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Plate tectonic reconstructions and paleogeographic maps of the central and North Atlantic oceans

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Abstract:

We have established a new plate kinematic model of the Central and North Atlantic oceans between North America, Africa, Meseta, Iberia, Flemish Cap and Galicia Bank from Late Triassic to Late Cretaceous in order to better understand the nature and timing of rifting of Nova Scotia and Morocco conjugate continental margins since Late Triassic. The maps of salt distributions at the Sinemurian/Pliensbachian limit (190 Ma) (after salt deposition) and in Middle Bajocian (170 Ma) show that an area of the Nova Scotia margin is devoid of allochtonous salt and that an area of similar size located oceanward of the West African Coast Magnetic Anomaly shows salt deposits suggesting that a portion of the Nova Scotia margin with its overlying salt deposits could have been transferred onto the Moroccan side right after the formation of the conjugate East Coast Magnetic Anomaly and West African Coast Magnetic Anomaly. Seven paleogeographic maps, from Late Triassic to Late Cretaceous, are presented with structural elements and magnetic lineations. They show that the connection between the Central Atlantic and the Tethys with an aborted rift between Iberia and North America ending in the North against the Flemish Cap-Galicia Bank dam started to deepen at the end of the first rifting phase (190 Ma ago) after the rupture of the thinned continental crust. It is only during the Early Cretaceous, after the rupture of the Flemish Cap-Galicia Bank dam, that the deep connection around Iberia was finally established between the central and north Atlantic, the Tethys and the Bay of Biscay.

Keywords: Paleogeographic maps ; North Atlantic ; Central Atlantic ; Plate kinematics

1. Introduction

The Gradstein et al. {, 2004 #488} geologic time scale is used all along this paper. Plate reconstructions in the Central Atlantic have been recently updated from Late Triassic (203 Ma) to present {Labails, 2010 #543}. However, there are still no published reconstructions between Iberia (IB) and North America (NA) for periods older than M0 (125 Ma). We propose to establish a series of plate kinematic reconstructions between NA, IB and Eurasia (EU) since Late Triassic to provide a set of paleogeographic maps for periods spanning from Late Triassic to Late Cretaceous. To fulfill this objective, we will i) re-examine newly obtained magnetic data in the Central Atlantic to better define the trends of the conjugate East Coast Magnetic Anomaly (ECMA) and West African Coast Magnetic Anomaly (WACMA) in order to update their fits; ii) establish maps of salt distribution at 190 Ma (after salt deposition) and 170 Ma to demonstrate that a portion of the Nova Scotia margin with its overlying salt deposits was probably transferred on the Moroccan side just after the formation of the conjugate ECMA and WACMA lineations (190 Ma), providing a new constraint on the kinematic reconstructions at 190 Ma. iii) Establish paleogeographic reconstructions of the central and north Atlantic oceans for seven periods:

1) Late Triassic - Pre-rift configuration (Norian/Rhaetian limit, about 203 Ma),

2) Early Jurassic - end of rifting (after occurrence of the Central Atlantic Magmatic Province (CAMP) and salt deposition) (ECMA, Sinemurian/Pliensbachian limit, 190 Ma): Paleogeography of Early Jurassic (Sinemurian-Toarcian),

3) Middle Jurassic (Blake Spur Magnetic Anomaly (BSMA), Middle Bajocian, 170 Ma): Paleogeography of Middle Jurassic (Bajocian-Bathonian),

4) Late Jurassic (M22, Tithonian, 150 Ma): Paleogeography of Late Jurassic (Oxfordian-Portlandian),

5) Early Cretaceous (M11, Valanginian, 136 Ma): Paleogeography of Early Cretaceous (Berriasian-Barremian),

6) Middle Cretaceous (M0, Late Barremian/Early Aptian, 125 Ma): Paleogeography of Middle Cretaceous (Aptian-Albian),

7) Late Cretaceous (C34, Santonian, 83.5 Ma): Paleogeography of Late Cretaceous (Cenomanian-Danian).

2. Northern prolongation of ECMA and WACMA

The magnetic grid of Verhoef et al. {, 1996 #298} has been updated by incorporating magnetic data available since this compilation and a detailed magnetic survey acquired in the northeastern prolongation of ECMA {Dehler, 2010 #557}. A color-coded representation of this grid is shown in Figure 1. Compared to the original map of Verhoef et al. {, 1996 #298}, this new compilation clearly shows that it largely benefits from the newly incorporated data set, some of them being of high resolution.

East of 58.5°W, the amplitude of the ECMA is considerably reduced and associated magnetic anomalies broaden (Figure 1). This contrasts the previous interpretations (e.g. Sahabi et al. {,

2004 #547}). Whereas in the south the ECMA features a single positive anomaly that locally splits into two branches, the northward continuation shows a rather different signature. First, the amplitude is two to three times smaller than in the south. Second, the northeastward prolongation mostly appears as a linear borderline between a large negative anomaly to the north (blue in Figure 1) and a gently varying positive anomaly to the south (cyan in Figure 1). Thus, the northeastward prolongation of the ECMA is straightforward for its landward side and, using the magnetic iso-contours up to 56.5°W, it could be defined as a stripe not wider than the ECMA southward. Alternatively, it might also be interpreted as an absence of the ECMA lineation over ~120 km. Further east, only individualized, shorter extent, anomalies could be interpreted as the possible prolongation of the ECMA. Notice that between 58.5°W and 57.4°W the trend is parallel to the margin, whereas further east, offshore the Laurentian Channel, it significantly departs from the trend of the shelf break.

Thus, the nature of the ECMA is different east and west of 58.5°W. Refraction lines SMART01 {Funck, 2004 #204}, SMART02 {Wu, 2006 #559} and OETR2009 {Luheshi, 2012 #638} are located west of 58.5°W. They show similar crustal features, in particular the presence of a high velocity, deep body interpreted as serpentinized peridotite. It has been suggested by forward modeling {Dehler, 2010 #557} that the ECMA may originate from the upper mantle decompressional melting as a very thin layer of volcanics located above the seaward end of the thinned continental crust, slightly extending to the northwest of the high velocity body. The ECMA may be also partly caused by the edge effect due to the juxtaposition of a ~6-km thick magnetized serpentinized body and the poorly magnetized thinned continental crust. East of 56.5°W, the disconnected small magnetic anomalies interpreted as a possible prolongation of the ECMA suggest that both the high velocity body and the partly overlying volcanic layer are probably discontinuous or severely reduced in size.

Figure 2 shows the northeastern central Atlantic magnetic grid of Verhoef et al. {, 1996 #298} updated with newly available data (courtesy of S. Delher, personal communication, 2010). Following the interpretation of Sahabi et al. {, 2004 #547}, the WACMA is bounded by a white line while our new identification in the north is shown with a red outline. The rotated ECMA is divided into two parts: one south of 30°N, is rotated as part of the Africa (AF) plate using the NA/AF rotation parameters of Labails et al. {, 2010 #543}, while the northern part, north of 30°N, is rotated as part of the Meseta (MES) plate using the NA/MES rotation parameters of Labails et al. {, 2010 #543}. The two rotated portions of ECMA are drawn in black.

North of 32.8°N, our identification of the WACMA (in red) does not follow Sahabi et al. {, 2004 #547} but is parallel to the Moroccan continental slope. It follows the S anomaly of Roeser et al. {, 2002 #544} up to 32.8°N and then follows a series of distinct positive anomalies similar to those of the ECMA located east of 56.5°W. Roeser et al. {, 2002 #544} do not identify S north of 33.4°N. If the portion of Labails et al. {, 2010 #543} WACMA located north of 33.4°N is rotated on the NA side with the MES/NA parameters of Labails et al. {, 2010 #543}, the rotated feature would be located on the NA continental shelf and significantly away from the ECMA trend. We consequently question the validity of Labails et al. {, 2010 #543} identification of the WACMA north of 33.4°N.

North of 33.4°N, the fit of our ECMA and WACMA is much better than the one of Labails et al. {, 2010 #543} though not perfect as ECMA and WACMA are tangent in the south but overlapping north of 32.5°N. This discrepancy in the fit might have various origins: 1) A different nature of ECMA north of 58.5°W or similarly north of 32.5°N for WACMA. 2) The possible lack of ECMA between 58.5°W and 56.5°W (Figure 1). 3) A wrong identification of the northern part of WACMA. However, a better fit between ECMA and WACMA is conceivable for portions of

anomalies belonging to the MES, i.e. north of 30°N in Figure 2. In a first attempt, we suggest Labails et al.'s {, 2010 #543} parameters of rotation to rotate the portion of WACMA south of 30°N with AF/NA parameters and to rotate the portion of WACMA north of 30°N with MES/NA parameters.

The good fit between the ECMA and WACMA lineations, even if their amplitudes significantly differ not only along strikes but also on each side of the central Atlantic Ocean, suggests that the two features are conjugate and thus can be used as isochrons for plate kinematic reconstructions. Louden et al. {, 2012 #642} also used the same NA/AF pole of rotation (Table 1) but without adding an additional rotation for the Moroccan Meseta. West of 64°W, the Nova Scotia margin is volcanic as illustrated by SDRs sequences observed along numerous multi-channel seismic (MCS) profiles and thickened high-velocity lower crust {Dehler, 2004 #643}, indicative of underplating. East of 64°W, neither excessive volcanism nor evidence of underplating is ~~not~~ observed, and non-volcanic extension occurred along both conjugate margins {Louden, 2012 #642}. Along the same set of conjugate MCS profiles, Louden et al. {, 2012 #642} show that the seaward limit of Nova Scotian and Moroccan continental crusts are adjacent on their reconstruction, another argument in favor of the validity of this reconstruction. However, on some of the conjugate margins MCS profiles, the thinned continental crust extends seaward of the salt basins, suggesting (1) a different age for the end of salt deposition on the two conjugate margins as observed on the Angola-Brazil conjugate margins {Karner, 2007 #501} or (2) a final breakup ending slightly after chron ECMA. For the sake of simplicity, we will assume that the breakup occurred at the end of the formation of chrons ECMA and WACMA.

The age of isochron ECMA is still debated. Several researchers have related the ECMA to the Central Atlantic Magmatic Province, with most of the volcanism occurring around 202-200 Ma (e.g. {Hames, 2002 #652}) but it is still disputed {Benson, 2002 #653} and other researchers suggest that breakup occurred sometime afterward (e.g. {McHone, 2003 #655}). The age of continental breakup is poorly constrained by the formation of oceanic crust, which spanned from 185 Ma to 175 Ma {Roeser, 2002 #544;Schettino, 2009 #565} or to 195 Ma to 185 Ma {Olsen, 1997 #656;Wade, 1990 #553}. In this paper we follow Sahabi et al. {, 2004 #547} who considered the Central Atlantic synrift salt basins as key constraints in the closure of thinned continental crusts of the Central Atlantic margins. They estimated the end of chron ECMA to be Late Sinemurian (190 Ma) on the basis of the age of salt deposits {Jansa, 1980 #617;Wade, 1990 #553}.

3. Reconstructions of the central and north Atlantic oceans

Before reconstructing the seven paleogeographic maps of this region, the rotations of the five plates involved in this work namely AF, MES, IB, Galicia Bank (GB) and Flemish Cap (FC) with respect to the NA plate, kept fixed in all the reconstructions of this study, have to be determined and/or validated. The AF/NA and MES/NA parameters of rotation of Labails et al. {, 2010 #543} will be used but we need to establish the IB/NA, GB/NA and FC/NA parameters of rotation for times earlier than M0 because the oldest IB/NA parameters of rotations were properly established only from chron M0 onward {Srivastava, 2000 #286}. We have to test several hypotheses. In particular: 1) What was the IB/MES motion during the Nova Scotia/Morocco rifting from Late Triassic to Early Jurassic? 2) Was Iberia attached to North America during most of the Jurassic, from Sinemurian (195 Ma) to around M25 (154 Ma)? 3) Was Iberia attached to Meseta and/or Africa from M25 until more recently to C13 (34 Ma, Late Eocene) as demonstrated by Srivastava et al. {, 1990 #126}? 4) What are the GB/IB parameters of rotation

and the timing of motions? 5) What are the FC/NA parameters of rotation and the timing of motions?

The rotation parameters used in this study appear in Table 1.

3.1. Methodology used for plate reconstructions

Figure 3a shows the M0 reconstruction with the main kinematic elements (magnetic picks, fracture zones and bathymetric contours) used to calculate the parameters of rotations for specific chrons (Table 1). We have adopted Labails et al.'s {, 2010 #543} parameters of rotation for the MES/NA and AF/NA from the tightest reconstruction (Norian/Rhaetian limit, about 203 Ma) to chron M0. The IB/NA reconstructions are well constrained from M0 onward (e.g. {Srivastava, 2000 #286;Srivastava, 1988 #288}) but poorly constrained for older periods. This is because the amplitudes of magnetic anomalies belonging to the M sequence are considerably reduced on the IB side compared with the NA side. An extensive study of abyssal peridotites {Oufi, 2002 #425} demonstrated that magnetic susceptibility remains modest for degrees of serpentinization lower than 75% but increases rapidly for higher degrees of alteration. Serpentinites also exhibit irregular natural remanent magnetization values, which may exceed 5 A/m. Thus, the contribution of peridotites to creating magnetic anomalies can become significant when they are highly serpentinized. Sibuet et al. {, 2007 #479} inverted magnetic data (Euler deconvolution) along an E-W trending profile located within the Iberian Abyssal Plain and showed that magnetic sources are N-S trending, horizontal 'cylindrical' bodies located within the highly serpentinized portion of exposed mantle. Although the magnetic anomalies are weak, they bear all the characteristics of seafloor spreading anomalies. Consequently, within transitional lithosphere characterized by exhumed mantle, sequences of magnetic anomalies may provide information about the timing of emplacement of the basement {Sibuet, 2007 #479}. Therefore, assuming the IB-NA magnetic lineations give the age of emplacement of the transitional lithosphere, we propose the IB/NA kinematic story for periods older than chron M0. We must note that the serpentinized mantle has been clearly identified on the NA side east of M15 {Lau, 2006 #644}. However, the older magnetic lineations up to M20 are located above a ~3-km thick thinned continental crust which overlays a 7.6 high-velocity body {Lau, 2006 #644}. We suggest that this high-velocity body might be also serpentinized mantle thus generating magnetic anomalies by the serpentinization process {Sibuet, 2007 #479}, even in the presence of an overlying thinned continental crust.

3.2. M0 reconstruction north of the Newfoundland/Gibraltar Fracture Zone

Parameters of rotation of Srivastava et al. {, 2000 #286} for IB/NA and Srivastava et al. {, 1992 #287} for EU/NA are used for the M0 reconstruction (Table 1 and Figure 3a). GB and FC are in their present-day positions with respect to IB and NA respectively.

3.3. M11 and M22 reconstructions north of the Newfoundland/Gibraltar Fracture Zone

Reasonable hypotheses have to be assumed for the M22-M0 period where magnetic picks exist between IB and NA, but mostly on the NA side:

a) Due to the lack of fracture zones pattern between IB and NA and to the extremely low number of magnetic picks, on the IB side, mostly identified on scarce deep-tow magnetic data {Srivastava, 2000 #286}, it is impossible to unambiguously fit conjugate magnetic anomalies. However, the comparison of the picks' distribution on both sides shows that the degree of

asymmetry is almost negligible. Thus, a symmetrical seafloor spreading is assumed and only the NA magnetic lineations are used, which are of high amplitude and clear.

b) Fits at M11 and M22 have been computed with respect to the M0 fit by doubling the M0-M11 and M0-M22 distances calculated on the NA side and, in the absence of fracture zones, by assuming that motions were parallel to the Newfoundland-Gibraltar Fracture Zone (NGFZ) (Figure 3a). The final results appear in Figure 3b and Table 1, showing a lateral continuity between the northern Iberia and northeastern Flemish Cap bathymetric trends, supporting the hypothesis of IB/NA motions occurring parallel to the NGFZ.

c) GB/IB closure is done assuming 105 km of extension between GB and IB during the M11-M22 period {Murillas, 1990 #353;Sibuet, 2007 #415} with the pole of rotation sent to 90° as the width of the N-S trending Galicia Interior Basin (located between IB and GB) is constant from north to south. Thus, at chron M11, GB was in its present-day position with respect to IB and at chron M22 in its full closure position.

d) The FC/NA angle of rotation {Sibuet, 2007 #415} has been adjusted to fit the 3000-m isobaths west of GB and southeast of FC. Indeed, Le Pichon and Sibuet {, 1981 #64} have demonstrated that for several starved passive margins, fitting the 3000-m isobaths roughly gives the pre-rift positions of continents.

3.4. Reconstruction at closure (203 Ma) north of the Newfoundland/Gibraltar Fracture Zone

The fit at closure (203 Ma) have been computed by assuming:

a) fit of the NA and IB 3000-m isobaths and along-strike continuity between northern Iberia and southeastern Flemish Cap bathymetric trends,

b) FC/NA closure as established by Sibuet et al. {, 2007 #415},

c) GB/IB closure as already established for M11 and M22 reconstructions.

The results displayed in Figure 3b are particularly satisfactory, with an excellent fit of the 3000-m isobaths of both southeastern Flemish Cap-west Galicia Bank and IB-NA.

3.5. ECMA reconstruction north of the Newfoundland/Gibraltar Fracture Zone

Salt deposits not only occurred on the Nova Scotia and Morocco margins from Rhaetian to Sinemurian but also between IB and NA during the same period {Tucholke, 2007 #482}, suggesting rifting also occurred in the Newfoundland-Iberia rift between 203 Ma and chron ECMA. Without any further constraint for the moment, we have assumed that IB and MES were moving together during this period, i.e. that a continuity in the amount of extension and direction of motion existed along the whole NA margin from Nova Scotia to Grand Banks. The GB/IB closure is complete as established for the M11 and M22 reconstructions. Thus, the FC/NA rotation angle has been calculated in order to fit the FC and GB 3000-m isobaths.

3.6. BSMA reconstruction north of the Newfoundland/Gibraltar Fracture Zone

Locations of IB/NA at chrons ECMA and M22 are so close that the resulting 20 km of differential motion, almost parallel to the NGFZ, can be distributed at any time between chrons ECMA and M22, possibly between chrons M22 and M25. If we assume this, IB, which was attached to MES prior to chron ECMA, became quasi-attached to NA from chron ECMA to almost chron M22. The GB/IB closure was complete as established for M11 and M22 reconstructions and the FC/NA rotation angle has been calculated to fit the FC and GB 3000-m isobaths.

3.7. C34 reconstruction

Parameters of rotation of Klitgord and Shouten {, 1986 #219} for AF/NA, of Srivastava et al. {, 1990 #126} for IB/NA and Srivastava et al. {, 1988 #289} for EU/NA are used for the C34 reconstruction (Table 1). The position of MES/NA have been computed in order to keep it as it was at chron M0. GB and FC were in their present-day positions with respect to IB and NA, respectively.

4. Paleogeography of salt deposits at chrons ECMA and BSMA

Figure 4 shows the distribution of salt deposits as derived from the published literature between MES-AF and Nova Scotia margins and between IB and NA on kinematic reconstructions at chrons ECMA and BSMA, respectively. The Late Triassic-Early Jurassic salt was deposited during the rifting episode on the surrounding margins of Nova Scotia, Morocco and Iberia, and in the intra-continental basins of the Grand Banks, Morocco, Algarve, Lusitania and Porto {Albertz, 2010 #567;Labails, 2010 #543;Sahabi, 2004 #547;Wade, 1990 #553;Hafid, 2008 #550;Maillard, 2006 #545;Nemcok, 2005 #552;Tari, 2005 #548;Davison, 2010 #549;Edwards, 2000 #554;Matias, 2005 #551}.

On the ECMA reconstruction (Figure 4a) the seaward salt deposits off Nova Scotia and Morocco fit well on the southern and northern parts of the conjugates but a gap still exists in the central part. Louden et al. {, 2012 #642} suggest that this gap might be due to the presence of basement highs, which prevents salt deposition during synrift time such as the tilted fault blocks off Nova Scotia and the Tafelney Plateau off Morocco.

Figure 5 shows two TGS seismic profiles located perpendicularly to the Nova Scotia margin (courtesy TGS-NOPEC) in areas where the autochtonous salt is absent (Province D) or present (Province B), respectively. Seaward of the shelf edge, Profile TGS644-109 shows the presence of a thin (about 0.4 sec t.w.t.) autochtonous salt layer located just above the thinned rifted continental crust, from which the salt structures originate and deform the overlying sediments, including the top Baccaro horizon (Late Jurassic). All TGS profiles located within the Provinces A, B and C display the same characteristics: the autochtonous salt layer is located just above the thinned continental basement and halokinesis deforms the overlying sediments. In the deepest part of Profile TGS644-109, the basement is irregular and seems to be affected by closely spaced normal faults.

Profile TGS 964-109 shows limited but clearly deformed autochtonous salt features within the Huron basin located beneath the continental shelf. Seaward of the shelf edge, the autochtonous salt disappears but the tectonic disturbance within the sedimentary cover above the top Baccaro horizon (Late Jurassic) suggests a migration of salt. At the southeastern extremity of the profile,

a major salt diapir, also lying above the top Baccaro, is rooted in the salt layer. Consequently, there is no allochtonous salt along this profile (Figure 5) and the limited amount of salt beneath the continental slope and rise had migrated later on from the Huron Basin. All other seismic profiles {Department of Energy, 2011 #639} show that the allochtonous salt is absent over 150 km along strike in Province D. In contrast to the Huron Basin, the basement is very smooth beneath the continental slope and extensional features are not observed below it (Figure 7a), suggesting that the basement is serpentinized mantle beneath the slope. Other available seismic profiles {Department of Energy, 2011 #639} show the same smooth basement in the whole Province D. Unfortunately, the OETR 2009 refraction profile follows the boundary between Provinces E and D (Figure 5) and does not give any constraint on the nature of the smooth basement of Province D. However, its morphological characteristics observed on Profile TGS 964-109 suggest it is exhumed mantle emplaced after a rift jump. To summarize, all TGS profiles located within Province D show the same features: below the continental slope, the basement is extremely smooth over a distance of ~50 km perpendicular to the margin, without extensional features suggesting that it is not continental but probably exhumed mantle. Further southeast, the basement is serpentinized mantle with minor volcanics on top.

In Province D, the amplitude of the ECMA is two to three times smaller than southwestward and corresponds, as seen before, to a linear borderline located between a large negative anomaly to the north (blue in Figure 1) and a gently varying positive anomaly to the south (cyan in Figure 1). It suggests that the observed smooth basement surface cannot be associated with the typical signature of a volcanic province. Further northeast, in Province E, the ECMA corresponds to a series of aligned positive anomalies. These observations combined with the interpretation of TGS seismic profiles suggest that ECMA might be absent in Province D and thus transferred onto the Moroccan side together with the autochtonous salt emplaced before chron ECMA. If this is true, the crust located southeast of the Huron Basin might be transitional lithosphere.

In Figure 4b, the dashed purple polygon located on the Moroccan side corresponds to the area where salt diapirs {Maillard, 2006 #545} are observed seaward of our new identification of the WACMA trend (Figure 2). The continuous purple polygon located on the Nova Scotia margin corresponds to the indentation of the autochtonous salt boundary outlined in Figure 5 {Albertz, 2010 #567} and a lack of autochtonous salt (Province D). The width of this polygon is ~50 km (Profile TGS 964-109). The two purple polygons present similar shape and surface suggesting that a ~50 km rift jump might have occurred at the end of chron ECMA, before mantle exhumation and formation of some volcanics by decompression melting, transferring a portion of the NA lithosphere on the Meseta side (Figure 6).

If these observations are correct, an additional constraint is provided concerning the MES/NA reconstruction at chron ECMA.

5. Updated reconstructions of the central and north Atlantic oceans

Using their lineations trends, Labails et al. {, 2010 #543} had to find a solution in order to match their ECMA and WACMA magnetic lineations off Morocco and Nova Scotia. A reasonable solution was obtained by introducing the Meseta plate, which is separated from the African craton by an intracontinental rift system affected by dextral movements during the Late Paleozoic, sinistral movements during the Triassic-Early Jurassic rifting and inversion and thrusting during the Cretaceous and Tertiary resulting in the formation of the Atlas mountains (e.g. {Beauchamp, 1999 #612;Frizon de Lamotte, 2000 #613}). All land studies attest that the

motion between MES and AF was small during the Mesozoic and in general did not exceed a few tens of kilometers. In the Labails et al.'s {, 2010 #543} reconstruction at chron ECMA, the AF-MES distance is null near WACMA, 40 km in the High Atlas and close to 100 km near the eastern part of the Meseta (Figure 4a). In a first trial let us try to have the Meseta plate in its present-day position with respect to Africa in chron ECMA reconstruction. In other words let us rotate the MES plate back to NA at chron ECMA with the Labails et al.'s {, 2010 #543} AF/NA parameters. The result is that the northern part of WACMA is now tangent to ECMA (Figure 4a), except for the extreme eastern portion of the WACMA lineation, which is located about 20 km southeast of ECMA. Further southwest the distance between ECMA and rotated WACMA lineations increases to a maximum of ~20 km. As can be inferred from geological informations (e.g. {Beauchamp, 1999 #612;Frizon de Lamotte, 2000 #613}), this means that the MES/AF motion at chron ECMA is null or very small, at least at the scale of this work. The fit at chron ECMA with a MES plate in its present-day position with respect to AF is thus considerably improved but can be still slightly adjusted with a minor MES/AF motion compared with the one proposed in Labails et al. {, 2010 #543}.

To summarize, in Labails et al.'s {, 2010 #543} Figure 6a, a 40-km overlap between the two ECMA and WACMA magnetic lineations is observed at the longitude of southwestern Nova Scotia though the fit is excellent over a length of 800 km down to Florida. Thus, the accuracy of their chron ECMA fit is ~40 km in the NW-SE direction, much less in the NE-SW direction (~20 km?). In our new proposed fit, in which the MES plate is in its present-day position with respect to AF, the accuracy in chron ECMA reconstruction is ~20 km.

Treating the MES and AF plates as closeby plates means that at chron ECMA time the location of MES with respect to NA was located about 70 km south-southeast of its position in Labails et al.'s {, 2010 #543} fit (Figure 4a). If we assume that the MES plate was close to its present-day position with respect to AF at the times of chrons BSMA, ECMA and the fit, the three positions of the MES plate with respect to AF and NA have to be moved ~70 km south-southeast of their positions in Figure 3b. To summarize, the fit at chron ECMA is significantly improved if the MES plate is in a position close to present with respect to AF. Doing so, the accuracy of the fit is ~20 km.

The BSMA fit might be also improved for two reasons. First, the BSMA magnetic anomalies have significant amplitude, typically 100 nT or so and are clearly recognisable in the contoured magnetic maps. Their African counterpart (ABSMA, Labails et al., {, 2010 #543}) corresponds to extremely weak magnetic anomalies, typically 10-20 nT in amplitude and are not recognisable in conventional magnetic maps. However, ABSMA exists on the African side and seems to be linked to a change in basement topography {Labails, 2010 #543} but its trend is poorly defined. Consequently, the fit at chron BSMA is rather poor and might be subject to revision. In addition, in the Labails et al. {, 2010 #543} reconstruction, MES/NA and AF/NA motions between chrons ECMA and BSMA are at a 50° angle with the direction of NGFZ rather than almost parallel to NGFZ. This problem was already identified by Bridget Ady (personal communication, 2011 and {Ady, 2011 #640}).

If the BSMA fit is modified, the MES/NA (or AF/NA) motion between chrons ECMA and BSMA may become more parallel to the NGFZ. This, however, requires a complete re-evaluation of chron BSMA fit with a re-appraisal of the ABSMA trend. It is outside the scope of the present study but needs to be done to solve this outstanding problem. In the following part, the paleogeographic maps will be established by using the Labails et al. {, 2010 #543} parameters for the central Atlantic reconstructions. This slight inaccuracy in Labails et al.'s {, 2010 #543}

parameters of rotations for the fit at ECMA and BSMA chrons does not change the basic informations we can expect from these maps.

6. Paleogeographic maps

The paleogeographic maps presented in Figures 7 to 10 are basically constructed from offshore paleofacies slices extracted from Figure 8.3 of Gradstein et al. {, 1990 #568}. The geological information for the onshore part of the plates was digitized from the Geological Map of North America {, 2005 #569} for North America and from the 1:5 Million International geological map of Europe and adjacent areas {, 2005 #573} for Iberia and Africa. Symbols used in the kinematic, magnetic, salt distribution and paleogeographic maps appear in Figure 7b.

To preserve the accuracy of reconstructions, the paleo-facies digitized from the Gradstein et al. {, 1990 #568} plates have been first rotated back to the present position using rotation parameters specifically computed, before rotating them with the parameters of this study for each of the reconstructions (Figures 7 to 10). Eventually, minor contour editings have been performed to ensure the continuity of structures and facies. The rotation of the geological features was performed using the *rot_xyz* program {Royer, 1992 #571}, modified to deal with geodetic latitudes. The main difference between the two sets of paleogeographic maps is the more accurate kinematics used in our set of maps from Late Triassic to chron M0.

The paleogeographic maps presented here span broad but generally adjacent time intervals, showing a continuity from Late Triassic to Late Cretaceous. The time interval~~s~~ for each map is about 20 Ma on the average, implying that short period changes in the facies may be under represented and that the plate tectonic configuration is a snapshot of an ever-evolving system, with possible motions of several tens of kilometers per stage. In addition, the coverage of geological data is highly variable in space {Gradstein, 1990 #568;Wade, 1990 #553}, which does not appear in the seven paleogeographic maps.

Basically, the informations which appear in the seven paleogeographic maps are the same than those in Gradstein et al.'s {, 1990 #568} maps, except that we have provided a reconstruction before rifting (Norian/Rhetian limit, 203 Ma), added the onshore geology and updated kinematic reconstructions. The main difference comes from the new proposed kinematics of IB, FC and GB with respect to NA. In particular, the timing of FC/NA and GB/NA is well constrained by the timing of opening of the Orphan and Galicia Interior basins. Seismic and stratigraphic relationships indicate that the first episode of rifting in the Orphan basin and further north to offshore Norway {Lundin, 2011 #651} is Late Triassic–Early Jurassic, based on the rifting age established from seismic correlations and well data in the Jeanne d'Arc Basin (e.g. {Enachescu, 2004 #198;Enachescu, 2004 #200}), creating a deep trough (East Orphan Basin) immediately landward of Flemish Cap–Orphan Knoll ridge. The age of the rifting phase creating the West Orphan Basin, located NW of the East Orphan Basin, is constrained by a second phase of rifting dated Late Jurassic to Early Cretaceous; this phase also reactivated the sedimentary features of the East Orphan Basin {Enachescu, 2004 #198;Enachescu, 2004 #200;Skogseid, 2004 #276}. Based on seismic and stratigraphic relationships, the Galicia Interior basin rifted from Late Jurassic to Valanginian {Murillas, 1990 #353}. Simultaneously, the Galicia margin formed in between but rifting ended later, at the Aptian/Albian boundary (e.g. {Tucholke, 2007 #476;Tucholke, 2007 #482}). The consequence is the potential presence of a FC-GB dam from Late Triassic to Late Jurassic, which prevented deep oceanic circulation to the north, except if there was some connection along the Flemish Pass. From Late Jurassic to Valanginian, the dam progressively disappeared during the rifting of the Iberia margin, west of Galicia Bank.

6.1. Late Triassic: Pre-rift configuration (Norian/Rhaetian limit, about 203 Ma) (Figure 7a)

The geological maps of the continents are presented on the pre-rift kinematic recontruction. The Triassic basins extend from the Gulf of Mexico to eastern United States, the Bay of Fundy, Grand Banks and then to the Western Approaches and Celtic Sea.

6.2. Early Jurassic (ECMA, Sinemurian/Pliensbachian limit, 190 Ma): Paleogeography of Early Jurassic (Sinemurian-Toarcian) (Figure 8a)

TGS and reprocessed Novaspan seismic lines on the Nova Scotia margin {Department of Energy, 2011 #639} show that the seaward boundary of the autochtonous salt approximately coincide**s** with the seaward side of the ECMA. Figure 4a shows the distribution of salt deposits between Iberia, Africa and North America on the kinematic reconstruction at chron ECMA. Ziegler {, 1982 #615} suggested that marine incursions with evaporites deposition started in western Europe during Carnian-Norian time and progressed southward with more than 2 km of salt deposited on the eastern Grand Banks and in the Newfoundland-Iberia rift during Late Triassic to Hettangian-Sinemurian time on top of extensive terrigenous redbeds {Jansa, 1980 #617}. Evaporite deposition progressed southward with evaporites of Late Carnian to Hettangian age on the Nova Scotia margin {Albertz, 2010 #567;Barss, 1979 #616;Gradstein, 1990 #568;Wade, 1990 #553}. On the conjugate Morocco margin, evaporites were deposited at the same period, perhaps ending in Sinemurian rather than Hettangian {Hafid, 2008 #550;Nemcok, 2005 #552;Tari, 2005 #548}. These huge amounts of salt were deposited close to sea level in subsiding rift basins during a short period of time corresponding to the continental rifting on both sides of the Nova Scotia-Morocco and Newfoundland-Iberia rifts. We suggest that a dam connecting Flemish Cap to Galicia Bank may have existed favoring either a shallow marine connection through it and then to the Bay of Biscay rift and the Pyrenean basins (Triassic salt in the Pyrenean basins (e.g. Mattauer {, 1971 #239})) or through northern Africa as already proposed {Busson, 1970 #618}, possibly through a passage located between northern Meseta and Iberia and then around Iberia.

The kinematic reconstruction at chron ECMA (Figure 8a) displays the Sinemurian-Toarcian facies. Chron ECMA corresponds to the rupture of continental crust and the onset of emplacement of transitional lithosphere made of serpentinized mantle overlain by decompression melting basalts and gabbros {Dehler, 2010 #557} at depths larger than 2.5 km. Refraction data collected on the Nova Scotia margin (profiles OETR 2009 {Makris, 2010 #558}, SMART1 {Funck, 2004 #204} and SMART2 {Wu, 2006 #559}) show~~s~~ the presence of a wide high-velocity (7+ km/s) body located seaward of the ECMA lineation that we interpret as exhumed mantle beneath thin "crustal" layers with mixed provenance (i.e. continental and oceanic). Contrastingly, there is no transitional lithosphere with serpentinized mantle offshore Morocco (Profile SISMAR04 {Contrucci, 2004 #534}). Assuming a constant spreading rate between chrons ECMA (190 Ma) and BSMA (170 Ma) and mantle exhumation starting at 190 Ma, the end of emplacement of the transitional lithosphere and the onset of oceanic crust would have occurred at 177 Ma (Late Toarcian). Thus, the Nova Scotia and Morrocco continental margins would have experienced two ‘breakups’ {Sibuet, 2012 #621}, first the rupture of the brittle continental crust 190 Ma ago and second, the eventual separation of the ductile sub-continental lithosphere 177 Ma ago, coincident with the onset of oceanic crust.

After salt deposition, a main facies change occurred in Sinemurian. A sea level rise and a widespread transgression in a warm and arid climate followed the red beds and evaporites deposition and was at the origin of the building of a large carbonate platform {Gradstein, 1990

#568} (Figure 8a). Simultaneously, in the rift depression created during rifting but after salt deposition, claystones of deep-water origin {Hinz, 1984 #619} were deposited off Morocco and deep neritic marls and marine shales {Ziegler, 1982 #615} in the Grand Banks, Portugal and further north in the Aquitaine Basin, the Western Approaches and the Celtic Sea. It suggests an open marine connection between the Central Atlantic and the Newfoundland-Iberia rift, probably terminating northward against the Flemish Cap-Galicia Bank dam. However, the Central Atlantic marine connection continues to northern latitudes either along the NFGFZ, the Tethys ocean, the Aquitaine Basin and the Bay of Biscay rift or through the Grand Banks basins and the proto-North Atlantic ocean {Skogseid, 2004 #276}.

6.3. Middle Jurassic (BSMA, Middle Bajocian, 170 Ma): Paleogeography of Middle Jurassic (Bajocian-Bathonian) (Figure 8b)

As previously discussed, the onset of normal oceanic crust might have occurred in at Late Toarcian (177 Ma), 7 M.y. before chron BSMA kinematic reconstruction of Figure 8b. In the middle part of the central Atlantic Ocean, the Bajocian-Bathonian sediments overlie typical oceanic crust while between Iberia and Newfoundland there is almost no extension, the emplacement of true oceanic crust being delayed to the Aptian-Albian limit {Tucholke, 2007 #476}.

Figure 3b shows that from chrons ECMA to BSMA, the MES motion with respect to NA occurred in the southeast direction, creating a significant elongated depression along the NGFZ. In chron BSMA paleogeographic map (Figure 8b), such an elongated depression exists along the whole NGFZ, connecting not only the elongated central Atlantic oceans and Newfoundland-Iberia rift but also the central Atlantic Ocean to the ancient Tethys, because IB, MES and AF were moving together in the southeast direction with respect to NA. At the time of 'breakup' of the transitional lithosphere (177 Ma), the maximum water-depth in both rifts was probably ~2-3 km, the depth of newly formed oceanic crust. However, as extension along the NGFZ continued the water-depth along the NGFZ depression might have increased and the distance between the deep basins on each side of the NGFZ was decreasing from ~500 km at 190 Ma (Figure 8a) to ~250 km at 170 Ma (Figure 8b) and to 0 by the end of Bathonian (164 Ma) as the MES/NA spreading rate increased from ~1 cm/yr to ~3 cm/yr at 170 Ma {Labails, 2010 #543}.

The Aalenian to Bajocian was a period of tectonic instabilities accompanied by regression, erosion, volcanism and many changes in depositional regimes {Gradstein, 1990 #568}. The Middle Jurassic regression is well documented in the Scotian Basin where Bajocian continental clastics of the Mohican formation prograded over the carbonate platform {Gradstein, 1990 #568}. Similar changes occurred in Morocco and were accompanied by basaltic volcanism and development~~s~~ of local angular unconformities {Hafid, 2006 #623;Monbaron, 1982 #622}.

6.4. Late Jurassic (M22, Tithonian, 150 Ma): Paleogeography of Late Jurassic (Oxfordian-Portlandian) (Figure 9a)

Unlike previous figures, the paleogeography of Oxfordian-Portlandian (161-145 Ma) is mostly preceding the age of the plate reconstruction (150 Ma) on which the Oxfordian-Portlandian paleogeography is overprinted (Figure 9a). The connection of deep waters between the central Atlantic and the Newfoundland-Iberia rift is fully achieved.

Transgressions during Late Oxfordian to Kimmeridgian led to widespread marine carbonate and clastic deposition. The Early Kimmeridgian probably marked the maximum extent of the

Jurassic shelf areas. Each of the sedimentary basins developed on continental margins has their own characteristics with regional trends frequently overprinted by local trends (Figure 9a). Generally, the Late Jurassic margins were areas of extensive development of carbonate platforms as the Abenaki formation off Nova Scotia {Jansa, 1981 #624} and similarly along the Moroccan margin in the Tarfaya and Essaouira basins and on the Mazagan Plateau {Von Rad, 1986 #625}.

The information in the deep central part of the oceans is better constrained by drilling data than during the Early and Middle Jurassic evolution: toleiitic basalts drilled at numerous sites of the Deep Sea Drilling project (Sites 105 {Hollister, #628}, 376 {Shipboard scientific party, 1978 #629}, and 534 {Shipboard Scientific Party, 1983 #630}) are overlain by pelagic deposits, which consist of two distinct sequences: 1) older pelagic marls, claystones and marly limestones overlain by 2) pelagic limestones of Late Tithonian to Hauterivian age {Gradstein, 1990 #568}. Turbiditic beds at the base of continental margins are common, with debris flows on the seaward side of carbonate platforms {Benson, 1982 #627;Jansa, 1984 #626}.

6.5. Early Cretaceous (M11, Valanginian, 136 Ma): Paleogeography of Early Cretaceous (Berriasian-Barremian) (Figure 9b)

Rifting on the Iberia and Newfoundland conjugate margins occurred from Late Jurassic to the Aptian-Albian boundary with extension concentrated in three episodes that culminated near the end of Berriasian, Hauterivian and Aptian time. The first two episodes appear to correlate with separation of continental crust in the southern and northern parts of the rift, respectively, suggesting that the rift opened from south to north in a two-step process. The third episode persisted through Barremian and Aptian time {Tucholke, 2007 #476}. During this period there was continued exhumation of subcontinental mantle lithosphere at the plate boundary, and that elevated in-plane tensile stress throughout the rift caused intraplate extension, primarily within the exhumed mantle {Sibuet, 2012 #621}. From chrons M22 to M11 (150 to 136 Ma) Galicia Bank moved ~105 km away from Iberia giving rise to the Interior Basin {Murillas, 1990 #353;Sibuet, 2007 #415} and rifting also occurred west of Galicia Bank. Thus, Flemish Cap was separating from Galicia Bank and rupturing the Galicia Bank-Flemish Cap dam.

Major block faulting and tilting took place on the conjugate margins of Iberia and Newfoundland with shallow marine carbonates of Tithonian age on the Galicia Bank margin, overlain by deep-water clastics of Early Cretaceous age {Boillot, 1988 #12;Groupe Galice, 1979 #327}. Submarine fans developed in front of deltaic depocenters as in the Scotian Basin, and off Morocco in the Aaiun and Tarfaya basins {Jansa, 1978 #631;Von Rad, 1986 #625}. The deep pelagic limestones continued into the Barremian but dark marls enriched in organic matter intercalated with carbonates {Jansa, 1979 #397}.

6.6. Middle Cretaceous (M0, Late Barremian/Early Aptian, 125 Ma): Paleogeography of Middle Cretaceous (Aptian-Albian) (Figure 10a)

Rifting of the Iberia and Newfoundland conjugate margins ended at the Aptian-Albian limit after the exhumation of ~400 km of transitional lithosphere which consists of serpentinized mantle. Since that time, true oceanic crust was emplaced {Sibuet, 2012 #621}.

The Aptian transgression led to the deposition of shallow-water marines shales over the entire NA shelf (Figure 10a). After a brief regressive period in Late Aptian to Early Albian, slow transgression continued with shallow marine and deltaic sands deposited on the NA shelves {Gradstein, 1990 #568}. The Middle Cretaceous was also the time of worldwide intense

volcanism, which culminated in the development of extensive unconformities and deep erosion in the Late Aptian and Early Albian {Tucholke, 2007 #482}. Erosion cut locally exposed lower Jurassic rocks {Jansa, 1975 #601} and peneplained tilted basement blocks on the shelf but also in the deeper part of continental margins. This was also found in the Bay of Biscay, on the Newfoundland Ridge and off the Galicia Bank {Boillot, 1988 #576;Graciansky de, 1985 #582;Grant, 1979 #632;Montadert, 1979 #241}.

6.7. Late Cretaceous (C34, Santonian, 83.5 Ma): Paleogeography of Late Cretaceous (Cenomanian-Danian) (Figure 10b)

All continental margins of the central Atlantic Ocean, between Iberia and Newfoundland and in the Bay of Biscay are in their post-rift stage and oceanic crust is continuously forming in the central and north Atlantic oceans and in the Bay of Biscay where spreading will cease at chron C33o (80 Ma) {Sibuet, 2004 #275}.

There are two distinct geographic lithofacies on the continental shelves: marls and chalks are predominantly deposited in the epeiric seas of the Iberian peninsula and in northwestern Africa; fine grained marls or clastics dominate the western margins of north America {Gradstein, 1990 #568}.

The global sea level reached a maximum in Late Cretaceous with 150 m {M l ler, 2008 #637} to ~250 m {Haq, 2005 #636} elevation above the present-day sea level. In most of the sedimentary basins around the Atlantic Ocean this change in sea level is reflected in a continuation of the transgression, which began in Aptian. The combined effects of sea level high and low land relief due to constant erosion of reliefs since Permian caused drastic reduction in the amount of clastic sediments entering in the oceans. Mudstones, marls and chalks were deposited in shelf areas while the sedimentation accumulation rate drastically decreased in the deep ocean (Figure 10b). From the Late Cenomanian to Maastrichtian, non-calcareous clays deposited at a 0.3 cm/kyr rate and in Maastrichtian the carbonate compensation depth dropped in the central Atlantic Ocean allowing the deposition of deep water chalk {Jansa, 1979 #397}.

7. Conclusions

The main conclusions of this study are as follows:

1. New magnetic data collected in the northeastern extremity of ECMA lineation and offshore Morocco in the area of the conjugate WACMA lineation were used to re-define the trends of these two lineations. Using Labails et al.'s {, 2010 #543} parameters for MES/NA and AF/NA in the reconstruction, the fit of these two lineations is greatly improved. The fit becomes even better if MES is close to its present-day position with respect to Africa at chron ECMA time. It means that even if movement occurred between MES and AF through time, the total offset was small compared to the present-day configuration at the time of chron ECMA.

2. Based on the shape of ECMA and WACMA, on the presence of salt seaward of WACMA and on the absence of an autochtonous salt domain of similar shape on the Nova Scotia margin, it suggests that a portion of Nova Scotia thinned continental crust was transferred on the Moroccan side at chron ECMA time. It might be a significant constraint for kinematic reconstruction at chrons ECMA. ABSMA being 5 to 10 times smaller in amplitude compared

with BSMA, its NA counterpart, a re-identification of the ABSMA location and trend as well as the constraint of the jumped salt domain would help to improve the BSMA/ABSMA fit.

3. The presence of a ~90-km wide stripe of transitional lithosphere (serpentinized mantle) seaward of ECMA and the absence of similar serpentinized mantle on the Moroccan side suggests that, at the end of formation of the transitional lithosphere, an eastward ridge jump occurred, leaving the whole high velocity body on the NA side. Assuming the spreading rate was constant between chrons ECMA and BSMA, the end of the formation of the transitional lithosphere and consequently the onset of oceanic crust occurred in Late Toarcian (177 Ma). Thus the 'breakup' of thinned continental crust occurred at chron ECMA time (190 Ma) and the 'breakup' of transitional lithosphere and onset of oceanic crust occurred in Late Toarcian (177 Ma).

4. From the pre-rift situation in Late Triassic to chron C34, the detailed plate kinematic reconstructions were established for seven periods. During the main rifting period from Late Triassic to chron ECMA (190 Ma), Iberia was attached to Africa and then, from chrons ECMA to ~M22, Iberia was attached to north America. The resulting paleogeographic maps show that salt deposited in two elongated bathymetric depressions formed during the Late Triassic to chron ECMA period between Nova Scotia and Morocco and in the Newfoundland-Iberia rift south of the GB-FC continental dam. Seismic and stratigraphic relationships indicate that the first episode of rifting in the Orphan basin is Late Triassic–Early Jurassic and the second episode of rifting occurred from Late Jurassic–Early Cretaceous, simultaneously with the rifting episode in the Galicia Interior Basin and west of Galicia Bank. The consequence is the potential presence of a FC-GB dam from Late Triassic to Late Jurassic, which prevents deep oceanic circulation to the north. From Late Jurassic to Valanginian, the dam progressively disappeared during rifting of the Iberia margin, west of Galicia Bank. After the end of salt deposition, from chrons ECMA to BSMA, the two elongated basins separated by the NGFZ subsided, becoming deeper and deeper. They connected through the transtensional NGFZ, an initially shallow elongated depression deepening through time with along-strike extension.

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Table

Table 1: Rotation parameters used in this study. The three values are from top to bottom the latitude (positive to the north), the longitude (positive to the east) and the angle of rotation (in degree). (1) Labails et al. {, 2010 #543}; (2) Klitgord and Shouten {, 1986 #219}; (3) this study; (4) Srivastava et al. {, 2000 #286}; (5) Srivastava et al. {, 1990 #126}; (6) Sibuet et al. {, 2007 #415}; (7) Srivastava et al. {, 1992 #287}; (8) Srivastava et al. {, 1988 #289}.

	fit	ECMA	BSMA	M22	M11	M0	C34
AF	64.28 (1) -14.74 -78.05	64.31 (1) -15.19 -77.09	67.09 (1) -13.86 -70.55	66.08 (1) -18.44 -62.80	66.02 (1) -19.07 -57.81	65.95 (1) -20.46 -54.56	76.55 (2) -20.73 -29.60
MES	66.23 (1) -11.28 -73.91	66.31 (1) -11.78 -72.95	69.47 (1) -9.56 -66.59	66.61 (1) -17.66 -61.83	67.10 (1) -17.95 -56.36	67.17 (1) -19.51 -53.01	79.40 (3) -19.11 -28.31
IB	66.88 (3) -14.57 -62.83	66.98 (3) -15.21 -61.88	66.26 (3) -15.94 -62.69	65.56 (3) -16.62 -63.52	65.22 (3) -17.59 -61.19	64.71 (4) -18.94 -58.11	87.18 (5) 57.43 -24.67
GB	66.16 (3) -15.53 -62.41	66.24 (3) -16.15 -61.45	65.53 (3) -16.85 -62.28	64.83 (3) -17.49 -63.11	65.22 (3) -17.59 -61.19	64.71 (4) -18.94 -58.11	87.18 (5) 57.43 -24.67
FC	46.17 (6) -49.09 43.0	46.17 (3) -49.09 35.0	46.17 (3) -49.09 28.0	46.17 (3) -49.09 22.0	46.17 (3) -49.09 17.0	-	-
EU	69.67 (7) 154.26 -23.17	69.67 (7) 154.26 -23.17	69.67 (7) 154.26 -23.17	69.67 (7) 154.26 -23.17	69.67 (7) 154.26 -23.17	69.67 (7) 154.26 -23.17	64.35 (8) 149.97 -19.21

Figures

Figure 1: Updated magnetic grid of the northwestern central Atlantic Ocean {Dehler, 2010 #557}. Mercator projection. Dashed black lines are contoured magnetic anomalies (every 20 nT from 0 to 80 nT) and continuous grey lines are bathymetric contours (200 m, 500 m and then every 1000 m) extracted from the ETOPO1 data set {Amante, 2009 #546}. In white the portion of ECMA already identified by Sahabi et al. {, 2004 #547} and in grey what we suggest as a reasonable northern prolongation of the ECMA.

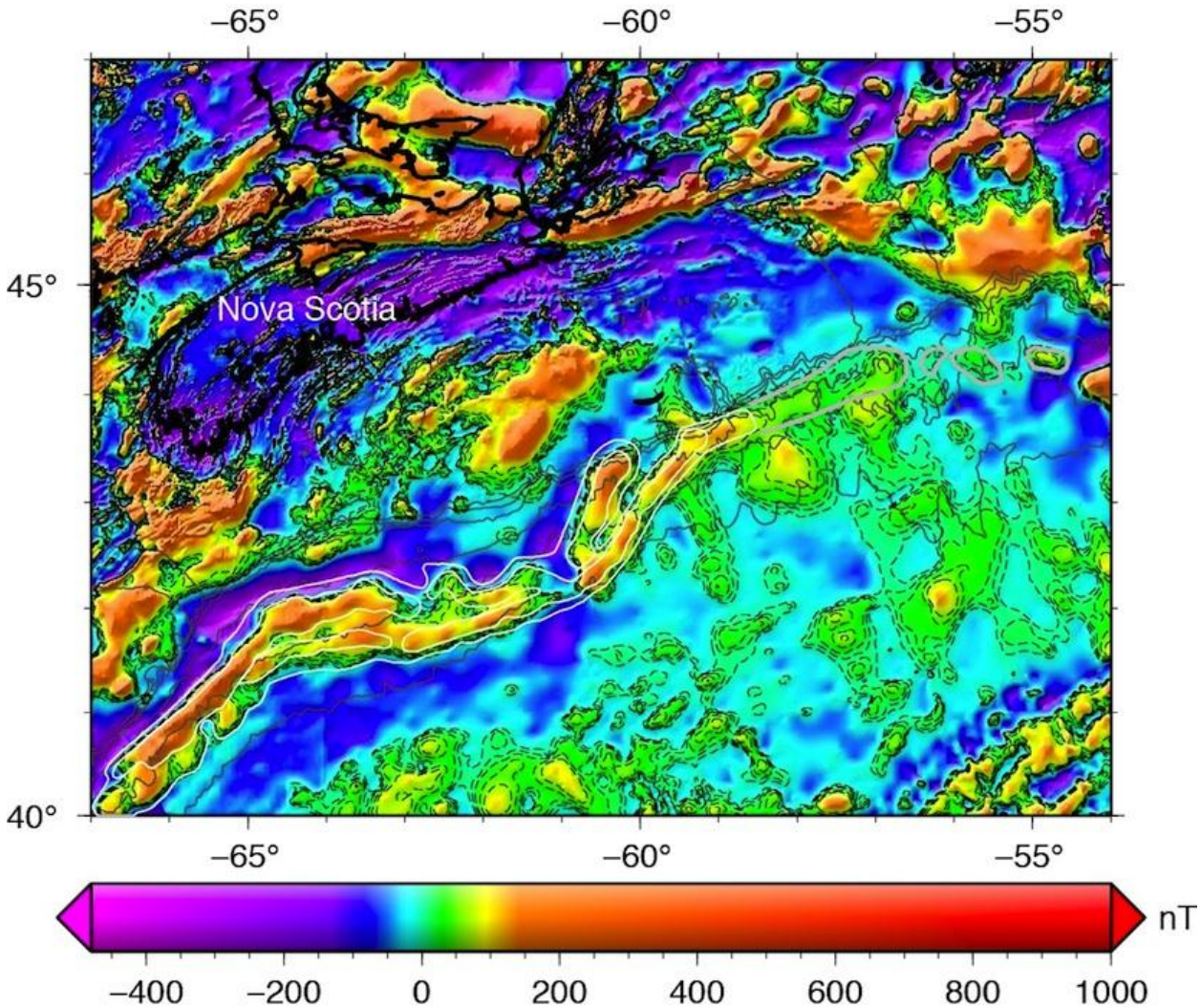

Figure 2: Northeastern central Atlantic magnetic anomaly map based on Verhoef {, 1996 #298} data set updated by S. Delher (personal communication, 2010). Mercator projection. We used the same color palette than in the Figure 1. In grey, bathymetric contours every km. Continuous white lines are the WACMA contoured magnetic anomalies of Sahabi et al. {, 2004 #547} and Labails et al. {, 2010 #543}; continuous black lines are the rotated contoured ECMA magnetic anomalies (MES/NA and AF/NA parameters of rotation of Labails et al. {, 2010 #543} (Table 1). In white the portion of ECMA identified by Sahabi et al. {, 2004 #547} and in red what we suggest as the possible northern prolongation of the WACMA.

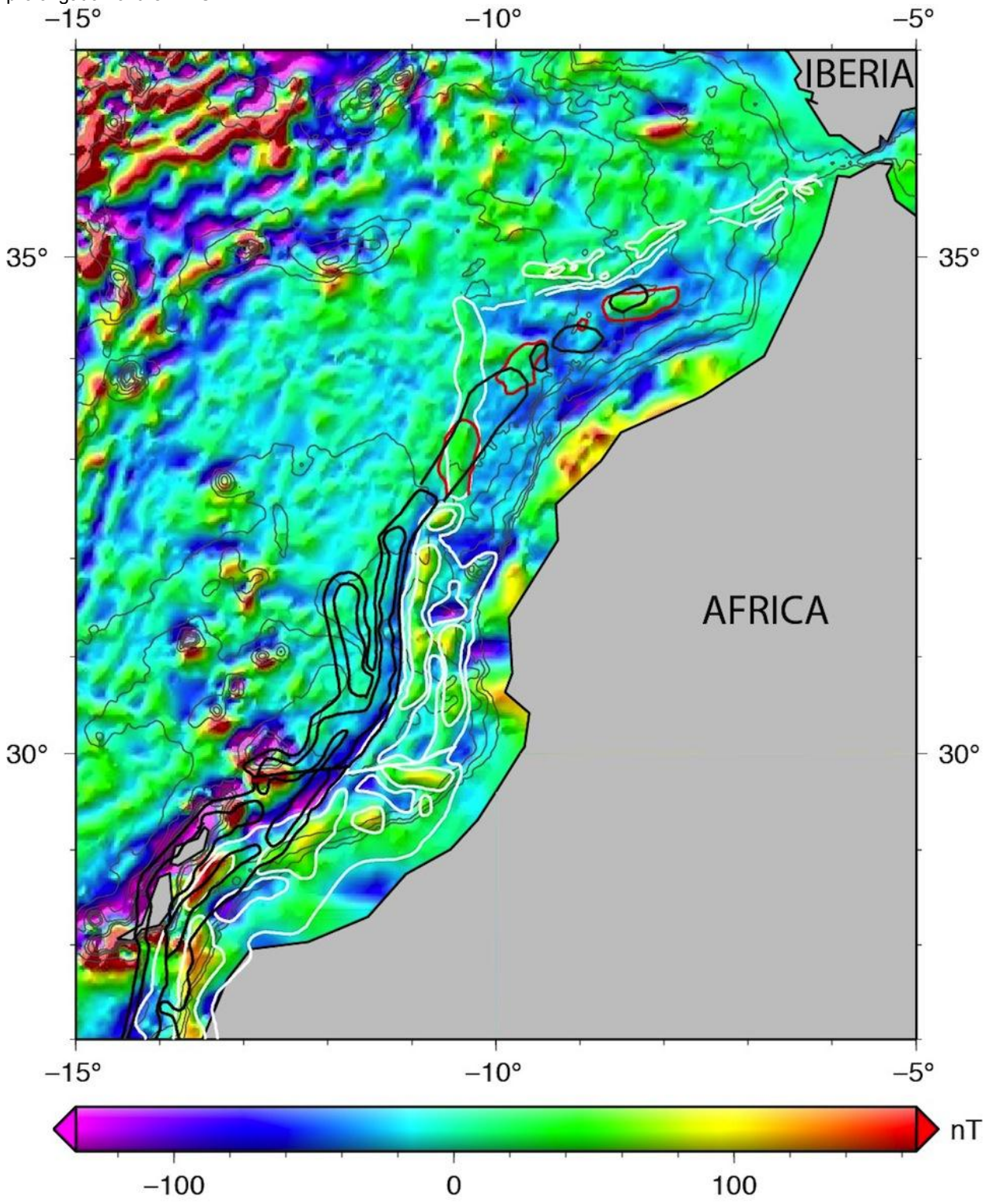

Figure 3: a) Reconstruction of the central and north Atlantic oceans at chron M0 (125 Ma, Late Barremian/Early Aptian). Mercator projection. The North America (NA) plate is fixed. Parameters of rotations in Table 1. Africa (AF), Meseta (MES), Iberia (IB), Galicia Bank (GB) and Flemish Cap (FC) are in cyan, blue, red, green and orange, respectively. Dotted lines for isobath 200 m and continuous lines for isobaths 1000 to 4000 m. The thick dotted grey line is the Newfoundland/Gibraltar Fracture Zone (NGFZ), while the thin grey lines are minor fracture zones. Magnetic anomaly identifications are displayed on the right-hand side of the figure. ABSMA is the African equivalent of BSMA. b) Summary of MES, AF and IB positions with respect to North America for periods spanning from the fit of the central Atlantic to M0. Parameters of rotations in Table 1. Mercator projection. FC and GB in their positions at closure. All grey symbols and grey lines refer to the M0 reconstruction.

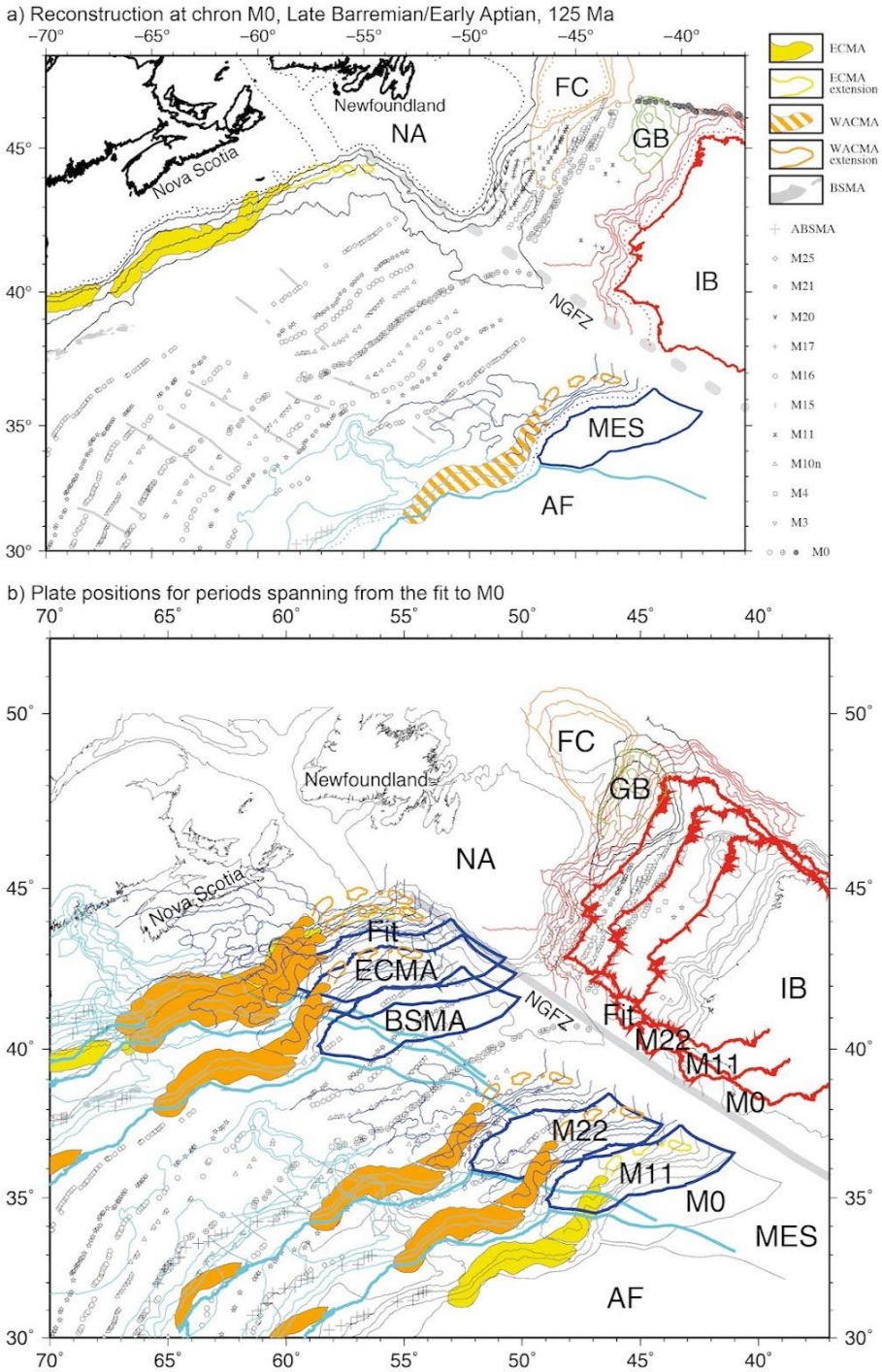

Figure 4: a) Distribution of salt deposits at the end of their deposition (chron ECMA, 190 Ma, Sinemurian/Pliensbachian limit). Parameters of rotations in Table 1. Mercator projection. On the Grand Banks, some salt deposits have not been shown because not released by the oil industry. The purple MES and purple WACMA lineations are rotated with the Labails et al.'s {, 2010 #543} AF/NA parameters of rotation. Note that the fit of the purple WACMA lineations with respect to ECMA lineations in yellow is much better than the fit of WACMA lineations in light brown rotated with the MES/NA Labails et al.'s parameters of rotation with respect to ECMA lineations. Legend of symbols in Figure 7b. b) Distribution of salt deposits on the BSMA reconstruction (170 Ma, Middle Bajocian), about 20 Ma after the end of salt deposition. Parameters of rotations in Table 1. Mercator projection. The dashed purple polygon on the Moroccan side corresponds to the area where the autochtonous salt is located seaward of the WACMA anomalies and which might have been transferred from the Nova Scotia margin (continuous purple polygon) after a ridge jump occurring just after chron ECMA. ECMA in yellow, WACMA defined in this study in light brown and rotated using Labails et al.'s {, 2010 #543} MES/NA and AF/NA parameters of rotation.

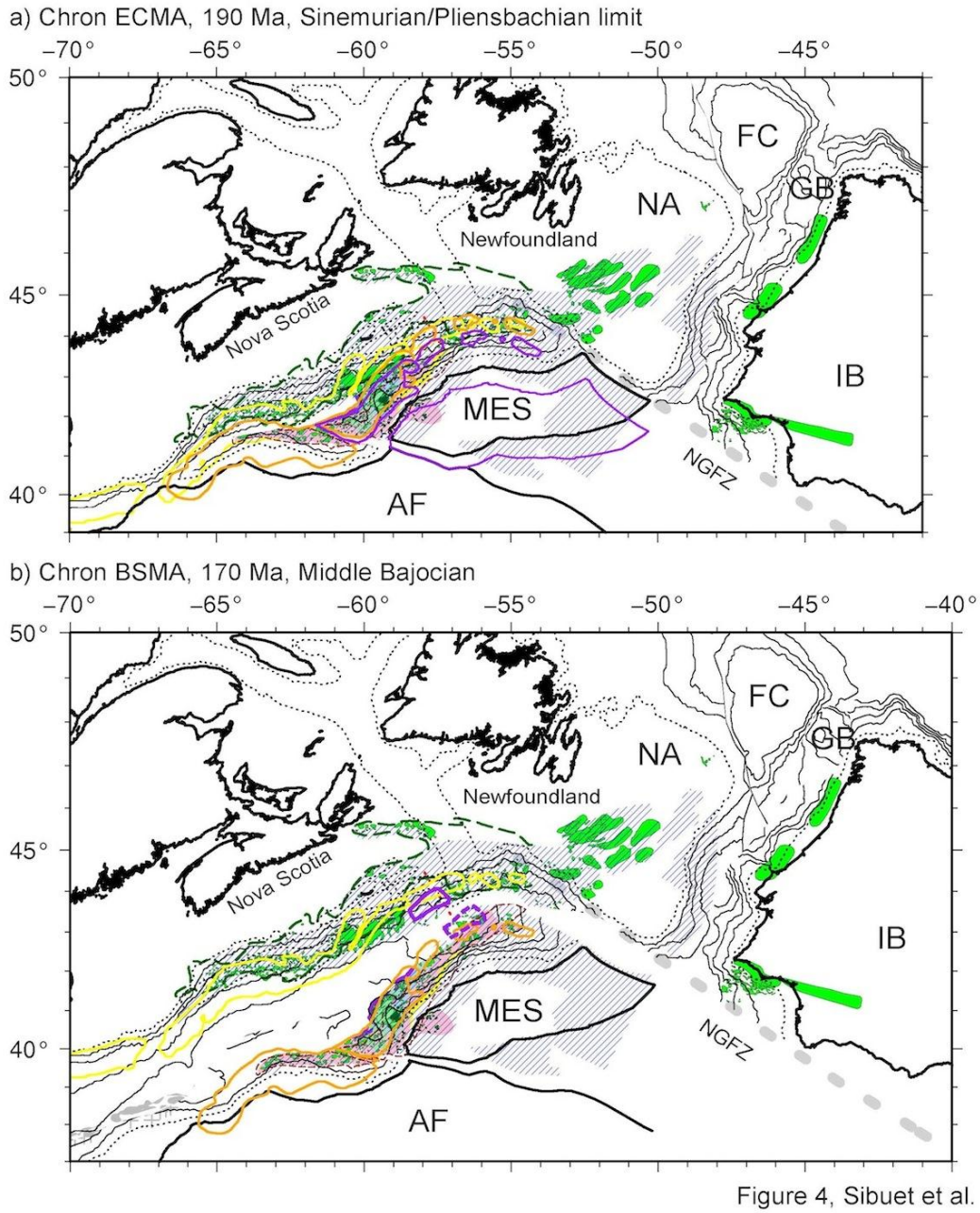

Figure 4, Sibuet et al.

Figure 5: Seismic profiles TGS 964-109 and TGS644-109 located in areas where the autochtonous salt is absent (Province D) or present (Provinces A, B, C and E) (courtesy TGS-NOPEC), respectively. a) Profile TGS 964-109 with interpretation (Colletta, personal communication 2011). In Province D the autochtonous salt is absent over a distance of ~50 km toward the center and possibly transferred onto the Moroccan side. b) Profile TGS 644-109 with interpretation (Colletta, personal communication 2011). The autochtonous salt lies directly above the thinned continental crust. c) Map of autochtonous salt (ALLOCHTONOUS_SALT_TVDSS.grd grid available in {Play Fairway Analysis Atlas, 2011 #641}) and different provinces off Nova Scotia (Colletta, personal communication 2011). Location of the two seismic profiles TGS 964-109 and TGS644-109 and OETR 2009 refraction line in green.

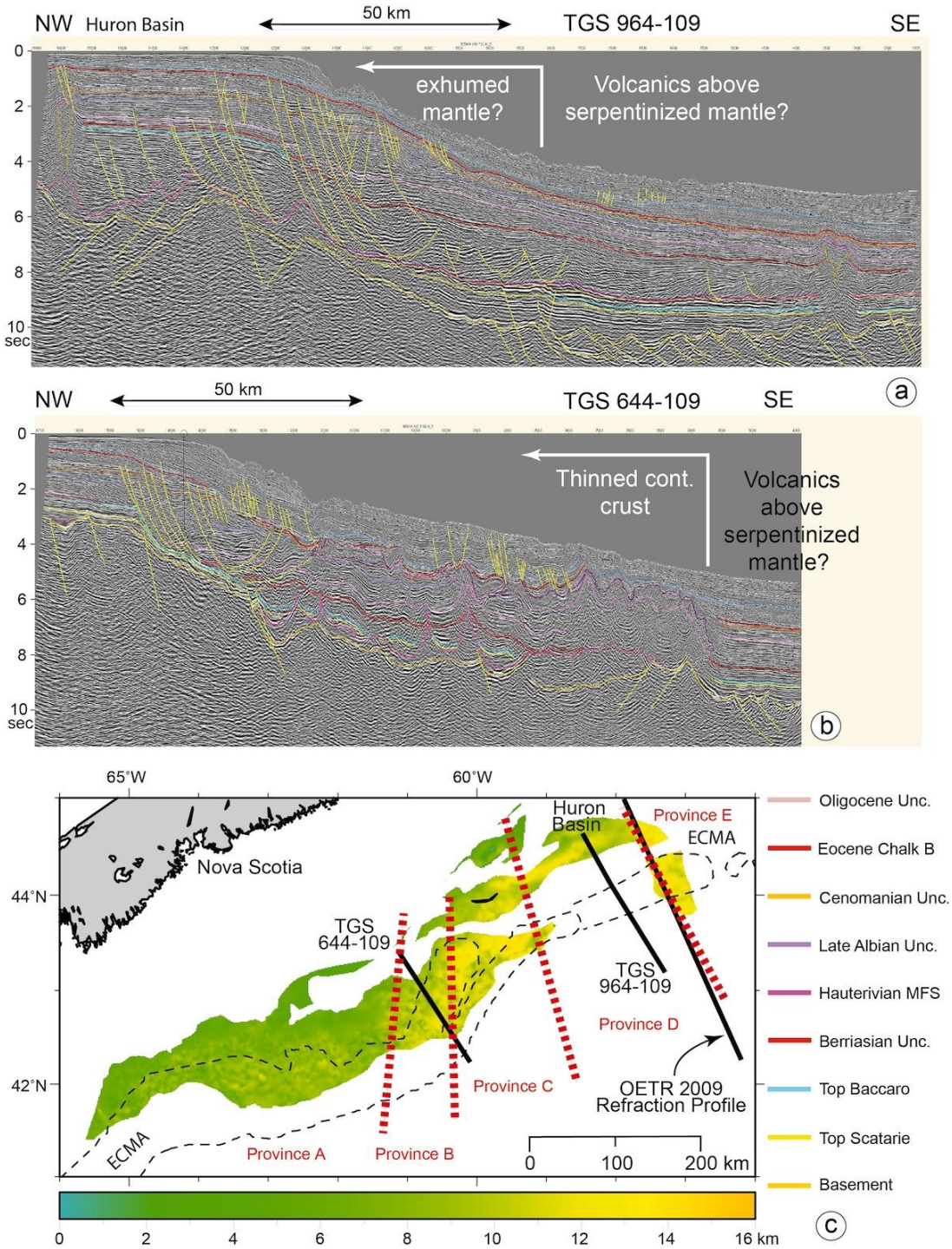

Figure 6: Sketch showing the two eastward rift/ridge jumps at 190 Ma explaining the presence of salt features westward of WACMA, and the eastward shift at 177 Ma explaining the absence of serpentinized peridotite on the Moroccan side, respectively. In other words, a westward shift clipped out a portion of the Nova Scotia margin and its overlying salt features on the Moroccan side, while a later eastward shift left the entire serpentinized mantle on the Canadian side.

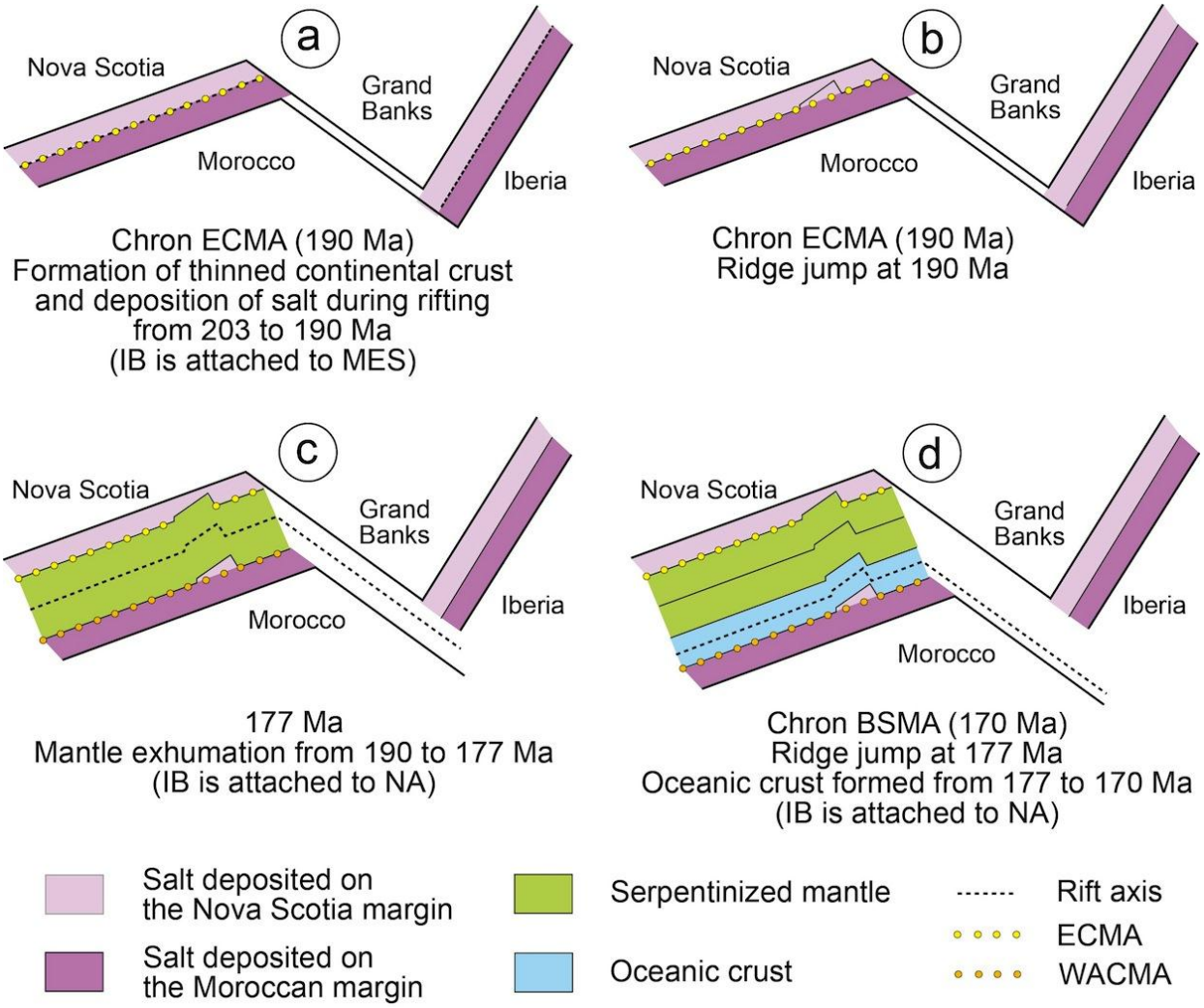

Figure 7: a) Pre-rift Late Triassic geologic map on kinematic reconstruction at the Norian/Rhaetian limit (203 Ma). Parameters of rotations in Table 1. Mercator projection. Bathymetric contours give the shape of the present-day edges of continents and not the true depth, which is close to zero at the time of reconstruction (presence of epi-continental seas of a few meters to a few tens of meters deep). b) Symbols used in the kinematic, magnetic, salt distribution and paleogeographic maps.

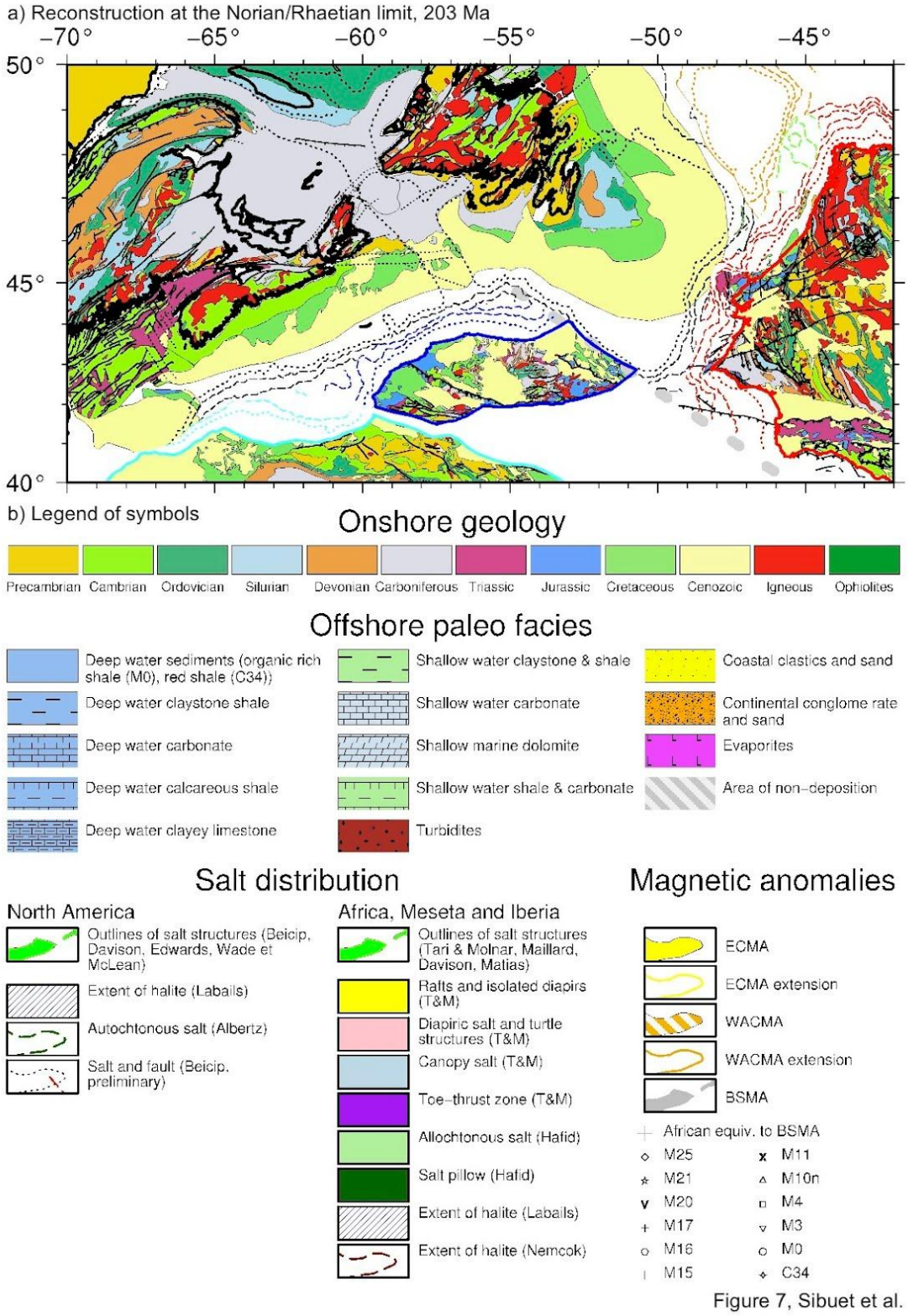

Figure 7, Sibuet et al.

Figure 8: a) Sinemurian-Toarcian paleogeographic map on kinematic reconstruction at chron ECMA (Sinemurian/Pliensbachian limit, 190 Ma). Parameters of rotations in Table 1. Mercator projection. Legend in Figure 7b. b) Bajocian-Bathonian paleogeographic map on kinematic reconstruction at chron BSMA (Middle Bajocian, 170 Ma). Parameters of rotations in Table 1. Mercator projection. Legend in Figure 7b.

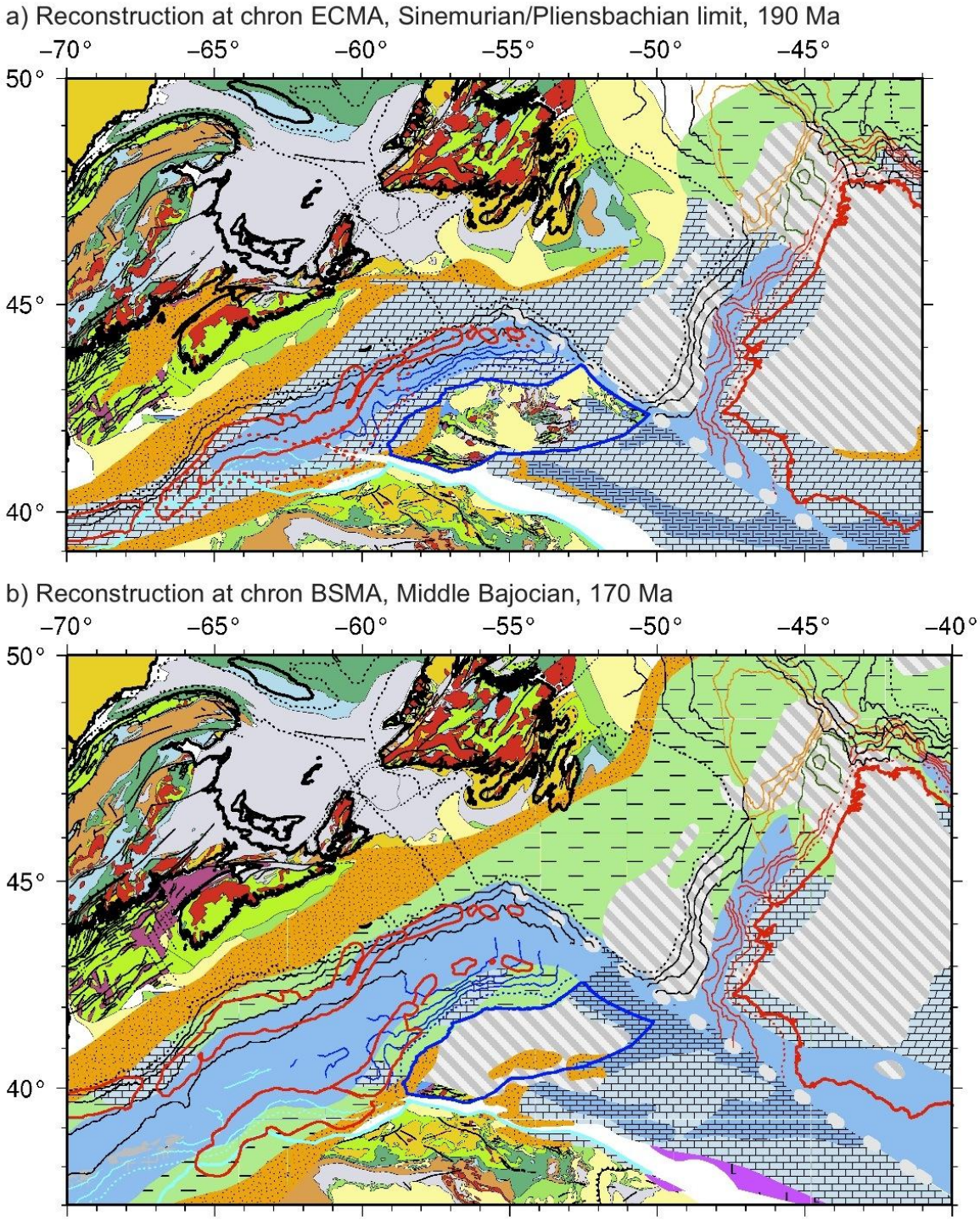

Figure 8, Sibuet et al.

Figure 9: a) Oxfordian-Portlandian paleogeographic map on kinematic reconstruction at chron M22 (Tithonian, 150 Ma). Parameters of rotations in Table 1. Mercator projection. Legend in Figure 7b. b) Berriasian-Barremian paleogeographic map on kinematic reconstruction at chron M11 (Valanginian, 136 Ma). Parameters of rotations in Table 1. Mercator projection. Legend in Figure 7b.

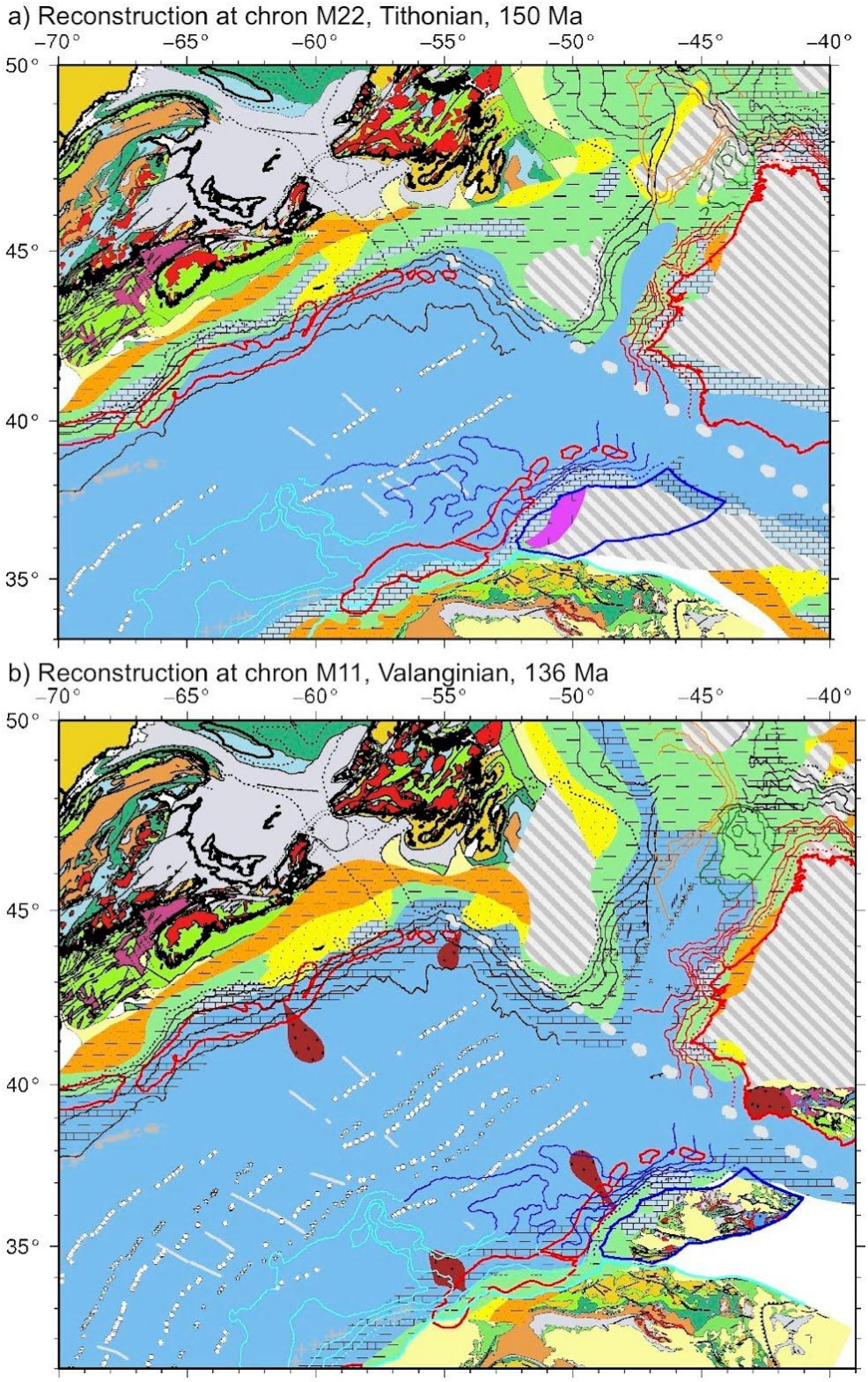

Figure 10: a) Aptian-Albian paleogeographic map on kinematic reconstruction at chron M0 (Late Barremian/Early Aptian, 125 Ma). Parameters of rotations in Table 1. Mercator projection. Legend in Figure 7b. b) Cenomanian-Danian paleogeographic map on kinematic reconstruction at chron C34 (Santonian, 83.5 Ma). Parameters of rotations in Table 1. Mercator projection. Legend in Figure 7b.

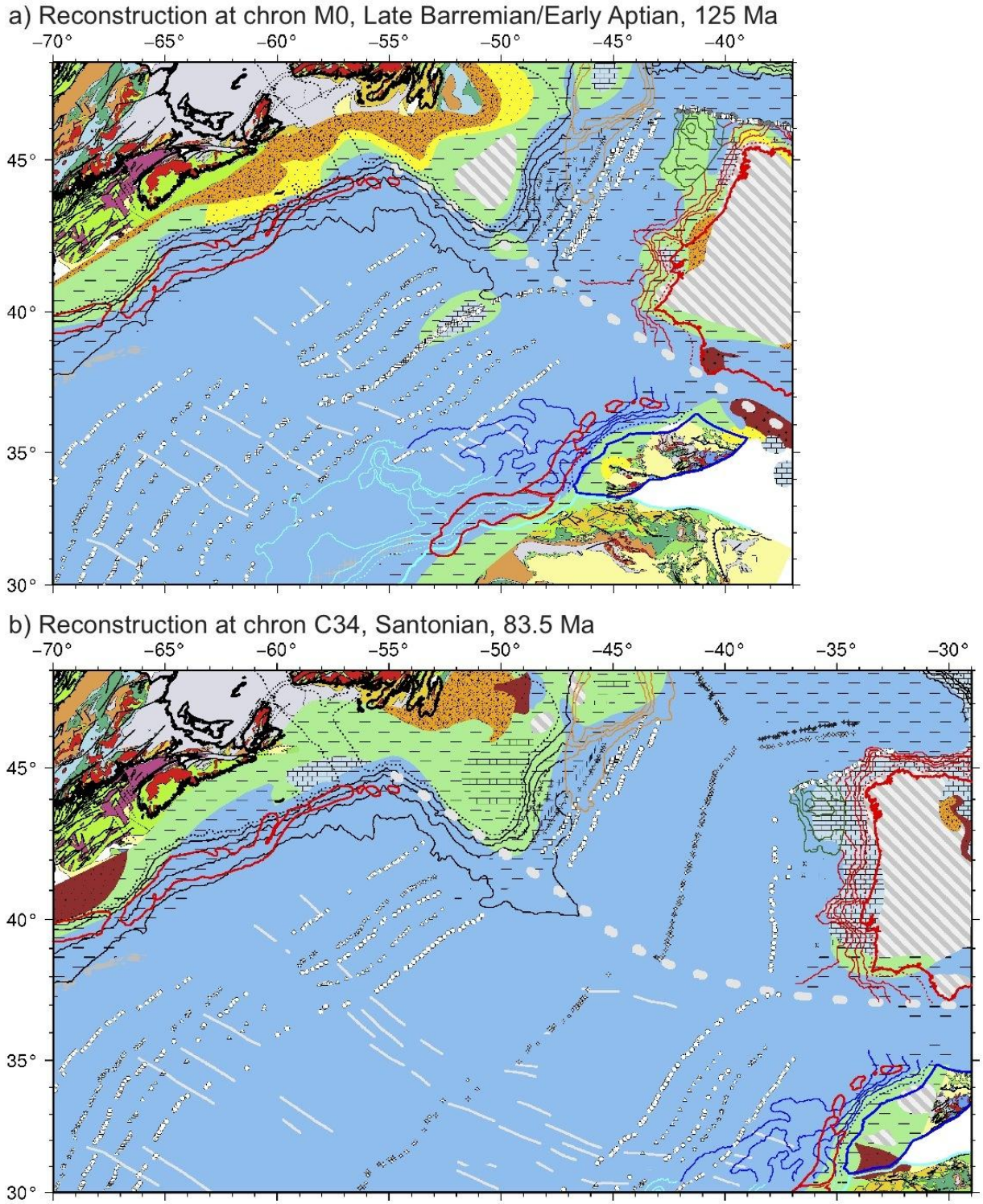

Figure 10, Sibuet et al.