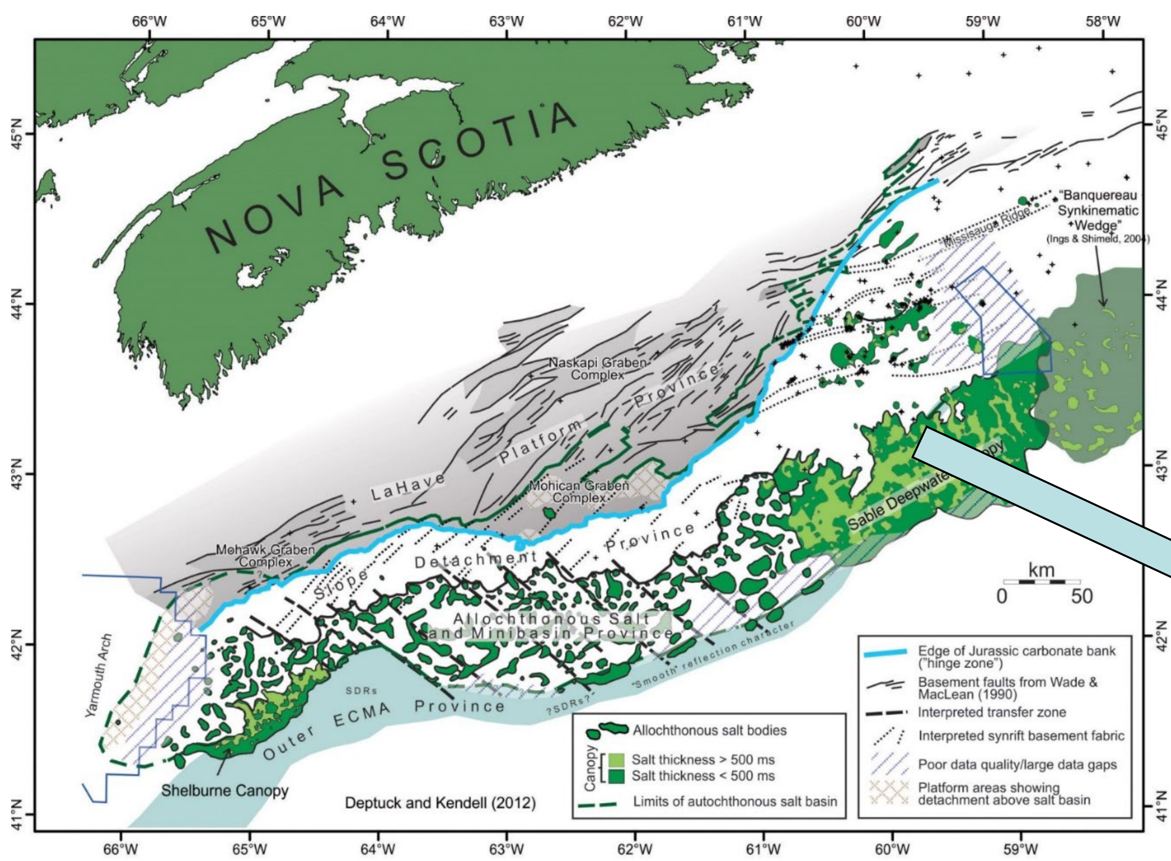


Figure 1.6. Salt basin on Nova Scotia margin (Deptuck and Kendell, 2012).

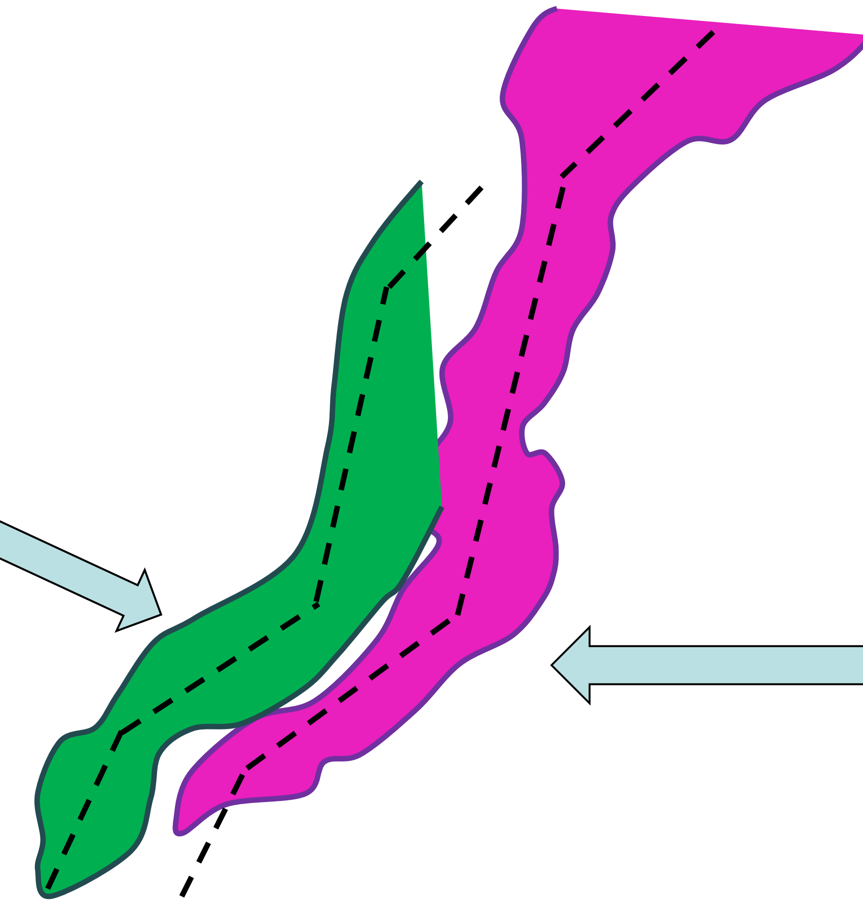


Figure 1.7. Approximative relative positions of salt basins at -180Ma.

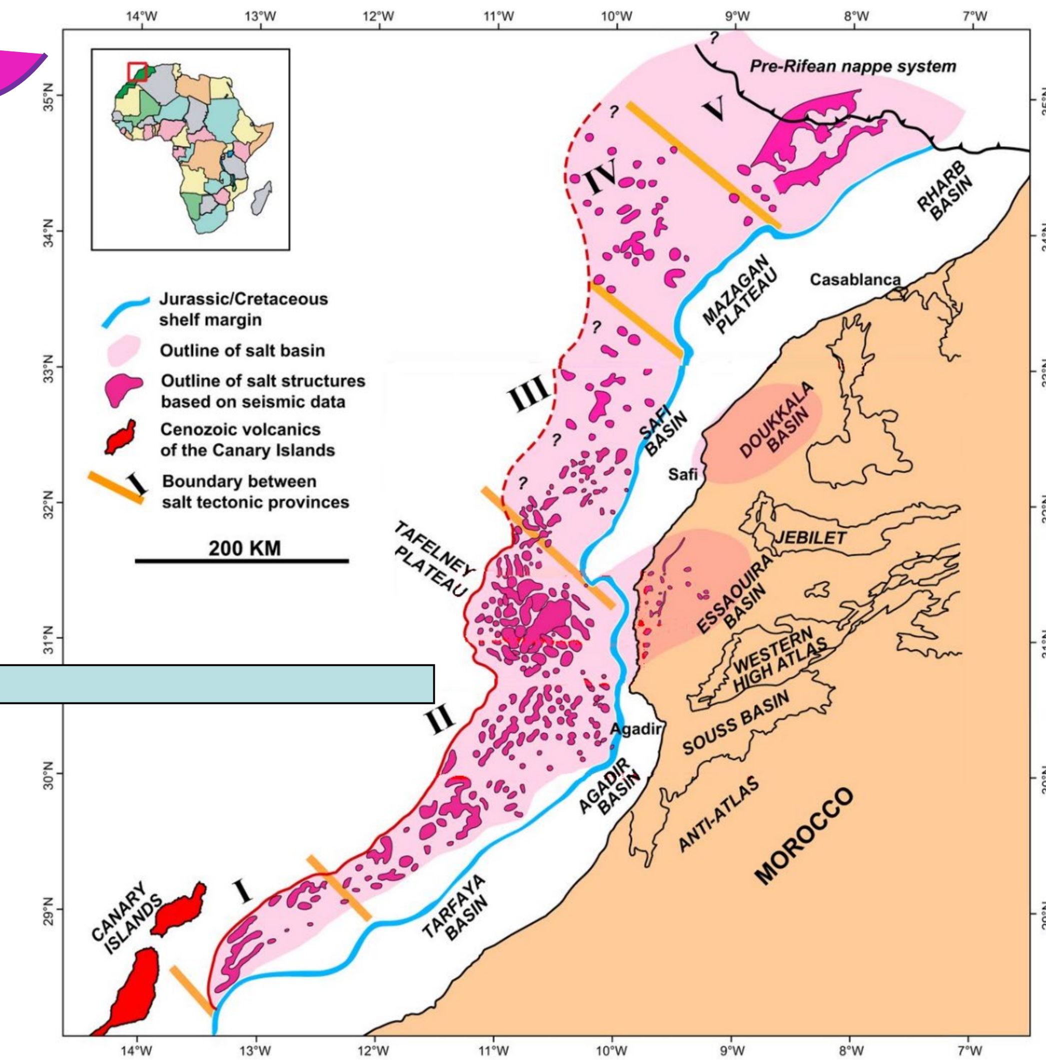
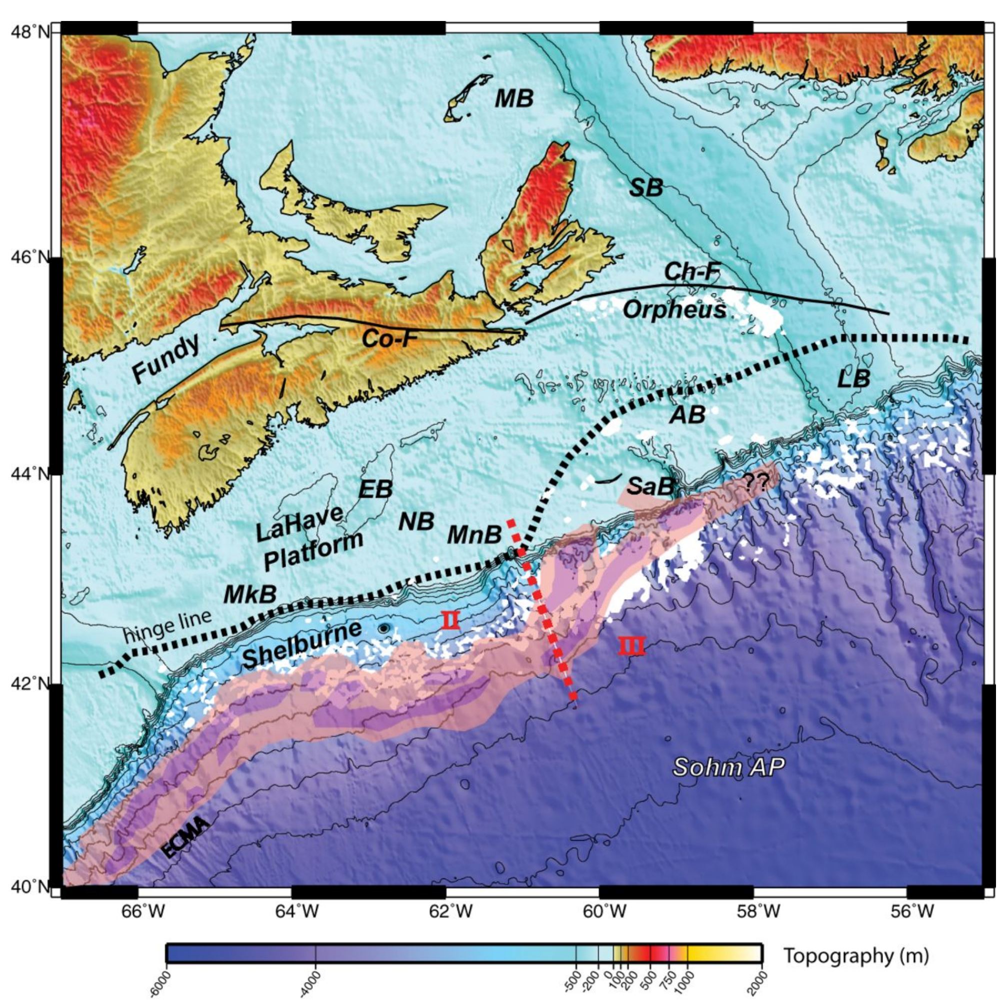


Figure 1.8. Salt basin on Morocco margin (G. Tari and H. Jabour, 2013)

Salt basin geometry

A good fit of the conjugate salt basins and arcuate geometry of the two margins is observed in the plate tectonic reconstruction at -180Ma.



AB, Abenaki; EB, Emerald; LB, Laurentian; MB, Magdalen; MkB, Mohawk; MnB, Mohican; NB, Naskapi; SaB, Sable; SB, Sydney. Ch-F, Chedabucto Fault; Co-F, Cobequid Fault; AP, abyssal plain.

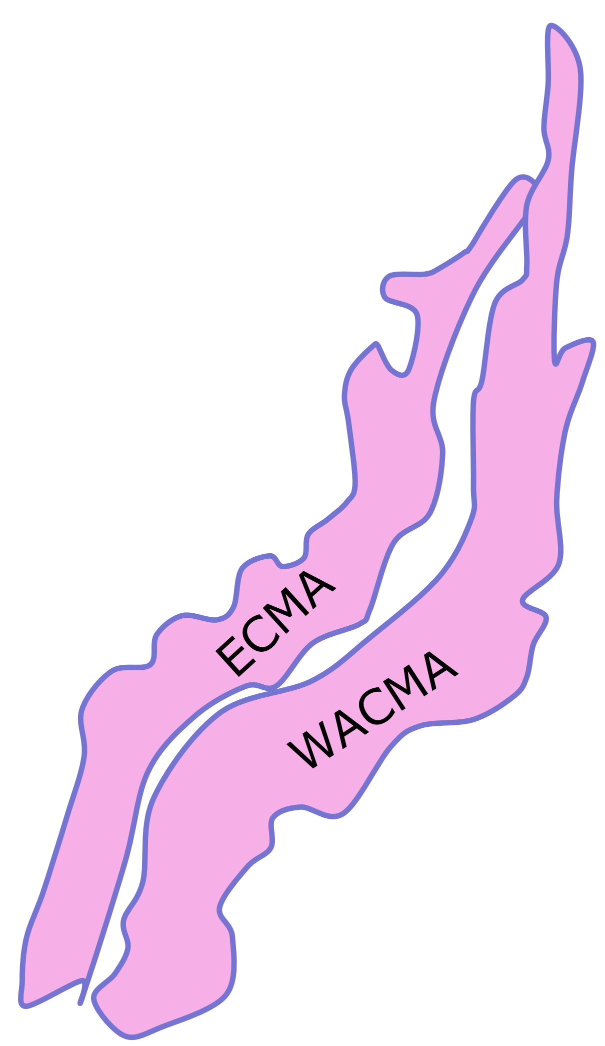
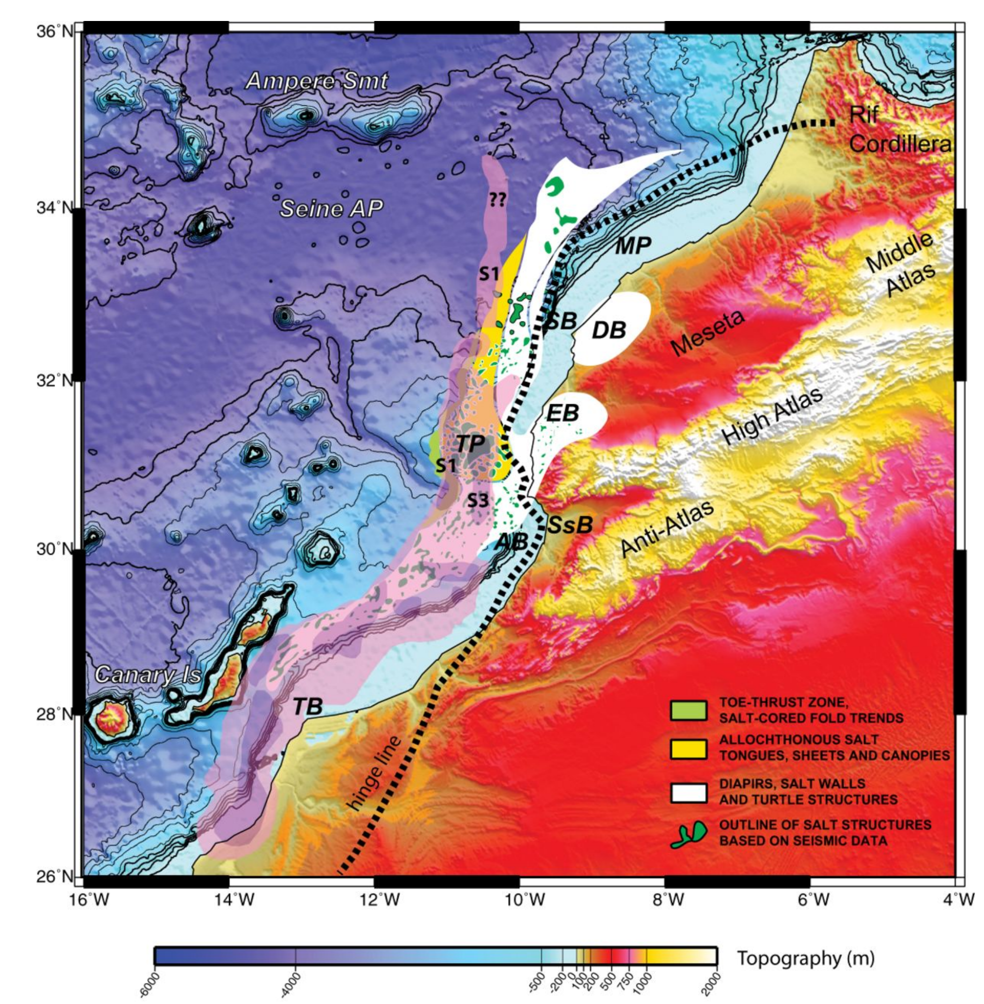


Figure 1.10. Approximative relative positions of ECMA and WACMA magnetic anomalies at -180Ma.



AB, Agadir Basin; DB, Doukkala Basin; EB, Essaquira Basin; MP, Mazagan Plateau; SB, Safi Basin; SsB, Souss Basin; TP, Tafelney Plateau; TB, Tarfaya Basin.

Magnetic anomalies ECMA and WACMA

The East Coast Magnetic Anomaly (ECMA) can be easily followed along the US 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. 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.

The ECMA has its conjugate on the Northwest African Margin where it has weaker amplitude: the West Coast African Magnetic Anomaly (WACMA including S anomalies). An anomaly S1 is observed on both sides of the Canary Islands. It is very similar to the ECMA in shape and position, with two major differences: a weaker amplitude and a continuation northward (anomaly S') not observed on the American side.

The comparison between the shapes of ECMA and WACMA anomalies shows a good correlation in plate tectonic reconstruction at 180 Ma.

The location of both ECMA and WACMA straddles the salt basins. These anomalies can be used as a good marker of the oceanic crust limit: the anomaly starts where the oceanic crust ends.

Figure 1.9 and 1.11. Bathymetry and magnetic anomaly on both margins (Louden et al. 2012)

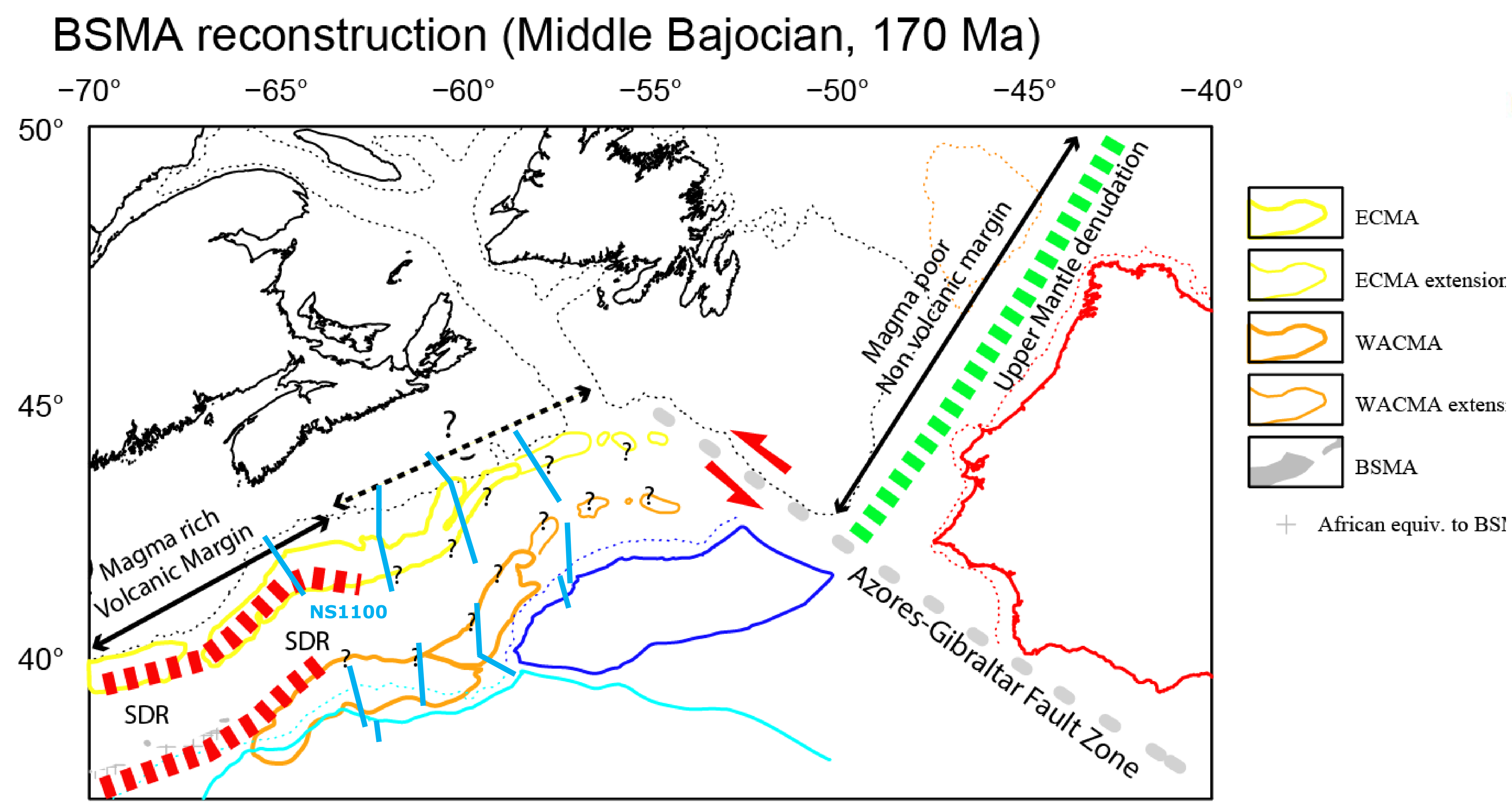


Figure 1.12. Plate reconstruction at 170 Ma (Blake Spur Magnetic Anomaly age) modified from Sibuet et al., 2011; Sibuet et al., 2012, showing two major segments of the Atlantic separated by the Azores-Gibraltar transform fault: the Nova Scotia–Morocco segment to the south and the Newfoundland-Iberia segment to the north. In the southwestern part of the southern segment the conjugate margins have the characteristics of a magma rich – volcanic - margin (red dotted lines) while the northern segment, where oceanic crust appeared after M3 (=125 Ma), has the characteristics of a magma poor - non volcanic- margin with upper mantle denudation (green dotted line). The northeastern part of the Nova Scotia-Morocco conjugate margins could not be defined precisely.
The position of the transects chosen for this study are shown in pale blue.

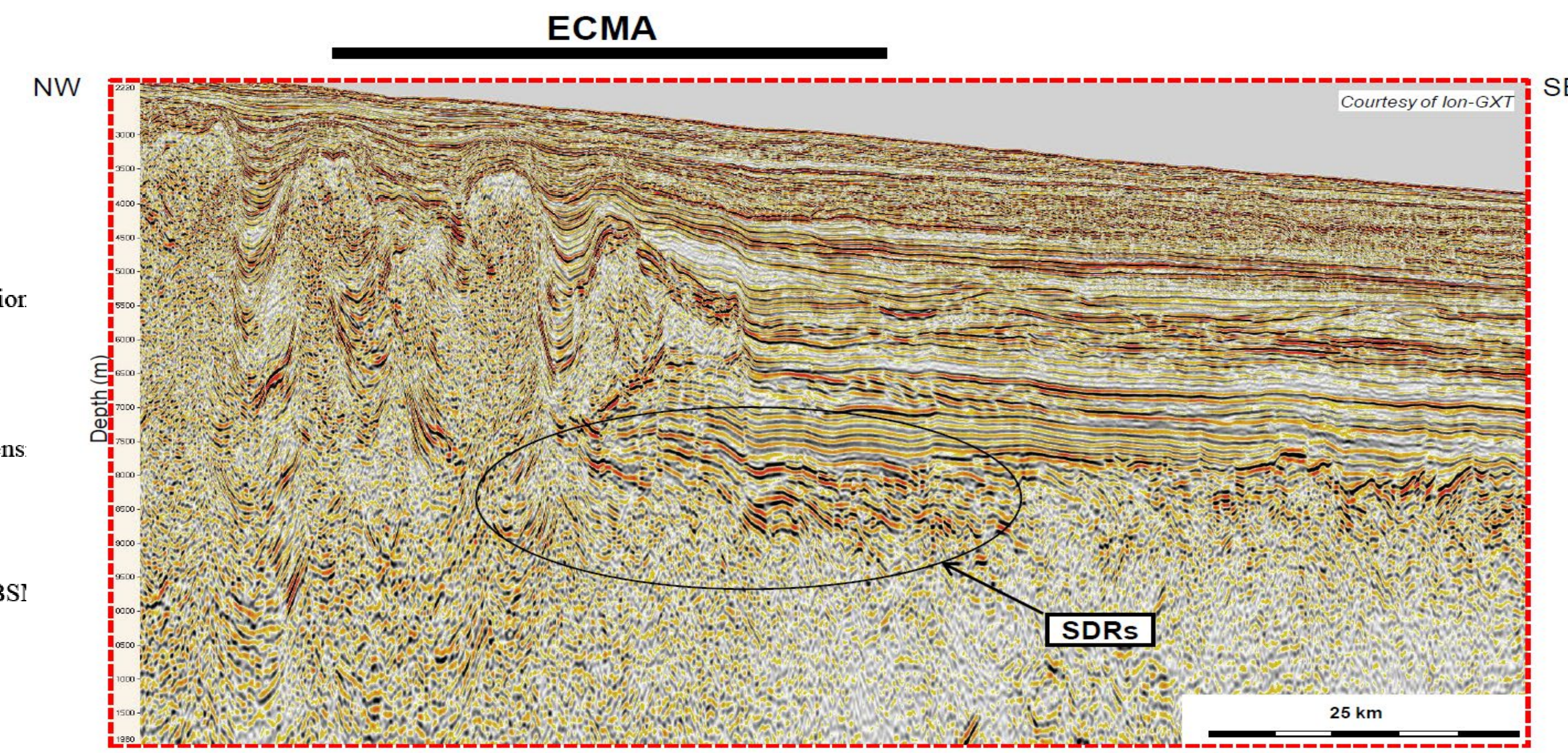


Figure 1.13. Seaward dipping reflectors, seismic reflection line – NovaSPAN reprocessed 2010 – line 1100 PSDM (see location on Figure 1.12)

Magma dominated or magma poor margin

The 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. The southwestern part of the margin (till 62°W) has all the characteristics of a magma dominated margin with clear seaward dipping reflectors (SDRs) (SMART3 and NS-1100) 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.

On the other side of the Atlantic, the NW Moroccan margin is located between the magma dominated province south of Canary Islands and the magma poor province of Iberia. Some volcanic flows northeast of Canary islands have been interpreted as derived from the Canary hotspot about 40-60 Ma. Rifting of the southern margin may have been associated with an older episode of magmatism (Bertrand et al., 1982). The northern part of the Moroccan Atlantic margin, however, shows no evidence of large scale syn or post rift magmatism and is generally considered to be non-volcanic in character.

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 the thermal regime and subsidence history that control source rock maturation and deposition of source rock and reservoir. Radiogenic heat of the continental crust contributes to source rock maturation while 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 basin modeling.

A primarily non-magmatic rift to drift process 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.

In contrast, if the rift followed an essentially volcanic process, it would imply uplift and sub-aerial extrusives characterized by seaward dipping reflectors (SDRs), 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 depositional system of Early Jurassic age could then be argued to be present along the whole margin and be of elevated richness because of the restricted marine depositional environment.

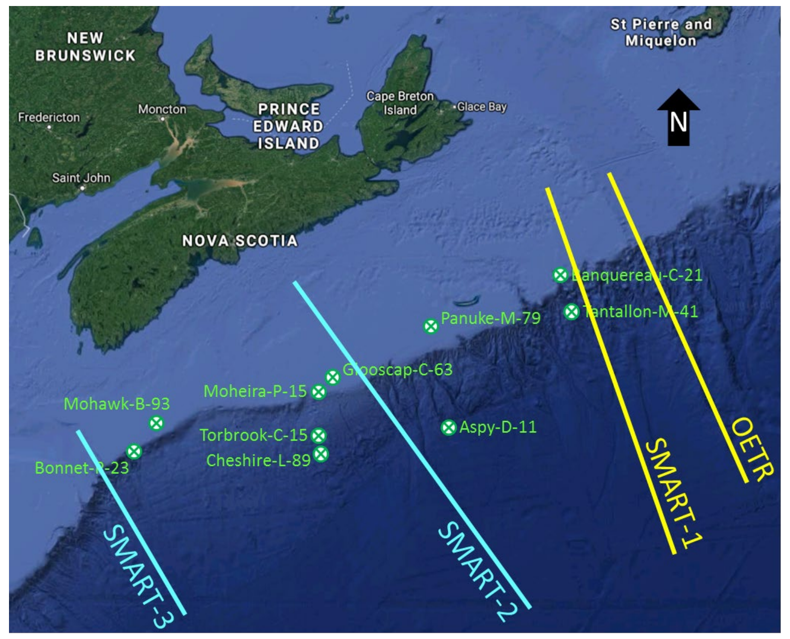


Figure 1.14. Map of the SMART-1/OETR profiles (Canada).

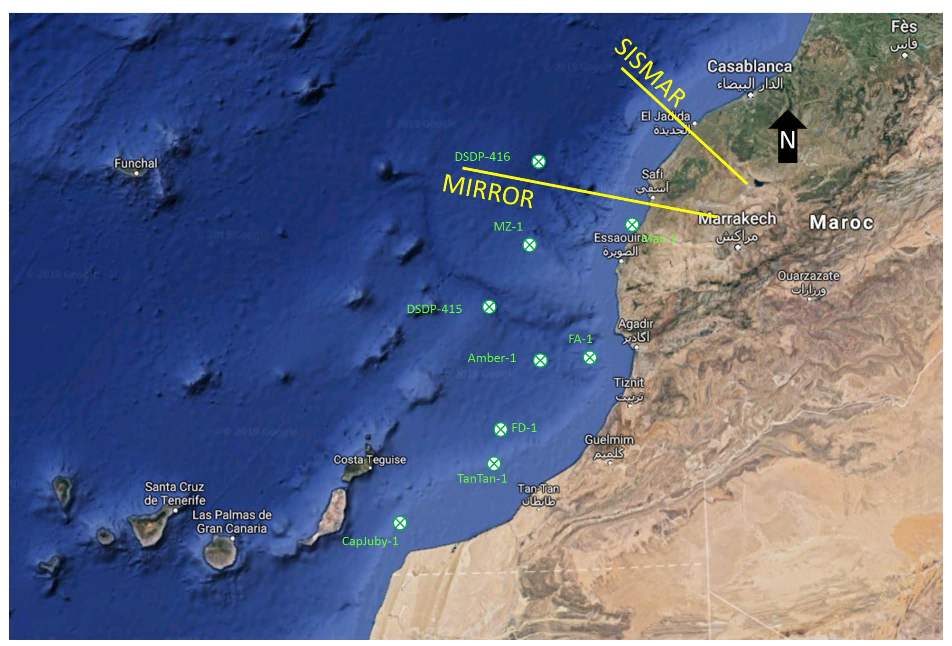


Figure 1.15. Map of the SISMAR-/MIRROR profiles (northern Morocco).

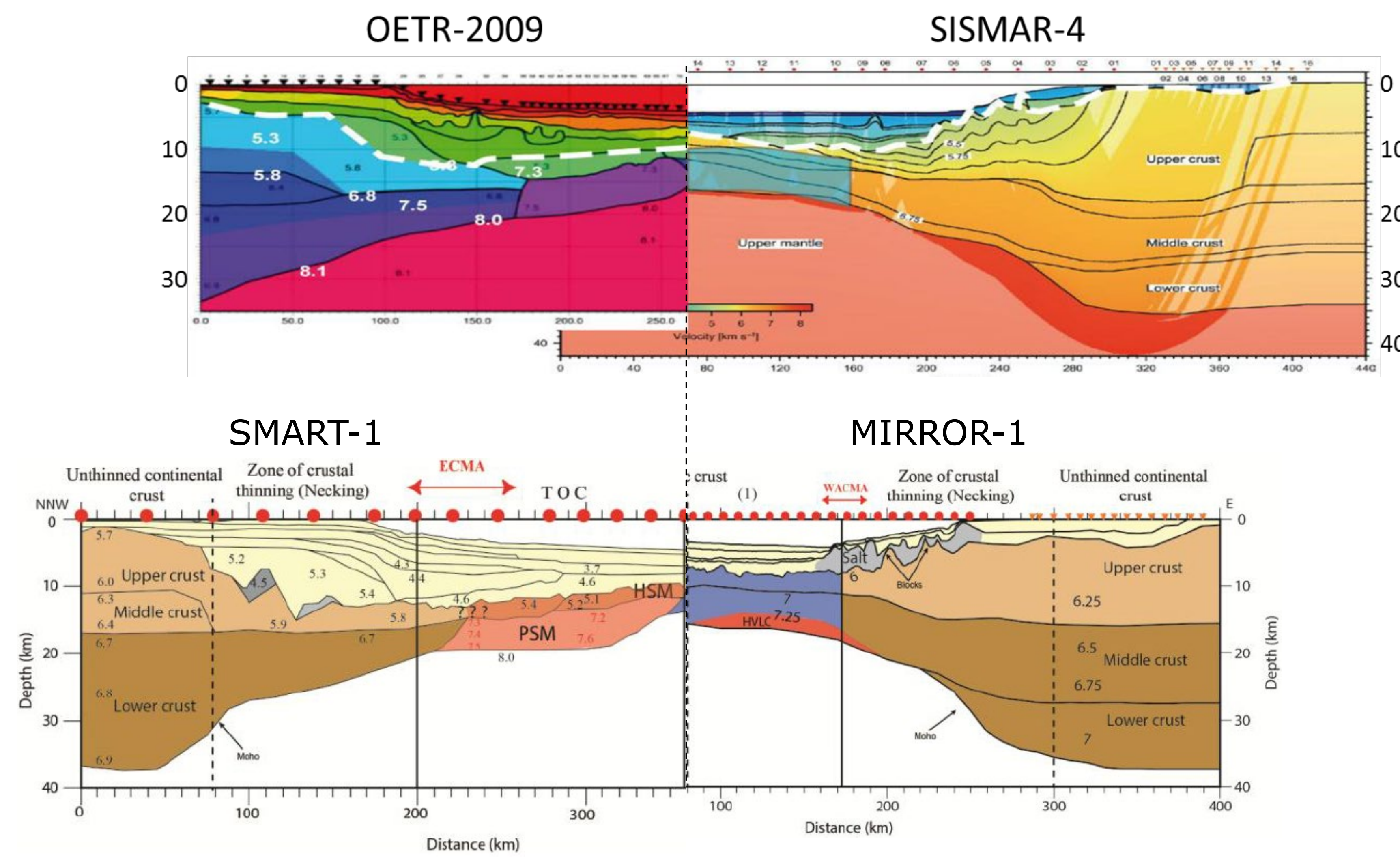


Figure 1.16. Conjugate Canadian and Moroccan margin profiles (OETR-2009 vs SISMAR-4, SMART-1 vs MIRROR-1) at -170Ma.

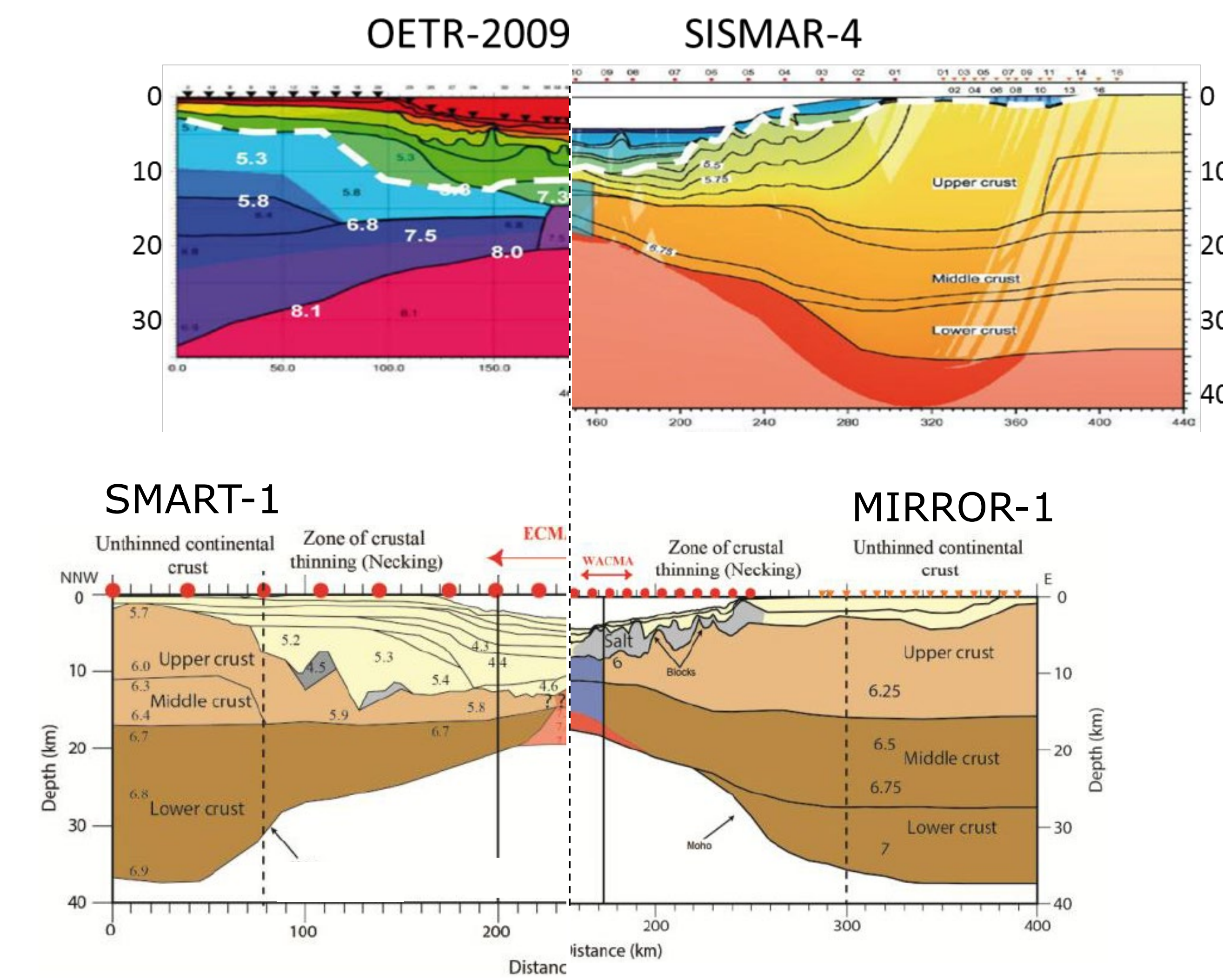


Figure 1.17. Conjugate Canadian and Moroccan margin profiles (OETR-2009 vs SISMAR-4, SMART-1 vs MIRROR-1) at -180Ma.

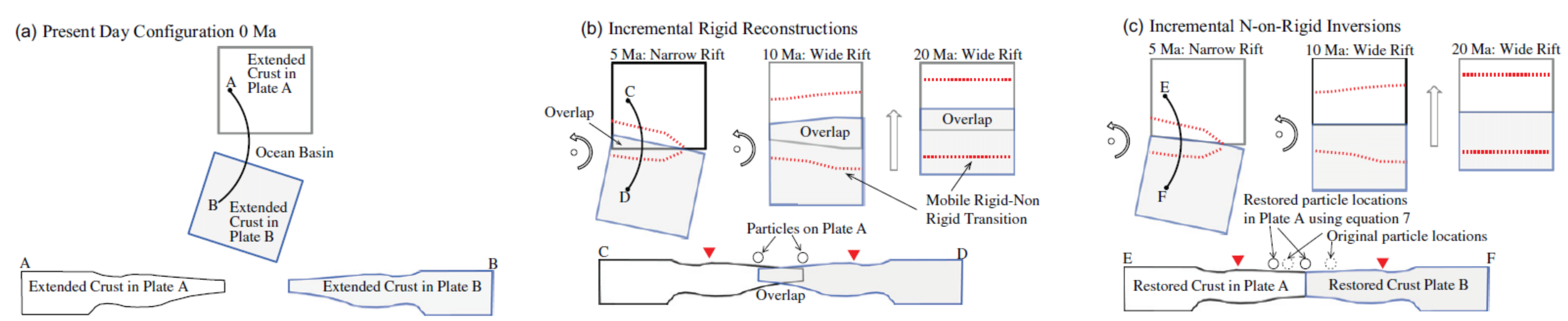


Figure 1.18. Schematic map view and crustal scale cross-section showing the importance of the restoration of stretched crust in kinematic reconstructions from Kneller et al. 2012.
Geometrical restoration of the stretched / thinned crust was only addressed through basement normal fault restoration and is probably underestimated in the present study. However these parameters directly control the thermal evolution of the margins and were considered in the basin modelling study.

Crustal model along Nova Scotia margin from SMART1

The velocity model has been developed and interpreted by Funck et al. (2004).
The continental crust is divided into 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 untill 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 in 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). An alternative interpretation based on the OETR 2009 refraction line with under plated magmatic body has been proposed (Luheshi et al. 2012).

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 SDRs at the offshore northern Morocco conjugate location has been reported by Maillard et al. (2006) and Roeser et al. (2002).

Crustal model along northern Morocco margin from SISMAR

Continental crustal thickness in northern Morocco was determined to be around 35 km (Contrucci et al., 2004), which is 7 km thicker than found for southern Morocco in this study. Both regions show deep sedimentary basins at the foot of the continental slope. Crustal thinning is more asymmetrical in the southern Moroccan profiles, where Moho depth decreases west of the increase of basement depth. No oceanic crust with anomalously high lower crustal velocities is found in northern Morocco on the SISMAR profile, but offshore central Morocco a high velocity lower crustal body associated with increased crustal thickness has been modelled from sonobuoy refraction seismic data (Holik et al. 1991), similar to the region of high velocities in oceanic crust found in this study.

Interpretation

Holik et al. (1991) interpret the high velocities as underplate from the passage of the Canary Hot Spot, but an alternative explanation might be serpentinite in the lower crust during the onset of seafloor spreading. The zone of continental thinning is about 150 km wide on the SISMAR-4 profiles

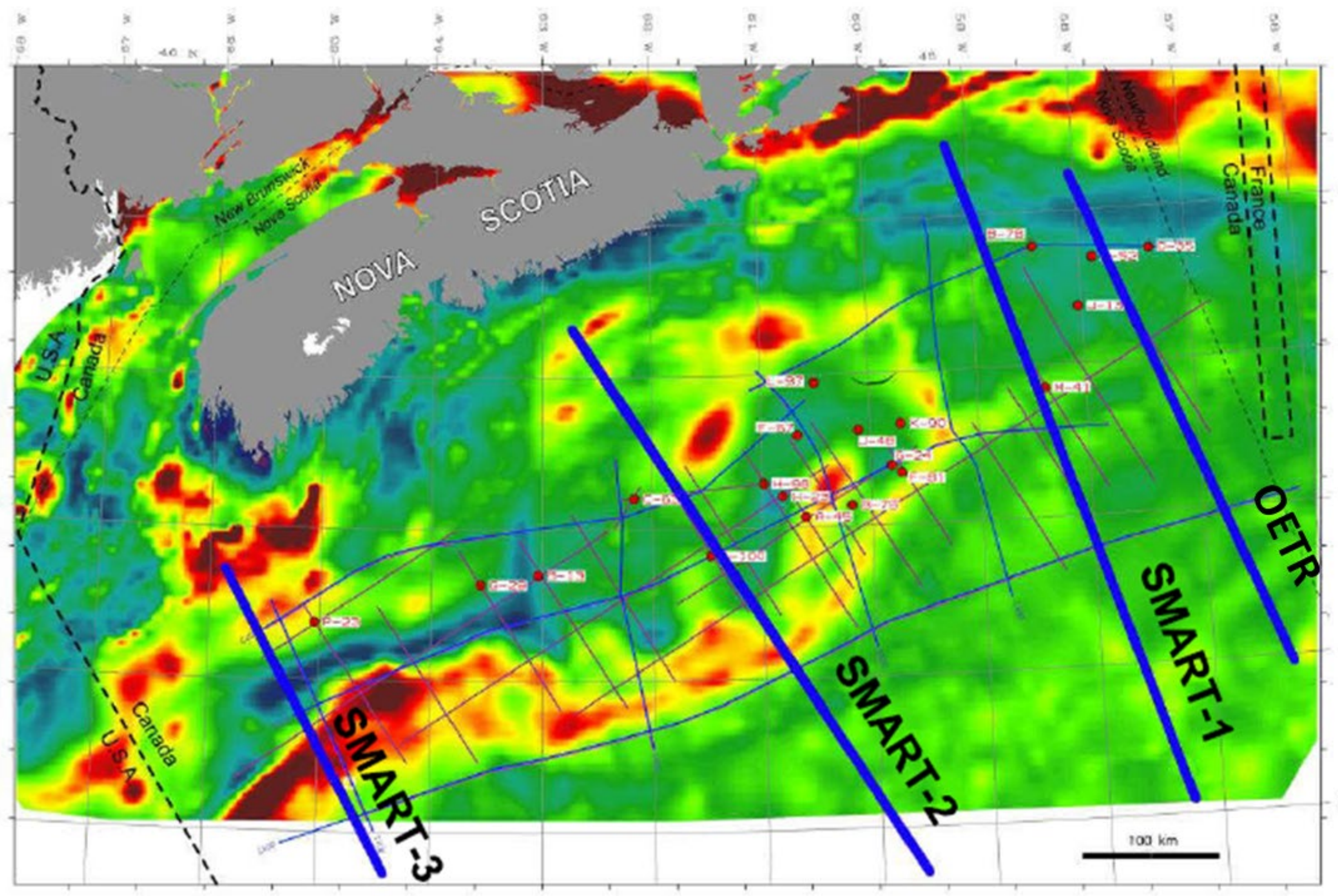


Figure 1.19. Location of the wide-angle seismic lines on the regional magnetic anomaly map.

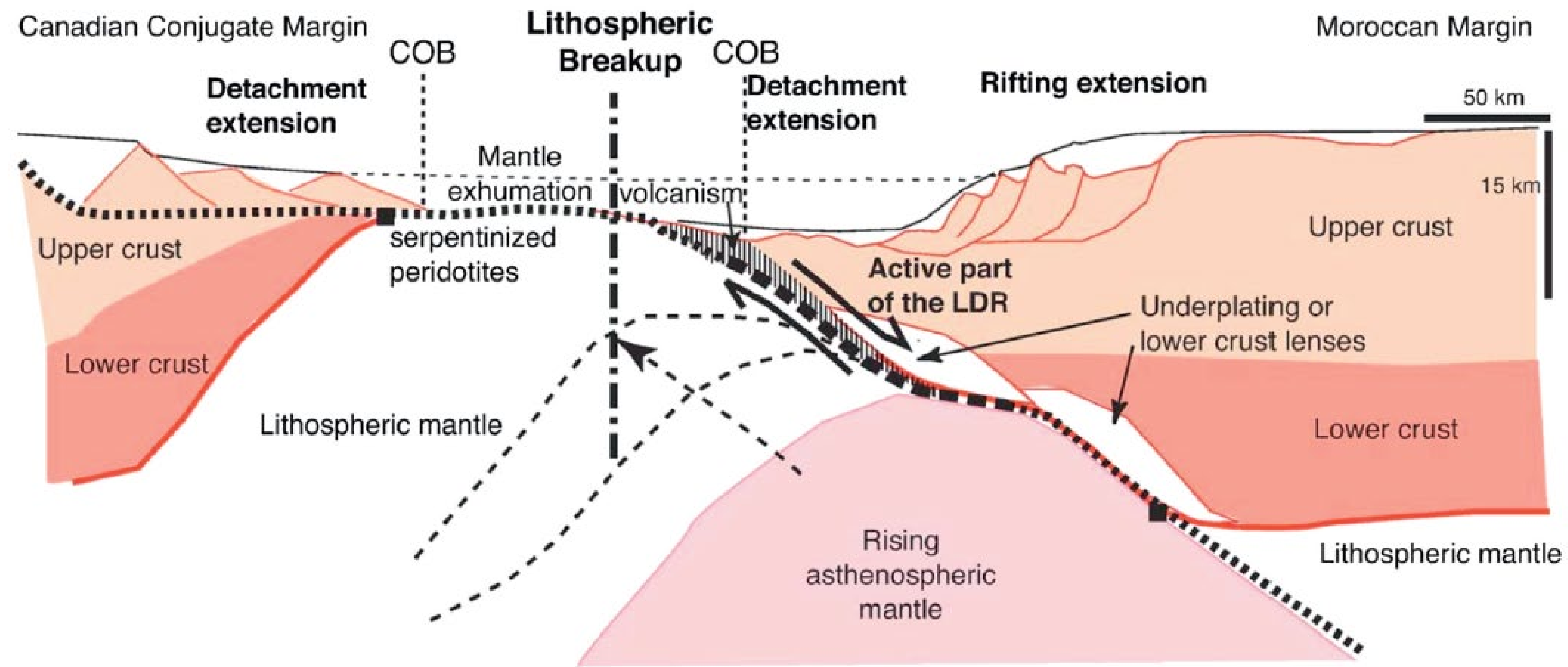


Figure 1.21. 2D-Model of the Morocco and Nova Scotia conjugate margins at a pre-rupture stage (based on the SISMAR and SMART 1 profiles, see location). The margin structure is based on seismic reflection and refraction data from the SISMAR and SMART cruises. Note the asymmetry of the margins at the continent-ocean boundary (COB). Black squares are homologous points along the large detachment fault, whose latest active part were landward dipping reflectors (LDRs) (from Maillard et al. 2006).

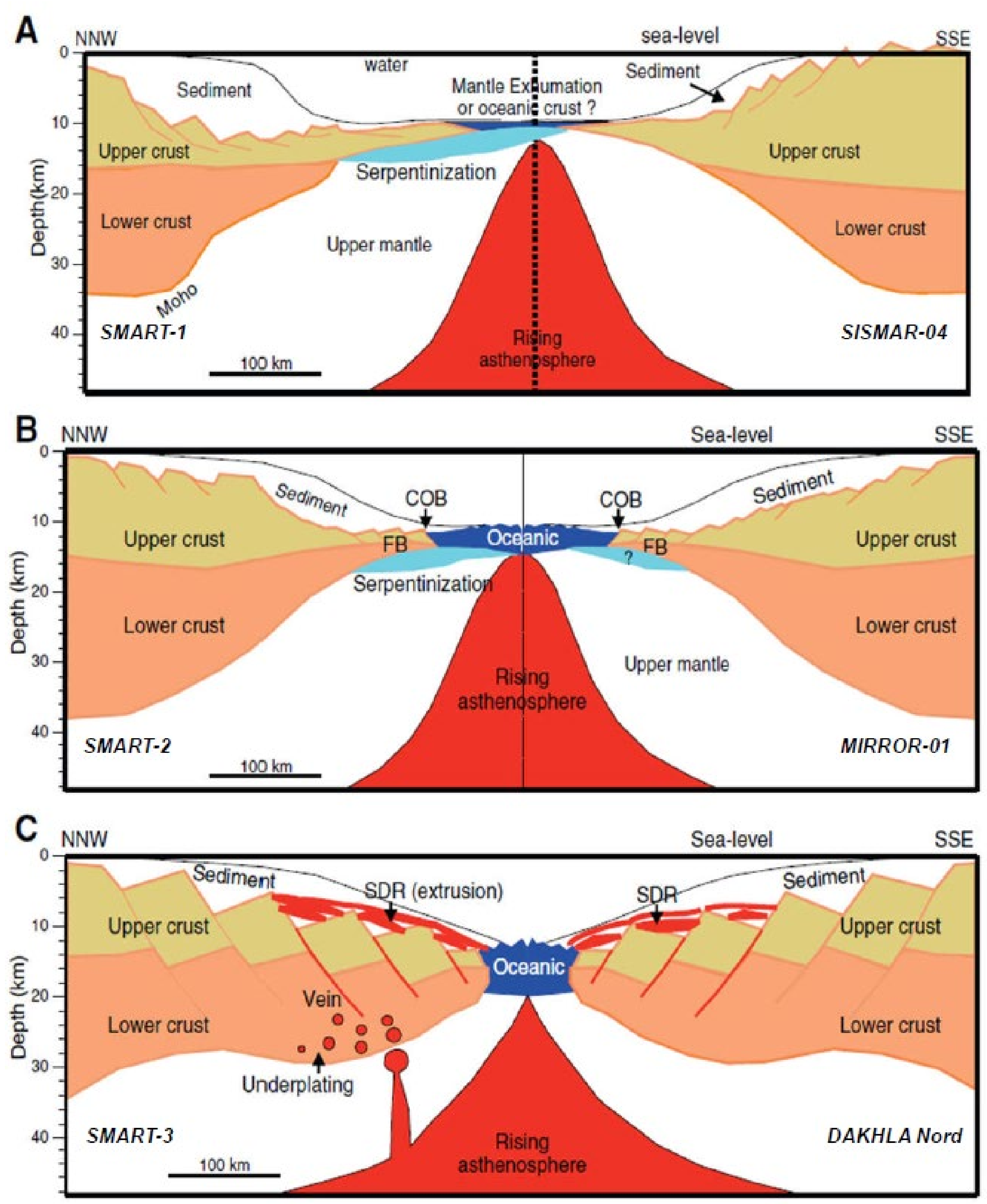


Figure 1.20. Schematic crustal scale cross-section showing possible architecture from mantle denudation with simple shear asymmetric margin (northeast) to symmetrical oceanic accretion pure shear margin (southwest) from "Systematic variations in basement morphology and rifting geometry along the Nova Scotia and Morocco conjugate margins", Louden et al., 2012.

Nova Scotia and Morocco: symmetrical or asymmetrical margins?

There is no definitive reason to conclude that the Nova Scotia and Moroccan passive margins, although conjugated, are asymmetrical margins.

Some differences exist however, as mentioned by Klingelhoefer et al., 2016 in *Crustal structure variations along the NW African continental margin: A comparison of new and existing models from wide-angle and reflection seismic data*.

The Moroccan passive continental margin reveals major along-strike variations in its deep structure. The unthinned continental crust in the Gulf of Cadiz region and along the northern Moroccan margin has a thickness between 35 and 37km. It thins towards the south to only 27km offshore DAKHLA. In the south, crustal thinning takes place in a narrow zone of 90 km with the upper crust thinning closer to the continent than the lower crust. The North Moroccan Basin is underlain by highly thinned continental crust only 6–8 km thick up to the position of the WACMA magnetic anomaly (Contrucci et al., 2004). Correspondingly the zone of crustal thinning is wider in the north, narrowing to the south. This difference indicates that rifting and initial opening of the oceanic basin has not followed identical mechanisms from north to south.

The ocean–continent transition zone shows a variable width between 40 and 70 km. Comparison of the seismic velocities in this zone with those of thinned continental crust, exhumed upper mantle and typical oceanic velocities indicates that rocks in this zone are probably of mixed continental and oceanic origin. Some elevated velocities are possibly associated with pockets of serpentinite or volcanic intrusions.

The SDRs are underdeveloped and are not a predominant feature present continuously along the complete margin, which was associated to only weak volcanism (Contrucci et al. 2004; Klingelhoefer et al. 2009; Biari et al. 2015).

The Nova Scotia conjugate passive margin is characterized by a decrease in the amount of volcanism associated with the original breakup from the south to the north. The amplitude of the ECMA decreases and vanishes at the latitude of 44°N. Comparison of both margins shows a similar continental crustal thickness and structure, however 3–4 km thinner oceanic crust on the American side than on the African margin (Funck et al. 2004; Biari et al., 2015). A zone of interpreted very thin continental crust underlain by serpentinized upper mantle present on the Canadian margin is not imaged along the NW African margin.

To conclude, if the margins are considered asymmetrical, this asymmetry appeared very early, probably even before the effective opening of the Atlantic ocean, during crustal thinning.

Asymmetrical or symmetrical margins?

Restoration at -190Ma

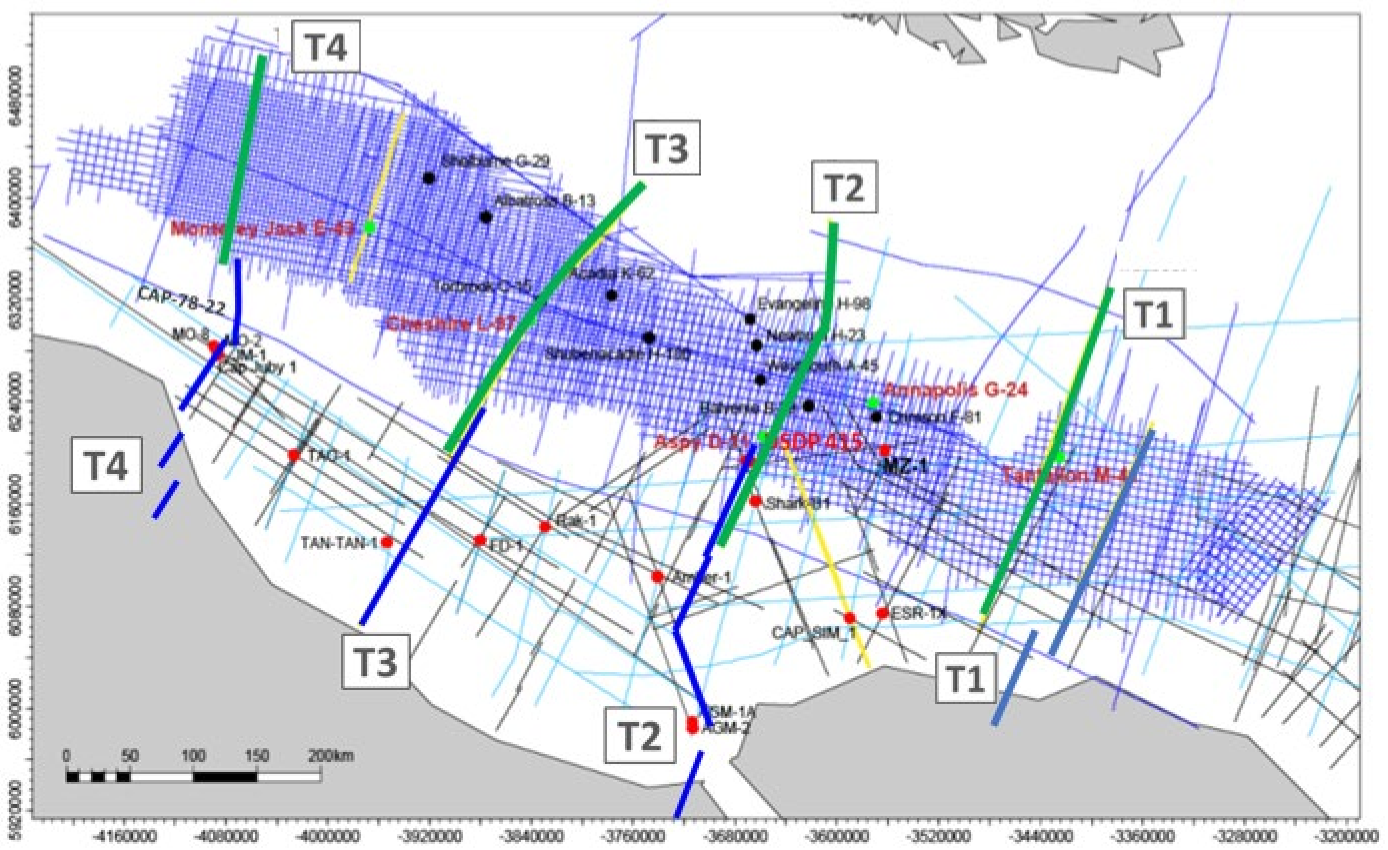


Figure 1.22. Reconstruction at -190Ma showing the relative location of the four transects. Tectonic Reconstruction performed with GPlates desktop software by D. Fraser Keppie, Nova Scotia Department of Energy, 2018.

Restoration at -170Ma

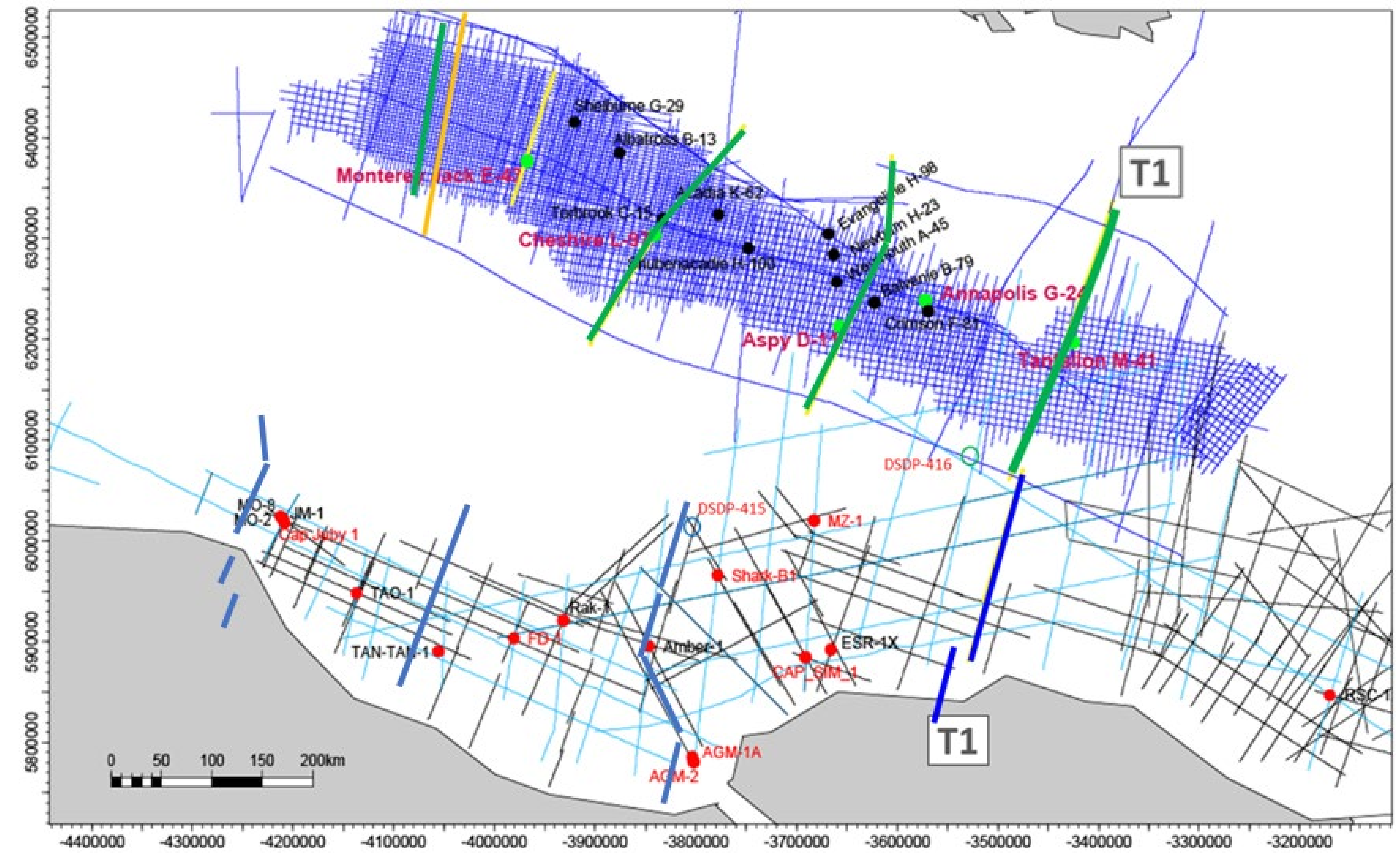


Figure 1.23. Reconstruction at -170Ma showing the relative location of the four transects. Tectonic Reconstruction performed with GPlate desktop software by D. Fraser Keppie, Nova Scotia Department of Energy, 2018.

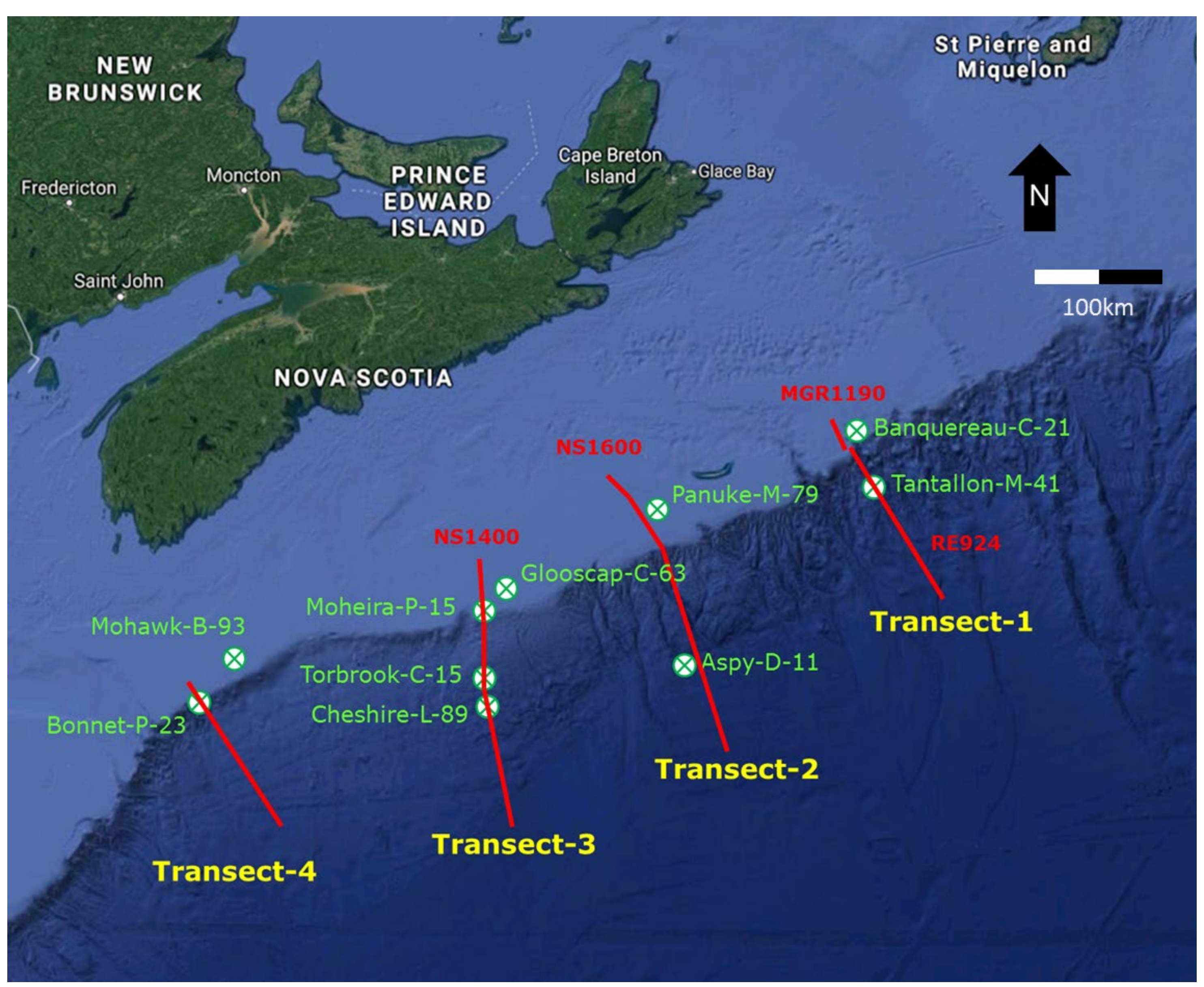


Figure 1.24. Map of the Canadian transects.

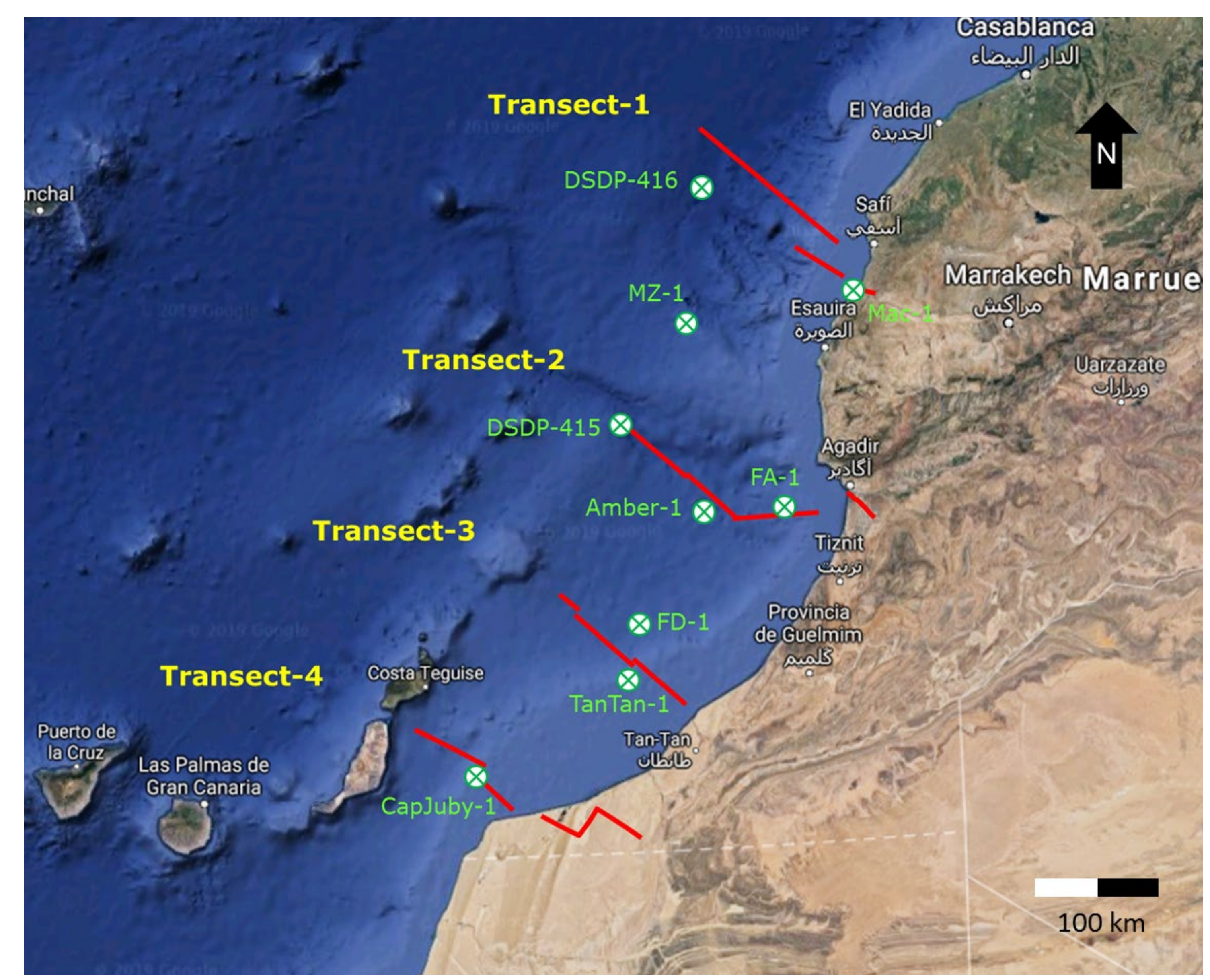


Figure 1.25. Map of the Moroccan transects.

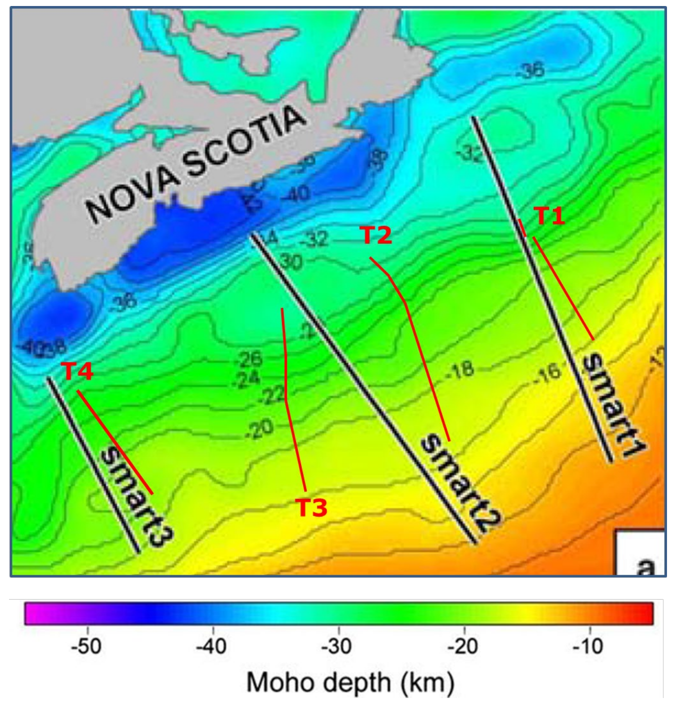
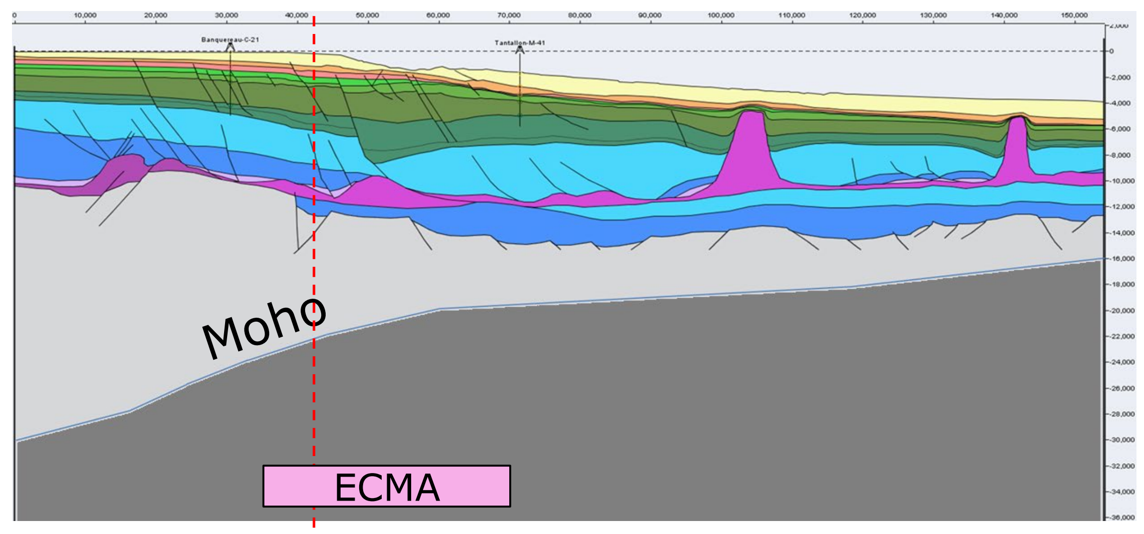
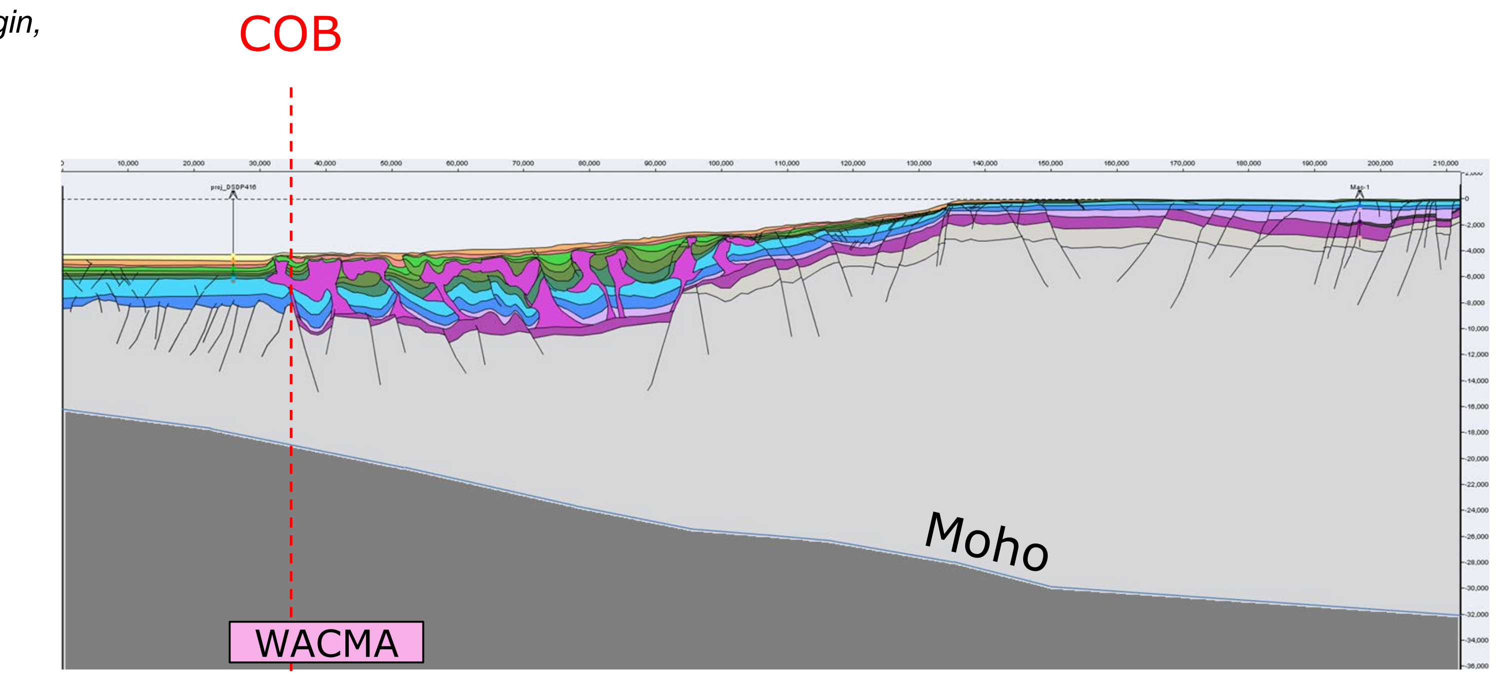
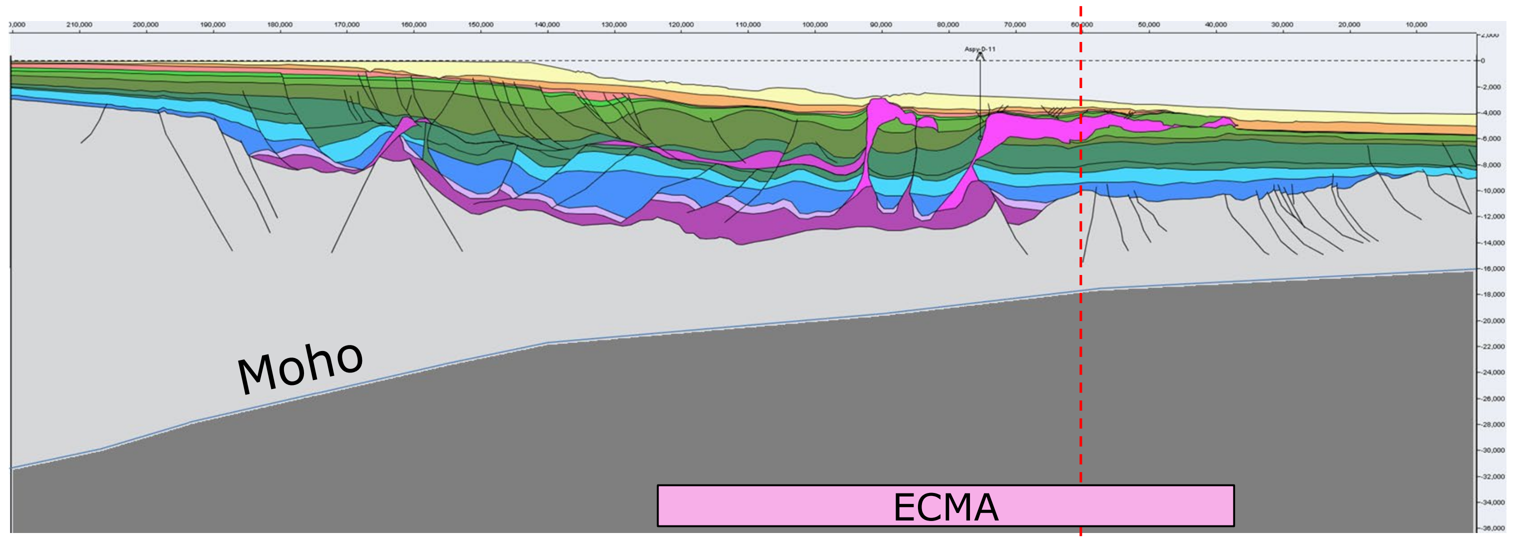
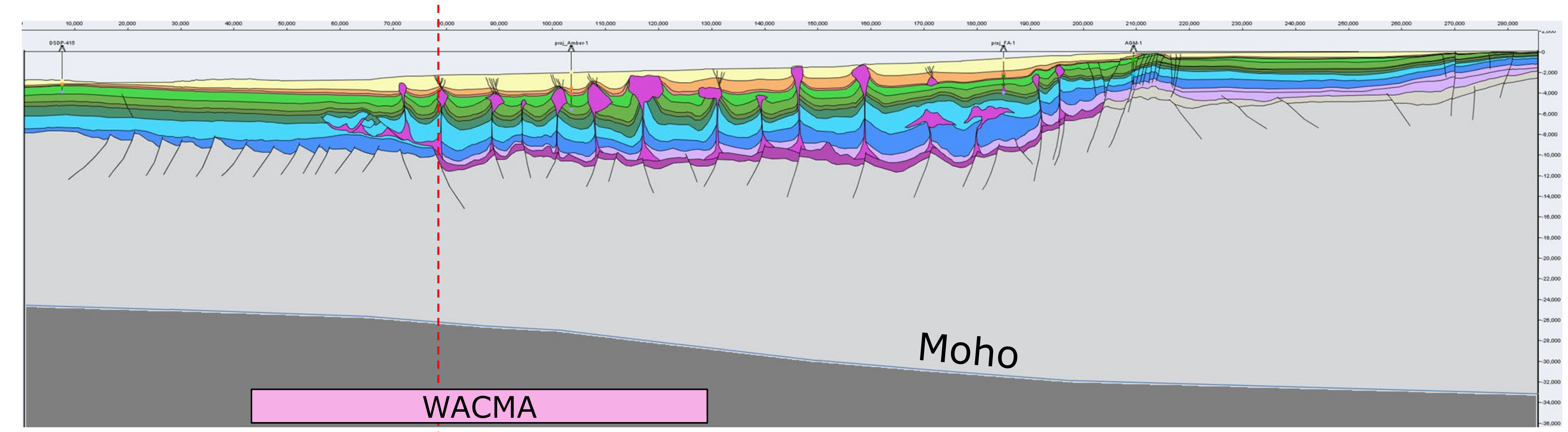


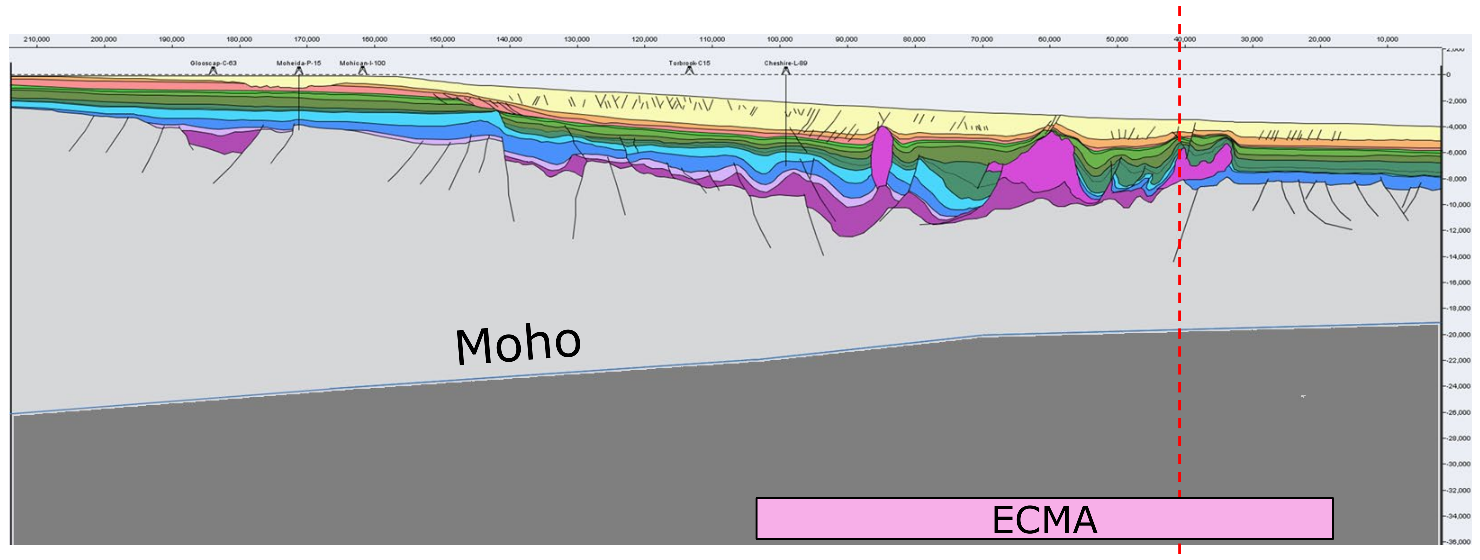
Figure 1.26. Moho depth maps after Dehler & Welford. Variations in rifting style and structure of the Scotian margin, Atlantic Canada, from 3D gravity inversion (Dehler & Welford, 2012)

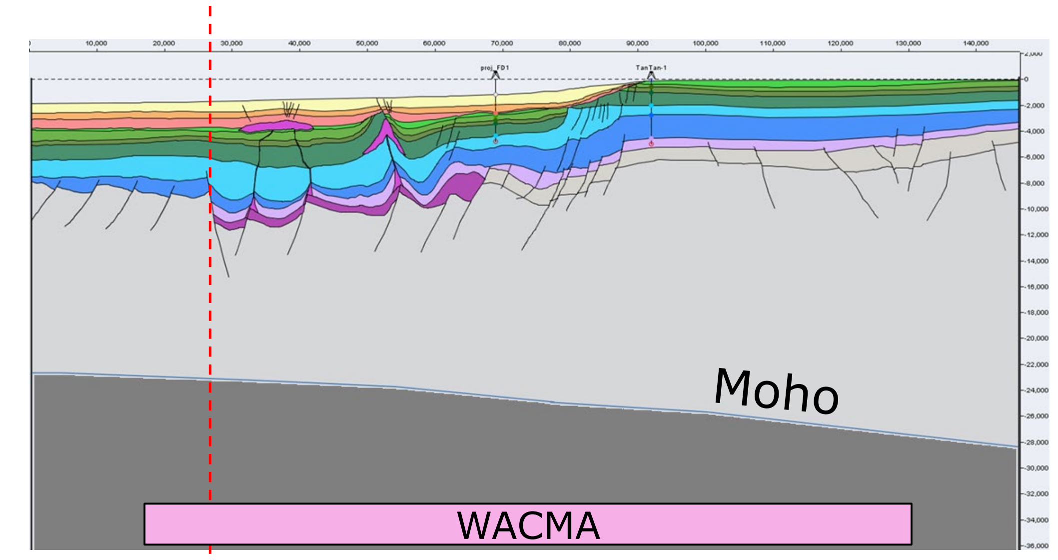


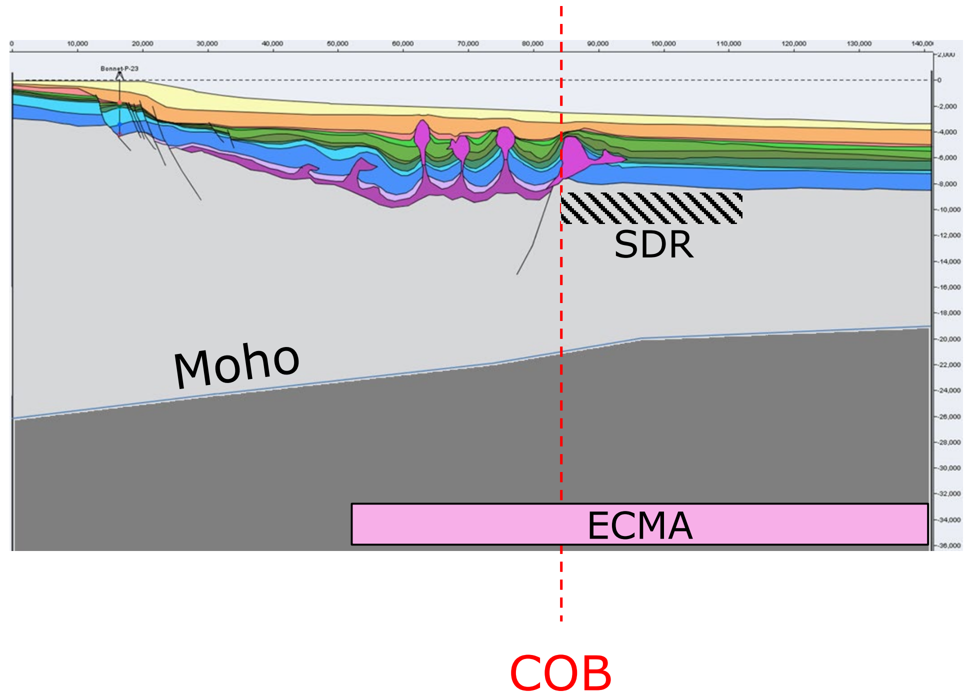












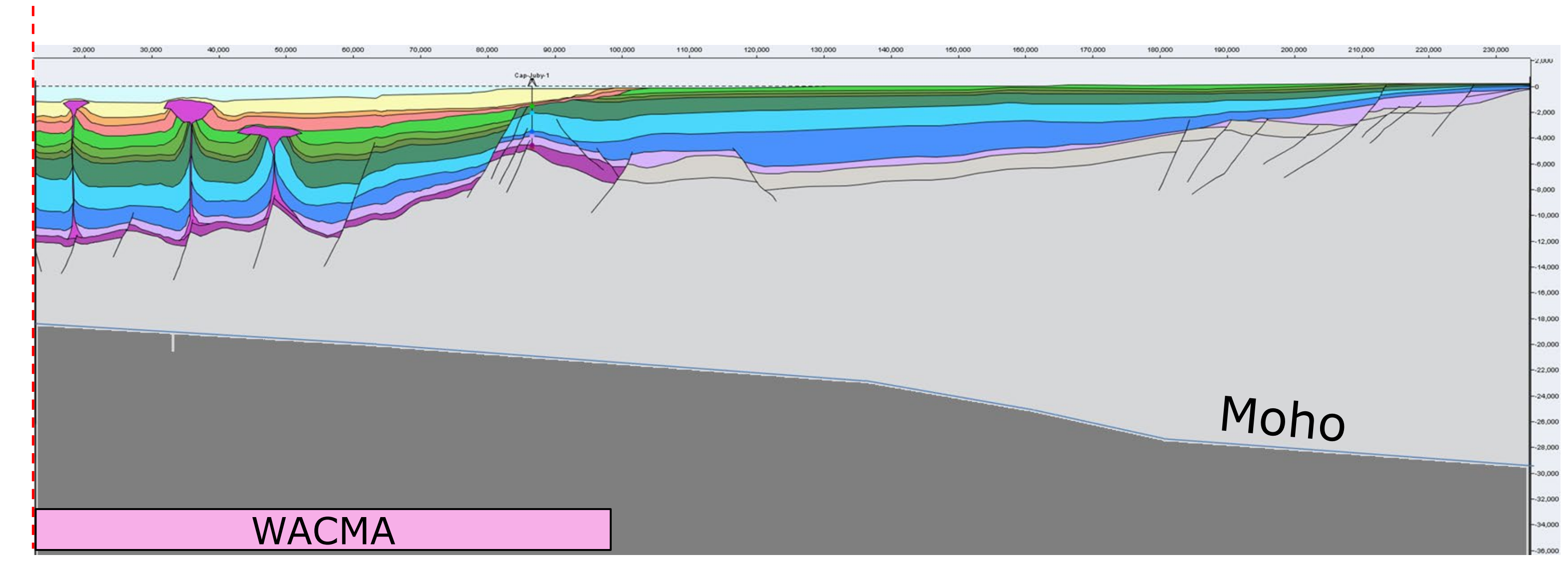


Figure 1.27. Moho estimation along each conjugate Nova-Scotia / Moroccan transect.
Approximative positions of SDR and magnetic anomalies are also displayed, where present.

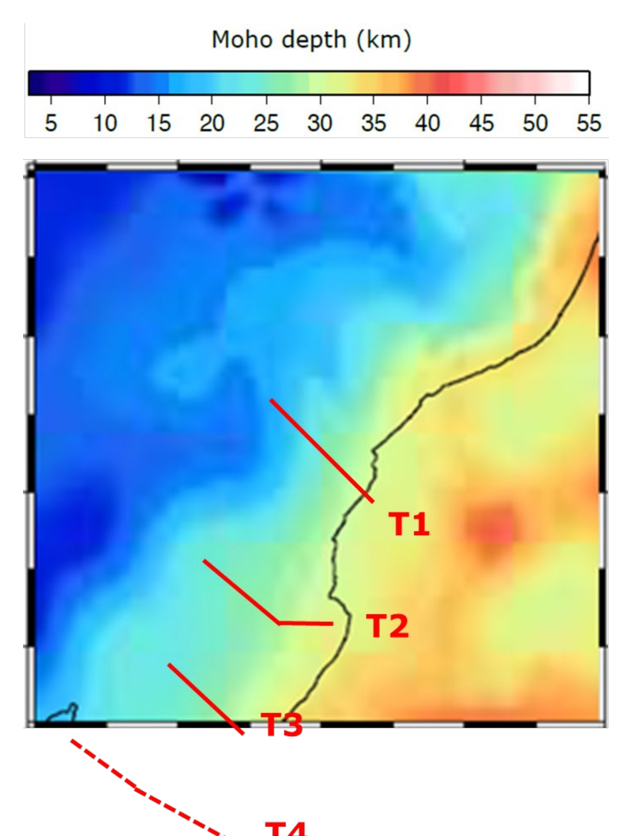


Figure 1.28. Crustal depth map from the joint interpolation of deep sounding seismic profiles and teleseismic receiver function estimations, completed with the CRUST1.0 model in the areas not sampled by seismic experiments.
From Diaz, J., Gallart, J. and Carbonell, R., 2016.

Transects, Moho depths and magnetic anomalies positions

Summary

- Plate reconstruction at 190 Ma provides a good fit of the main elements of the conjugate margins
- ECMA and WACMA restoration at 190 Ma suggests deep symmetrical processes between 190 and 170 Ma
- Asymmetry exists:
  - Slight asymmetric rate of opening in the early stages of opening
  - Moho geometry slightly asymmetric
- Inherited faults control salt basins and plate break-up geometry (zig-zag pattern)
- Along strike variations on both margins with significant differences:
  - Compressional event of the High Atlas during Neogene-Quaternary times produced reverse and strikes-slip faults in the offshore domain of the Tafelney plateau
  - Canaries and Madeira volcanism since 60 Ma controls Tarfaya and Agadir Basin geometries
  - Probable influence of hot-spot event on the maturation processes

Uncertainties

- Difficult to select a single geodynamic model: “pure shear” versus “simple shear” or “magma poor” versus “magma rich”.
- Distinct geodynamic evolution of the two margins since the Cretaceous
- Impact of the slight asymmetry on petroleum systems is difficult to evaluate