AGU PUBLICATIONS

Tectonics

RESEARCH ARTICLE
10.1002/2017TC004596

Key Points:
- Asymmetric spreading creating amagmatic crust on the Canadian side and magmatic oceanic crust on the Moroccan margin
- Oceanic crust in the Moroccan margin might have been modified and thickened by the presence of the Canary hot spot
- Thick layers of volcanic underplate and seaward dipping reflector sequences are imaged only along the U.S. continental margin

Correspondence to:
Y. Biari,
biari@cerege.fr

Citation:
Biari, Y., F. Klingelhoefer, M. Sahabi, T. Funck, M. Benabdellouahed, M. Schnabel, C. Reichert, M.-A. Gutscher, A. Bronner, and J. A. Austin (2017), Opening of the central Atlantic Ocean: Implications for geometric rifting and asymmetric initial seafloor spreading after continental breakup, *Tectonics*, *36*, 1129–1150, doi:10.1002/2017TC004596.

Received 4 APR 2017
Accepted 1 JUN 2017
Accepted article online 9 JUN 2017
Published online 26 JUN 2017

Opening of the central Atlantic Ocean: Implications for geometric rifting and asymmetric initial seafloor spreading after continental breakup

Y. Biari[1,2,3,4], F. Klingelhoefer[1], M. Sahabi[2], T. Funck[5], M. Benabdellouahed[3], M. Schnabel[6], C. Reichert[6], M.-A. Gutscher[3], A. Bronner[1], and J. A. Austin[7]

[1]Department of Marine Geosciences, Ifremer, Plouzané, France, [2]Laboratoire Géosciences marines et Sciences des sols-URAC 45, Université Chouaïb Doukkali - Faculté Des Sciences, El Jadida, Morocco, [3]Institut Universitaire Europeen de la Mer, UMR 6538 Laboratoire Géosciences Océan, Plouzane, France, [4]Now at Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, Europôle Méditerranéen de l'Arbois, Aix-en-Provence, France, [5]GEUS-Geological Survey of Denmark and Greenland, Copenhagen, Denmark, [6]Bundesanstalt fuer Geowissenschaften und Rohstoffe, Geozentrum Hannover, Hannover, Germany, [7]John A. and Katherine G. Jackson School of Geosciences, Institute for Geophysics, University of Texas at Austin, Austin, Texas, USA

Abstract Study of the deep structure of conjugate passive continental margins combined with detailed plate kinematic reconstructions can provide constraints on the mechanisms of rifting and formation of initial oceanic crust. In this study the central Atlantic conjugate margins are compared based on compilation of wide-angle seismic profiles from NW Africa Nova Scotian and U.S. passive margins. The patterns of volcanism, crustal thickness, geometry, and seismic velocities in the transition zone suggest symmetric rifting followed by asymmetric oceanic crustal accretion. Conjugate profiles in the southern central Atlantic image differences in the continental crustal thickness. While profiles on the eastern U.S. margin are characterized by thick layers of magmatic underplating, no such underplate was imaged along the African continental margin. In the north, two wide-angle seismic profiles acquired in exactly conjugate positions show that the crustal geometry of the unthinned continental crust and the necking zone are nearly symmetric. A region including seismic velocities too high to be explained by either continental or oceanic crust is imaged along the Canadian side, corresponding on the African side to an oceanic crust with slightly elevated velocities. These might result from asymmetric spreading creating seafloor by faulting the existing lithosphere on the Canadian side and the emplacement of magmatic oceanic crust including pockets of serpentinite on the Moroccan margin. After isochron M25, a large-scale plate reorganization might then have led to an increase in spreading velocity and the production of thin magmatic crust on both sides.

1. Introduction

The structure of conjugate passive margins provides information about rifting styles, the initial phases of the opening of an ocean, and the formation of its associated sedimentary basins. Deep seismic surveys acquiring reflection and wide-angle seismic data together with gravity and magnetic data allow scientists to image the deep crustal structure as well as sedimentary geometries along passive margins from unthinned continental crust out to normal oceanic crust. The study of conjugate margin pairs enables us to test recent rifting models, including those proposing low-angle detachments allowing mantle exhumation during continental breakup following an initial phase of symmetric stretching [*Whitmarsh et al.*, 2001; *Manatschal*, 2004; *Péron-Pinvidic and Manatschal*, 2008]. These models predict the delayed establishment of oceanic spreading and a phase of accretion of unusually thin oceanic crust. However, most of these models are based on the comparison of the West Iberian and Newfoundland conjugate margin pair, and only few studies have addressed other magma-poor margin pairs. In contrast, South Atlantic margins are interpreted to be composed of wide regions of thin upper continental crust that were underlain by hot asthenosphere at the time of rifting and therefore lack lower crust and mantle lithosphere [*Huismans and Beaumont*, 2011]. Here no continental upper mantle is interpreted to be exhumed at the seafloor, and thin layers of magmatic underplate have been interpreted from velocity models [*Contrucci et al.*, 2004a; *Moulin et al.*, 2010; *Evain et al.*, 2015; *Klingelhoefer et al.*, 2015]. Accretion of normal oceanic crust sets in soon after breakup. However, during this initial phase of opening and at very slow spreading rates and accordingly low mantle temperatures, most of the material available may originate from the upper mantle. These circumstances can lead to the accretion of a proto-oceanic crust including basaltic flows on top of a layer of serpentinized upper mantle material. At a later stage when spreading rates increase, thin and irregular igneous oceanic crust can be accreted [*Lau et al.*, 2006; *Shillington et al.*, 2006; *Van Avendonk et al.*, 2006; *Dean et al.*, 2015; *Klingelhoefer et al.*, 2015]. This phase can last up to ~15 Myr with mid-ocean ridge basalt-type magmatic activity alternated with tectonic spreading phases [*Jagoutz et al.*, 2007].

These two different types of margins have been proposed to be end-members of magma-poor rifts, where in the first type depth-dependent extension results in crustal-necking before mantle-lithosphere breakup, and in the second type, decoupling between the upper and lower lithosphere leads to depth-dependent extension and can include flow of lower crust [*Aslanian et al.*, 2009; *Huismans and Beaumont*, 2011; *Aslanian and Moulin*, 2012].

In this study existing wide-angle seismic transects from the central Atlantic passive continental margins are revisited, and regions of exhumed upper mantle, seaward dipping reflectors (SDRs), and thin oceanic crust are identified and mapped. The detailed and complete history of margin formation was interpreted in different regions, since the structure of the margin can be modified at a later stage, through volcanism, compression, or extension. Plate kinematic reconstructions allow us to reposition the major plates and tectonic blocks in their original configuration at the moment of initial breakup and early seafloor spreading. Where available, the geometry of the continental crust and the necking zone are compared on conjugate profiles to determine the degree of asymmetry of the rifting phase. This allows us to propose an opening mechanism for the northern central Atlantic Ocean including symmetric rifting and later asymmetric oceanic spreading with magmatic oceanic crust on the African and amagmatic spreading on the Canadian side. For the southern central Atlantic the existing data do not allow us to calculate the degree of symmetry of the opening. However, the fact that volcanism is distributed very asymmetrically implies that opening was probably different from the north.

2. Study Area: Central Atlantic Conjugate Margins

The central Atlantic Ocean that separated the northeast American and northwest African margins is bordered to the north by the Pico and Gloria fracture zones and by the 15°20′N and Guinea fracture zones to the south (Figure 1). It is one of the oldest oceans. A protracted period of extension preceded the rifting leading to breakup of the central Atlantic Ocean. During this phase, the extension led to the formation of a series of rift basins along both margins [*Withjack et al.*, 2012]. Seafloor spreading started around 180–200 Ma either during the Late Sinemurian (195 Ma) [*Sahabi et al.*, 2004] or during the Middle Jurassic (175 Ma) [*Klitgord and Schouten*, 1986] associated to only minor intercontinental deformation and is therefore a natural laboratory to test different rifting models. While the continental margin of the eastern United States is characterized by a more volcanic rifting style including the deposition of thick layers of SDRs and volcanic underplate as imaged in reflection and wide-angle seismic data [*LASE Study Group*, 1986; *Tréhu et al.*, 1989; *Austin et al.*, 1990; *Holbrook et al.*, 1994a, 1994b], the Nova Scotia continental margin off Eastern Canada marks a transition from a more volcanic to a magma-poor style of rifting [*Funck et al.*, 2004; *Wu et al.*, 2006; *Louden et al.*, 2010]. The conjugate NW African margin appears to be largely magma poor, with no or only few SDRs and an absence of underplate layers [*Roeser et al.*, 2002; *Contrucci et al.*, 2004b; *Klingelhoefer et al.*, 2009; *Labails and Olivet*, 2009; *Jaffal et al.*, 2009; *Biari et al.*, 2015; *Klingelhoefer et al.*, 2016; *Benabdellouahed et al.*, 2017].

Proposed rifting models for the northern central Atlantic include asymmetric rifting leading to exhumation of serpentinized upper mantle material along a deep detachment fault as well as symmetric rifting followed by asymmetric accretion of early oceanic crust [e.g *Tari and Molnar*, 2005; *Maillard et al.*, 2006]. Interpretations of reflection seismic data from the Canadian margin led to the proposition that a mix between shear extension in the crust and pure shear in the mantle lithosphere preceded opening of the ocean basin [*Keen and Potter*, 1995a]. Modeling of wide-angle seismic data along the same transect (SMART-1, Figure 1) indicates the presence of a 150 km wide zone of exhumed mantle material [*Funck et al.*, 2004], similar in seismic characteristics to those of the Iberian margin. On the conjugate part of the Moroccan margin, early work included the acquisition of four combined wide-angle and multichannel seismic profiles across the northern Moroccan salt basin [*Contrucci et al.*, 2004b; *Maillard et al.*, 2006; *Jaffal et al.*, 2009]. Although these profiles are not exactly conjugate (Figure 2) to their homologues on the Canadian side, they have been used to propose possible mechanisms of opening of the central Atlantic. The existence of exhumed upper mantle only on the

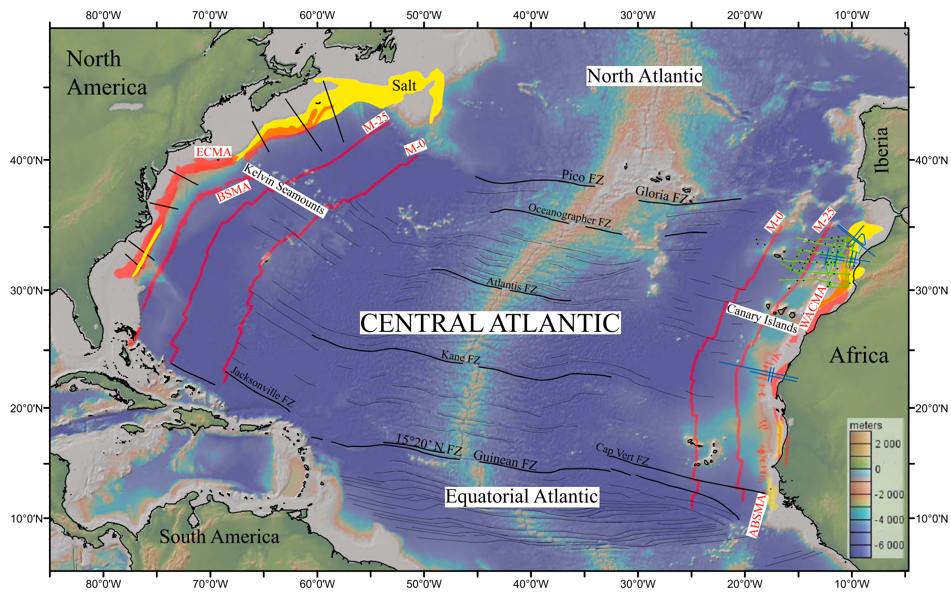

Figure 1. Overview of the central Atlantic Ocean, located between the Pico and Gloria fracture zones to the north and the 15°20′N, and the Guinea fracture zones to the south (thick black lines), bathymetry and topography from [*Ryan et al*., 2009]. Major magnetic anomalies ECMA-East Coast, WACMA-West African Coast, BSMA-Blake Spur, ABSMA-African Blake Spur, M25, and M0 are shown in red from *Klitgord and Schouten* [1986], *Sahabi et al*. [2004], and *Labails et al*. [2010]. The position of the salt (light yellow) is taken from *Sahabi et al*. [2004], *Davison* [2005], *Tari et al*. [2012], and the location of the seismic profiles discussed in this study are shown as follows: In blue, wide-angle seismic profiles acquired during the Sismar, DAKHLA, and Mirror cruises [*Contrucci et al*., 2004b; *Klingelhoefer et al*., 2009; *Biari et al*., 2015]. Black dots and green profiles are the positions of sonobuoys and MCS profiles from *Holik et al*. [1991]. Black lines along the North American margin, represent wide-angle seismic profiles of the SMART-1, -2, and -3 [*Funck et al*., 2004; *Wu et al*., 2006; *Louden et al*., 2010], LASE, EDGE-801, USGS-32, and BAa-6 [*LASE Study Group*, 1986; *Tréhu et al*., 1989; *Austin et al*., 1990; *Holbrook et al*., 1994a, 1994b; *Lizarralde et al*., 1994; *Lizarralde and Holbrook*, 1997] going from north to south.

Canadian side and the interpreted higher upper to lower crustal ratio on the African side have led to the proposition of asymmetric rifting and opening analogous to that proposed for the West Iberian and Newfoundland margin pair [*Tari and Molnar*, 2005; *Maillard et al*., 2006; *Sibuet et al*., 2012], where the African margin acted as upper plate margin. Based on additional industrial profiles, this hypothesis was extended along the NW African margin, and the Tafelney Plateau was proposed to be a high-relief accommodation zone, leading to the Canadian margin being the upper plate margin south of the plateau

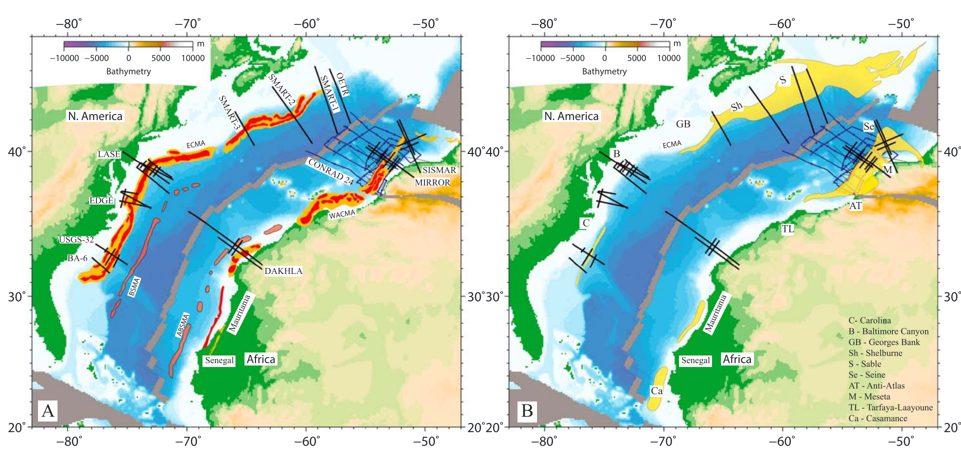

Figure 2. Reconstruction of the central Atlantic at M25, pole from *Seton et al*. [2012]. Locations of wide-angle seismic profiles are marked by black lines. (a) Location of the magnetic anomalies ECMA = East Coast Magnetic Anomaly; WACMA = West African Coast Magnetic Anomaly, BSMA = Blake Spur Magnetic Anomaly, and ABSMA = African Blake Spur Magnetic Anomaly. (b) Location of the main salt basins shown in yellow.

[*Tari and Molnar*, 2005]. New data from the NW Moroccan margin off Safi acquired along a profile exactly conjugate to the SMART-1 profile led to the proposition of symmetric rifting with asymmetric spreading emplacing thin oceanic crust on the Canadian side and normal oceanic crust on the African side in this segment of the central Atlantic margin [*Biari et al*., 2015].

For the southern central Atlantic, opening mechanisms include rifting accompanied by volcanism and magmatic underplating leading to the formation of a volcanic margin [*LASE Study Group*, 1986; *Tréhu et al*., 1989; *Austin et al*., 1990; *Holbrook et al*., 1994a, 1994b]. Based on the existence of shallow water carbonate platforms present at the continental slope along both margins, *Labails and Olivet* [2009] propose that the margin opened in a symmetric manner, with thinned crust in the basin remaining a high position. An unusually hot mantle or flow of the lower crust might explain this thinning without subsidence [*Labails et al*., 2010].

3. Plate Kinematic Reconstructions of the Central Atlantic

Magnetic anomalies marking the end of rifting and the onset of oceanic accretion together with the position of salt basins along both margins can be used to define the paleogeographic situation at the opening of the Atlantic [*Klitgord and Schouten*, 1986; *Sahabi et al*., 2004; *Labails et al*., 2010]. On both conjugate margins of the central Atlantic, the East Coast Magnetic Anomaly (ECMA) on the American side and the lower amplitude West African Magnetic Anomaly (WACMA or S1) on the African side were used to identify the continent-ocean transition zone.

The decrease in volcanic products observed toward the north along the North American margin can be correlated to a decrease in amplitude of the East Coast Magnetic Anomaly (ECMA) toward the north. The ECMA vanishes completely at about 44°N. Seaward of the ECMA, a second magnetic anomaly has been identified, called the Blake Spur Magnetic Anomaly (BSMA) [*Vogt*, 1973; *Sheridan et al*., 1982; *Klitgord and Schouten*, 1986]. Along the NW African margin volcanic products are much scarcer and mainly linked to the proximity of the Canary hot spot. Accordingly, the conjugate West African Coast Magnetic Anomaly (WACMA) has a relatively lower amplitude compared with the ECMA. A weak magnetic anomaly called the African Blake Spur Magnetic Anomaly (ABSMA) has been identified seaward of the WACMA and is proposed to be the conjugate to the BSMA [*Labails et al*., 2010]. However, it can be traced farther north than the ECMA and reaches the North African salt basin [*Sahabi et al*., 2004]. A basic segmentation of the two border anomalies ECMA and WACMA can be identified, with both anomalies displaying a double maximum in the southern segment and a single maximum in the north.

The distribution of evaporite basins along the two margins is symmetric and therefore provides an additional constraint for plate kinematic reconstructions [*Sahabi et al*., 2004; *Shimeld*, 2014]. On the North American margin, evaporite basins are located in Nova Scotia and Georges Bank and in the basins of the Grand Banks of Newfoundland to the north. They are dated by drilling to have formed during the Rhaetian to the Late Sinemurian [*Jansa et al*., 1980; *Wade and MacLean*, 1990], and therefore, this region is related to the history of the Triassic salt basins of the North Atlantic [*Olivet et al*., 1984].

A salt basin has been imaged in the Carolina Basin at the base of the ECMA in a very narrow evaporite band [*Dillon and Popenoe*, 1988]. On the African side, the distribution of evaporite basins is similar to those of the American margin: a deep salt basin is present along the Moroccan margin, comparable in size to that of Nova Scotia. However, no evaporite basin is imaged south of the Canary Islands. In the regions of DAKHLA and Laayoune, only a narrow band of evaporites is located in the Mauritania Basin, which represents the conjugate to the Carolina Basin. Farther south, evaporites were observed in the Casamance Basin, which has no conjugate in the U.S. margin as it faces the Blake Plateau (Figure 2b).

The kinematic history of the opening of the central Atlantic has been the object of detailed studies. A detailed study of magnetic anomalies proposed a kinematic model in which they placed the WACMA anomaly as conjugate to the BSMA and included a ridge jump at the time of BSMA [*Klitgord and Schouten*, 1986]. On the basis of this reconstruction, an age of 175 Ma was obtained for the onset of seafloor spreading and the formation of the first oceanic crust. Based on additional information from the location of the salt basins along both margins, interpretations of seismic lines, and a new interpretation of the magnetic anomaly data, *Sahabi et al*. [2004] proposed a new set of reconstructions which provide a more coherent position of ECMA relative to the African conjugate Magnetic Anomaly (WACMA). *Sahabi et al*. [2004] conclude that both the ECMA and

WACMA coincide with the limit of the salt basin and propose an age of initial opening at Sinemurian times (195 Ma), about 20 Ma earlier than proposed by *Klitgord and Schouten* [1986]. In 2010, *Labails et al.* [2010] using the rotation poles of *Sahabi et al*. [2004] and additional new geophysical data proposed an alternative scenario for the Mesozoic spreading rate history of the central Atlantic Ocean with no changes to the poles themselves [*Labails et al*., 2010]. According to the authors, the initial spreading rate at the onset of seafloor spreading was very slow (0.8 cm/yr full spreading) in the Early and Middle Jurassic but increased to 1.6 cm/yr in the Late Jurassic. A peak in spreading velocities (3 cm/yr) is proposed to be related to a major plate reorganization between M25 and M22 magnetic anomalies, associated with a decrease in spreading rate to 1.3 cm/yr [*Labails et al*., 2010]. The aim of this study was not to refine existing plate reconstruction, and in this work we use the reconstruction poles of *Seton et al*. [2012] and the spreading rates of *Labails et al*. [2010]. Offsets introduced by the use of different plate reconstruction parameters, especially those which do not including a separate Meseta plate and therefore neglecting the Atlas formation, can introduce offsets no larger than 15 km. This is in good agreement with existing studies of the statistical error of plate kinematic reconstructions [e.g., *Hellinger*, 1981; *Kirkwood et al*., 1999; *Cande et al*., 2000] and does not impact the conclusions drawn in this paper.

The mapping of the extension of the marginal evaporite basins and the character of the magnetic anomalies (ECMA-WACMA) suggest a division of the central Atlantic into two main segments separated by the Kelvin Seamounts and the Canary Islands [*Sahabi et al*., 2004; *Labails et al*., 2010]. Each segment shows a second-order segmentation at a wavelength of 500–600 km:

1. On the northern segment, the margin is characterized by the presence of wide salt basins (Novia Scotia and Meseta basins), double peaks of ECMA and WACMA anomalies. In this segment are located the deep seismic profiles SISMAR-4 and MIRROR-1 on the African side and SMART on the Canadian side. Here the BSMA and the ABSMA are absent.
2. In the southern segment the margin can be divided into two subsegments. The northern one is not associated with any evaporitic basins The ECMA and WACMA here show single peaks and the deep seismic profiles DAKHLA on the African margin and LASE on the American margin are located in this subsegment. In the southern subsegment, evaporites are identified in the Carolina and Mauritania basins, and the ECMA and WACMA are characterized by double peaks. In the south a double peak opening anomaly suggests the existence of the BSMA and ABSMA. In this region only the American margin has been sampled by wide-angle seismic data (USGS 32 and BA-6) (Figures 1 and 2). BSMA and ABSMA can be identified throughout both subsegments.

4. Deep Crustal Structure of the Conjugate Margins

In the following chapters, for both conjugate margins, sediment and crustal thickness, as well as the nature of the crust shown, are taken directly from the original interpretations of these profiles by their authors. As these original interpretations of the nature of the crust were based on additional data such as multichannel seismic or gravity data we have not tried to reinterpret these existing studies. All models discussed in this paper are published and cited in the text.

During the SMART cruise in 2001 three wide-angle refraction seismic profiles were acquired across the Nova Scotia margin. The 490 km long refraction seismic SMART-1 line was acquired using 19 ocean bottom seismometers (OBS). It was coincident with two deep reflection seismic line (line 89–1 of *Keen and Potter* [1995b] and an unpublished line 89–12 from the German Federal Agency of Geosciences and Natural Resources (BGR)). The data were modeled using a 2-D iterative damped least squares traveltime inversion from the RAYINVR software [*Zelt and Smith*, 1992]. The model is well constrained with a total RMS misfit of 103 ms between calculated and picked travel times. A resolution calculation was performed as well as gravity modeling. The SMART-2 refraction seismic line of 500 km length is profile is coincident with previous deep reflection profiles. The velocity model was developed by forward modeling [*Zelt and Smith*, 1992] using 21 OBS. The model has a total RMS misfit of 82 ms, and it is additionally constrained by gravity modeling. The southernmost SMART-3 profile was acquired using 20 OBS and is located parallel to an existing reflection seismic line. The data were forward modeled using software from GeoPro (Hamburg). There is no information provided specific to the error analysis for this line or whether gravity modeling or synthetic data calculation was performed.

Table 1. Acquisition Parameters and the Associated Error on the Depth of the Moho for All Profiles Used in This Study

Name	Years	Profile Length (km)	Stations: OBS/OBH/ESP/Land Stations (Ls)	Method Used	Other Data and Methods Used	Instrument Spacing (km)	Error Bars (km +/−)
SISMAR	2001	400	14 OBS/11 Ls	Forward/Gravity/synthetic	MCS	18	1
MIRRO-R	2011	400	28 OBS/15 Ls	Forward/Gravity/synthetic	MCS/Grav/Mag/Bathy	9	0.5
DAKHL-A	2002	750	33 OBS/11 Ls	Forward/Gravity/synthetic	MCS/Grav/Mag/Bathy	7–28	1
SMART-1	2001	490	19 OBS	Forward/Gravity	MCS	20–40	1
SMART-2	2001	500	21 OBS	Forward/Gravity	Sonic well/log data/MCS	32–40	1
SMART-3	2001	280	20 OBS	Software from GeoPro	MCS	14	1
LASE	1980s	400	5 ESP	ESP modeling	MCS	25–40	2–3
EDGE	1990	240	10 OBS	Ray trace modeling	MCS	13–28	2–3
USGS-32	1985	~200	7 OBS along 3 ESP	ESP modeling	MCS	70	2–3
BA-6	1988	180	9 OBS	Forward	MCS	19	2–3

The wide-angle seismic lines located along the U.S. Atlantic margin were acquired in the 1980s and 1990s with lower instrument density and quality data as the more modern Canadian and African surveys. The 490 km long LASE Line 6 was modeled based on five expanding spread profiles (ESPs). The line is close to two deep stratigraphic wells and coincides with a seismic reflection line No information is provided specific to the error analysis for this line. During the EDGE Mid-Atlantic seismic experiment in 1990 a 240 km long combined wide-angle and reflection seismic profile has been acquired using 10 OBS. Velocity modeling was performed using the RAYINVR software [*Zelt and Smith*, 1992], and RMS misfits were estimated in several sections of the model including the lower crust in the OCT (RMS misfit of 0.13 s) in the lower oceanic crust (RMS misfit of 0.09 s). Synthetic seismograms and gravity models were calculated. Three wide-angle seismic lines were acquired in the Carolina Trough using seven OBS coincident with existing gravity, magnetic, and seismic reflection data. The velocity model was obtained by tau-sum recursion [*Diebold and Stoffa*, 1981], and gravity modeling was also performed. Combined wide-angle and reflection seismic BA-6 profile was acquired using nine OBS and modeled using a 2-D traveltime inversion [*Zelt and Smith*, 1992] including resolution and tests as well as gravity modeling.

The profiles located on the African margin were acquired between 2002 and 2011 by French research vessels using comparable marine instruments from Ifremer, a large volume airgun array, and a 4.5 km digital streamer for the coincident reflection seismic profiles. All data were modeled using the RAYINVR software package [*Zelt and Smith*, 1992] and additionally constrained by gravity modeling, resolution analysis, and synthetic data calculations. Additional constraints for all three surveys came from margin parallel profiles. During the SISMAR marine seismic survey (2001), deep reflection seismic profiles recorded by ocean bottom seismometers were acquired using 14 ocean bottom seismometers and 14 land stations deployed along a 400 km profile long. The resulting model is well constrained with a total RMS misfit of 0.132 s. In 2011 the 400 km long combined reflection and wide-angle seismic MIRROR profile was acquired using 28 ocean bottom seismometers and 15 land stations. The final model has a total RMS misfit of 0.137 s. The southern Moroccan margin segment was studied during the DAKHLA cruise 2002, along a 750 km long reflection and wide-angle profile, using 33 OBS and 14 land stations. Modeling resulted in a RMS misfit of 0.126 s for this profile.

While the error on the depth of the Moho for a study using sparse ESP profiles might be as large as several kilometers [e.g., *LASE Study Group*, 1986], modern profiles have errors between 500 m and 1 km on the deeper layers [e.g., *Biari et al.*, 2015]. The older profiles do include less detailed information about boundary geometry and small lateral velocity changes due to the larger receiver spacing; however, the constraints will be largely sufficient to detect the nature of the crust and the approximate extent of each of the domains imaged along the profile and used in this study. We compiled the acquisition and processing parameters for all lines and propose an estimation of the depth uncertainty on the deeper layers (Table 1). Of the four profiles discussed in greater detail in the following chapters, the LASE profile dating from the 1980s was the oldest and the MIRROR profile (2011) the most recent data acquisition. As the LASE profile does not constrain unthinned continental crustal thickness, the degree of symmetry or asymmetry of the opening of the southern central Atlantic margin cannot be assessed, but comparison of the OCT and oceanic crustal structure is still relevant to questions regarding the existence of underplate and oceanic crustal structure. In the northern segment the SMART and MIRROR profiles are of comparable resolution, using OBS and land station data and therefore allow detailed analysis of all aspects of conjugate margin pairs. The error inherent in the plate kinematic reconstructions is difficult to estimate; however, comparison of the geometry using different sets of rotation poles indicates that for this region differences are less than 15–20 km.

4.1. Northeast American Margin

Along the Nova Scotian margin, the three wide-angle seismic profiles SMART-1, -2, and -3 (Figure 3) were acquired in order to sample the margin at locations where the ECMA is strong, where its amplitude is weak and where it disappears. Accordingly, the objective of the experiment was to image the deep structure of the margin along this transition from volcanic to nonvolcanic rifting style. The northernmost profile, SMART-1, shows no evidence for a magmatic underplate layer beneath the continental crust. Instead, it images a 150 km wide zone of material characterized by velocities between 7.2 km/s and 7.6 km/s, too high to represent either thinned continental or normal oceanic crust. It is interpreted to consist of partially serpentinized upper mantle rocks derived by exhumation along a lithospheric fault during rifting [*Funck et al.*, 2004].

Between model distances of 200 and 350 km along the SMART-1 profile, a 2 to 3 km thick layer with velocities between 5.3 and 5.4 km/s overlies a layer of 7.2 to 7.6 km/s (Figure 11). Between model distance 230 and 280 km, the upper layer is interpreted to be either very thin continental crust or exhumed upper mantle serpentinized by the seawater (model distance 270–350 km). The latter possibility is in better agreement with the hypothesis that the ECMA located west of this region marks the end of continental breakup. In both cases the lower layer is composed of mantle material serpentinized to a degree of 10–25% [*Funck et al.*, 2004]. Between model distances 270 and 350 km, a layer of 2–3 km thickness and *P* wave velocities of 5.1–5.2 km/s overlies the layer proposed to be serpentinized peridotite, already identified between 270 and 350 km model distance. The upper layer here is proposed to represent exhumed mantle peridotite with a degree of serpentinization of 85 to 100%.

These interpretations are based on the existence of thin oceanic crust next to this region and the absence of SDRs. This argues in favor of a magma-poor system and therefore does not support an interpretation in which the 7.2–7.6 km/s layer represents a magmatic underplate. Also, rifting probably started at 230 Ma [*Welsink et al.*, 1989] and seafloor spreading either at 175 Ma [*Klitgord and Schouten*, 1986] or at 195 Ma [*Sahabi et al.*, 2004]. Hence, according to the melt generation model of *Bown and White* [1994], the long duration of rifting is sufficient to cool the asthenospheric mantle and inhibit melt production. The fact that the basement has a very different character in this zone seems to rule out the possibility of thin oceanic crust overlying serpentinized upper mantle material here. Seaward of this region, an oceanic crust of only 3–4 km thickness was imaged.

SMART-2 is located 250 km south of the SMART-1 profile. The model of *Wu et al.* [2006] shows relatively high lower crustal velocities of up to 7.4 km/s in an up to 2 km thick layer in a zone extending 90 km seaward of the interpreted continent ocean boundary. This layer is interpreted as a mixture of serpentinized mantle and gabbroic layer 3. The continent-ocean transition zone is underlain by material with seismic velocities between 7.6 and 7.9 km/s, probably representing partially serpentinized mantle material. Serpentinization in this case likely resulted from water intruding the mantle through thin crust [*Wu et al.*, 2006]. No volcanic underplate was imaged along the profile suggesting a primarily magma-poor rifting across the central Nova Scotia margin. However, it cannot be ruled out that this might be the extremity edge of a magmatic underplate coming from the south. In contrast, the southernmost line (SMART-3) images a 100 km wide region of thin crust underlain by a 5 to 10 km thick body interpreted to be magmatic underplate neighboring normal oceanic crust of 7 km thickness [*Louden et al.*, 2010] with a smooth basement [*Keen and Potter*, 1995b].

The U.S. continental margin has been imaged from the north to the south by the LASE, EDGE, USGS-32, and BA-6 profiles, although unfortunately, none of these profiles extend out to the BSMA (Figures 1 and 4) [*LASE Study Group*, 1986; *Tréhu et al.*, 1989; *Holbrook et al.*, 1994a, 1994b; *Sheridan et al.*, 1993]. The northernmost profile, LASE, images an up to 10 km thick carbonate bank overlying synrift sediments underlain by a crust of 7 to 10 km thickness characterized by velocities up to 7.5 km/s and therefore higher than those found in normal oceanic or continental crust [*LASE Study Group*, 1986]. The LASE study group proposed this crust to be of oceanic origin, heavily intruded and with a thick layer of underplated material at the base of the

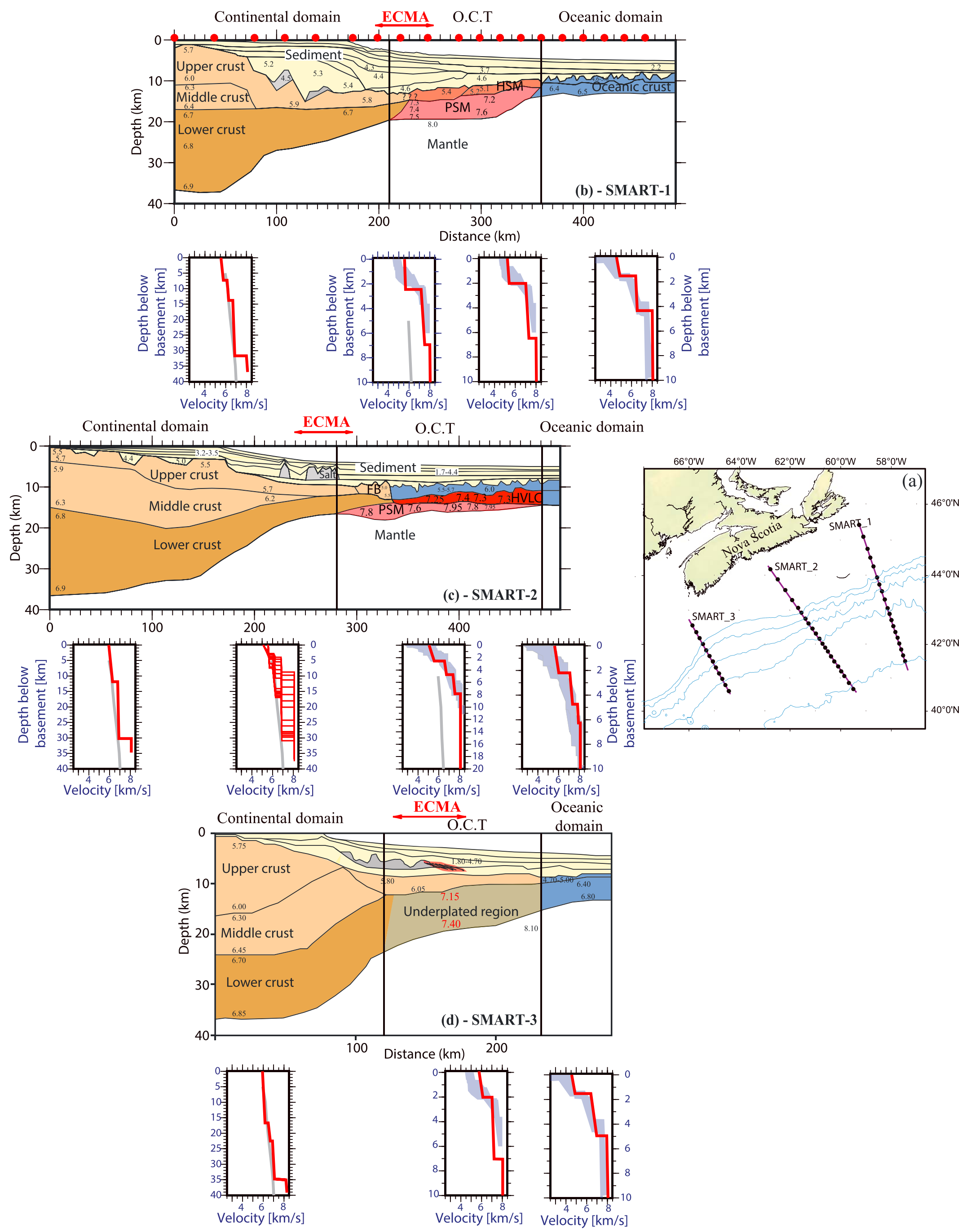

Figure 3. (a) Location of the wide-angle seismic profiles acquired during the SMART project on the regional bathymetry and topography map [*Maruyama et al.*, 1999; *Ryan et al.*, 2009]. (b) Crustal structure modified from the SMART-1 profile [*Funck et al.*, 2004], (c) SMART-2 [*Wu et al.*, 2006], and (d) SMART-3 [*Louden et al.*, 2010]. PSM = partially serpentinized mantle, HSM = highly serpentinized mantle HVLC = high-velocity lower crust, and FB = fault blocks. Numbers represent seismic layer velocities (km/s). Graphs located underneath the profiles represent 1-D velocity-depth profiles extracted from the original velocity models below the top of the basement (vz profiles) from the domain underneath which they are situated. Red lines represents mean vz profiles, the blue shaded area bounds a compilation of velocity profiles of typical Atlantic oceanic crust [*White et al.*, 1992], and bold gray profiles correspond to mean velocity profiles of thinned continental crust [*Christensen and Mooney*, 1995].

crust. The oceanic crust along this profile is between 8 and 10 km thick. Farther south, a 100 km wide body interpreted as magmatic underplate and a thick layer of SDRs, probably of volcanic origin, were modeled along the EDGE-801 profile [*Sheridan et al.*, 1993; *Holbrook et al.*, 1994a]. Similarly, a thick layer of underplate and SDRs were imaged along line USGS-32 [*Tréhu et al.*, 1989]. Although its size and extent are

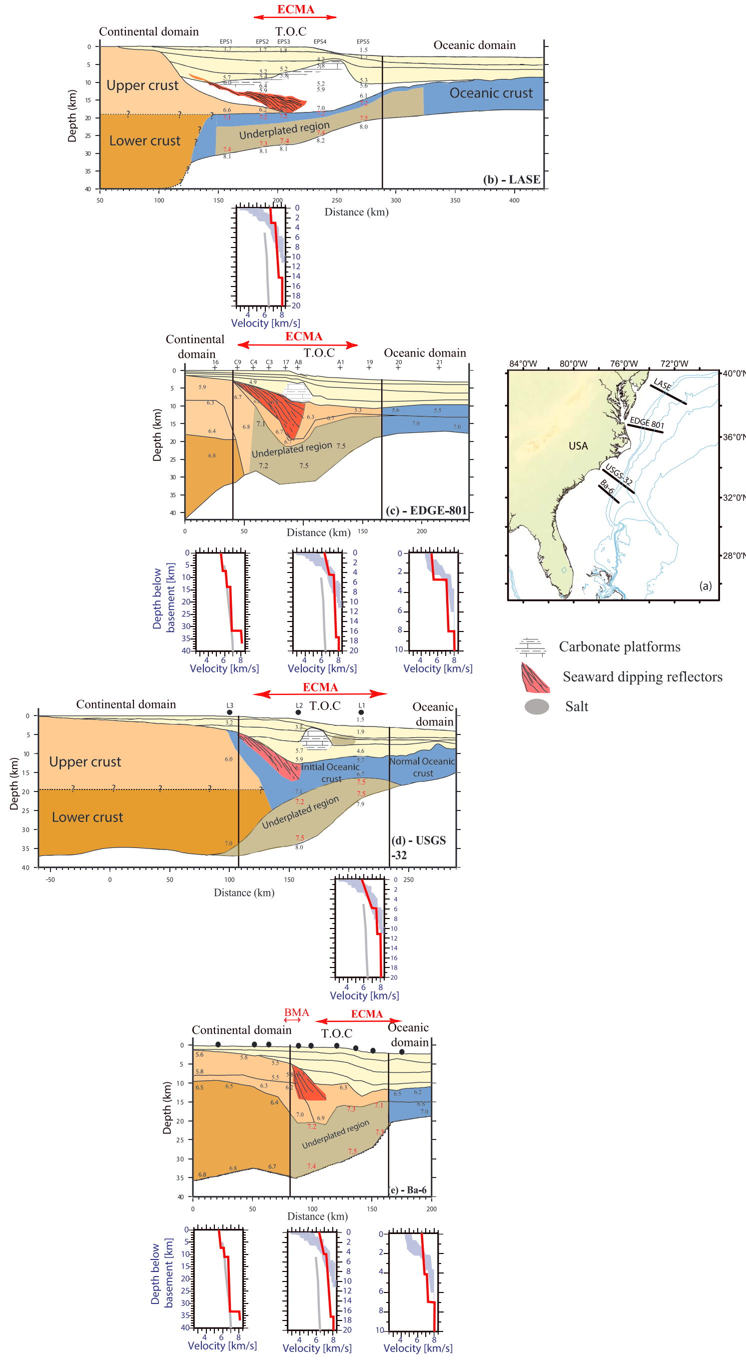

Figure 4. (a) Location of the wide-angle seismic profiles acquired along the U.S. continental margin on the regional bathymetry and topography map [*Maruyama et al.*, 1999; *Ryan et al.*, 2009]. Crustal structure modified after (b) LASE profile [*LASE Study Group*, 1986], (c) EDGE-801 [*Holbrook et al.*, 1994a], (d) USGS-32 [*Tréhu et al.*, 1989], and (e) Ba-6 [*Austin et al.*, 1990; *Holbrook et al.*, 1994b]. Numbers represent seismic layer velocities (km/s). (For comparisons see also *Sahabi et al.* [2004] and *Labails* [2007]). Graphs located underneath the profiles represent 1-D vz profiles extracted from the original velocity models below the top of the basement from the domain underneath which they are situated. Red lines represent the mean vz profiles, the blue shaded area bounds a compilation of velocity profiles for typical Atlantic oceanic crust [*White et al.*, 1992], and the bold gray profiles correspond to mean velocity profiles for thinned continental crust [*Christensen and Mooney*, 1995].

poorly constrained, *Tréhu et al.* [1989] propose that this part of the margin is magma rich in character. However, *White and McKenzie* [1989] suggest an alternative model in which the magmatic underplating was emplaced after rifting by the Cape Verde hot spot. Farther to the south along profile BA-6, as well as farther north along EDGE-801, the thickness of the underplated layer is similar to that observed along the

USGS-32, thus indicating that its origin is related to rifting rather than to the proximity of a hot spot [*Austin et al.*, 1990; *Holbrook and Kelemen*, 1993]. Along all profiles, oceanic crust of normal thickness for Atlantic-type oceanic crust as defined by *White et al*. [1992] is first observed seaward of the ECMA. The thickness of the unthinned continental crust remains poorly constrained due to the lack of seismic stations on land, except on the EDGE-801 profile where the unthinned crust is between 37 and 40 km thick (Figure 4b).

4.2. Northwest African Margin (SISMAR, MIRROR, and DAKHLA)

The NW African margin has been the target of four combined wide-angle and reflection seismic surveys. In the north, the deep structure of the margin is imaged along the SISMAR-04 profile. Here the WACMA deviates from the coast and forms a 150 km wide basin that is thought to be underlain by thinned continental crust (Figures 1 and 2) [*Contrucci et al*., 2004b]. However, plate kinematic reconstructions show that this profile, located in the North African salt basin, is not exactly conjugate to the SMART-1 profile on the Canadian margin (Figure 2). Oceanic crust imaged oceanward of the WACMA is about 7 km thick, comparable to "normal" Atlantic oceanic crust [*White et al*., 1992] (Figure 5). Farther south and conjugate to the SMART-1 line, the MIRROR-1 wide-angle seismic profiles image a 37 km thick continental crust thinning to about 8 km over a 150 km wide region (Figure 5c). Neighboring oceanic crust seaward of the WACMA is 8 km thick, and thus about 1 km thicker than normal, and characterized by elevated velocities at the base (7.2–7.4 km/s) [*Biari et al*., 2015]. Earlier work from the *Conrad* cruise imaged crust with a similar thickness and elevated velocities in this part of the margin, up to the position of the M25 magnetic anomaly [*Holik et al*., 1991]. *Holik et al*. [1991] propose that the proximity of the Canary hot spot at 60 Ma caused thickening of the crust in this region by magmatic underplating and an increase of the seismic velocities in the lower crust by intrusions. However, an alternative hypothesis is that both might be related to slow accretion at the onset of seafloor spreading, which then accelerated at the time of M25 [*Biari et al*., 2015]. The southernmost data set includes the DAKHLA profiles "*Nord*" and "*Sud*," imaging a thinner continental crust (~27 km) and a more narrow ocean-continent transition zone (Figure 5d) [*Klingelhoefer et al*., 2009]. Seaward of the WACMA, the lower oceanic crustal layer is characterized by high seismic velocities similar to those observed along the MIRROR profiles. As in the CONRAD data set [*Holik et al*., 1991], velocities in the lower crust change to values normal for oceanic crust (6.60–6.90 km/s) at the time of the M25 magnetic anomaly, therefore corroborating the theory that high velocities might be related to the changes in spreading velocity and the major plate reorganization that took place at the time of the M25 magnetic anomaly.

The fact that the continental crust is thinner along the DAKHLA profiles than in the north of the African continent might be due to depth-dependent stretching and the presence of the Precambrian Reguibat Ridge in this region [*Klingelhoefer et al*., 2009]. None of the three surveys detected a layer of underplate at the ocean-continent transition zone. Volcanic products in this region are scarce, with some weakly expressed SDRs identified in multichannel seismic (MCS) data sections [*Roeser et al*., 2002]. Volcanic products observed here such as dikes, sills, and small seamounts can be related to the presence of the Canary hot spot.

Since the 1980s the understanding of rifting processes, the genesis of the central Atlantic passive margins, and the formation of the ocean basin have been largely studied based on seismic data acquired along one segment of the margins without regard to their conjugate and to the kinematic reconstruction. Combining refraction results of different seismic cruises acquired along conjugate margins and placing them in detailed kinematic paleoreconstructions in order to compare the exact conjugate profiles, the geometry of the margins at the time of their formation was restored.

All of the above mentioned seismic profiles were acquired using ocean bottom seismometers or expanding spread profiles, and most were additionally imaged by reflection seismic profiles and constrained by gravity modeling. However, the dates of acquisition span from the 1980s for the LASE, USGS-32, and EDGE profiles up to 2011 for the MIRROR profiles. Data for the SMART, SISMAR, and DAKHLA profiles were acquired in 2001, 2002, and 2003, respectively. Generally, data quality has increased with time and with reduced instrument spacing, helping improve the model resolution, as more instruments are available today. While only five 30–40 km spaced expanding spread profiles constrain the crustal structure along the LASE profile, the seafloor instrument spacing was between 10 and 20 km for the SMART, DAKHLA, and SISMAR data and minimal 7 km for the MIRROR cruise.

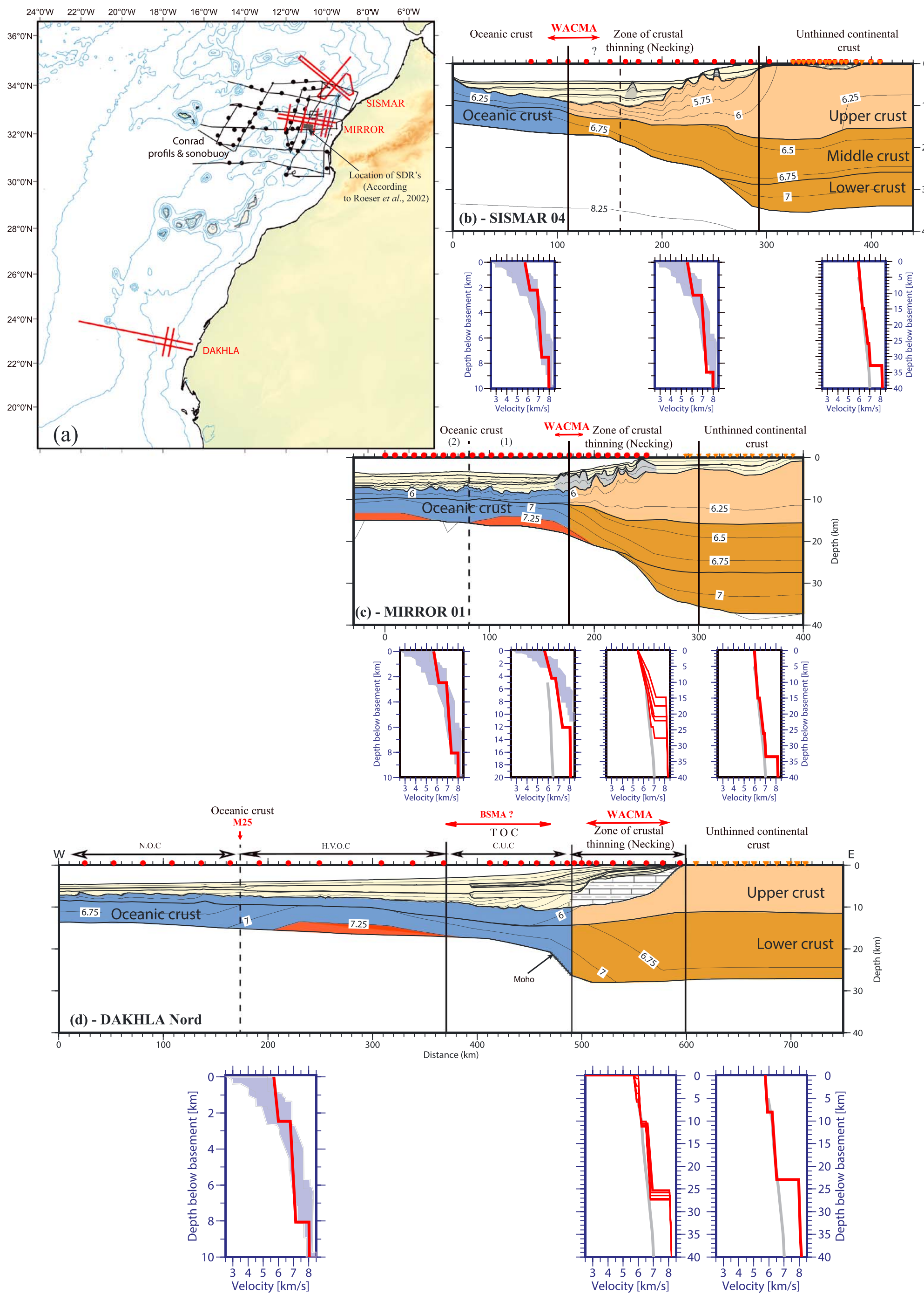

Figure 5. (a) Location of the wide-angle seismic profiles acquired along the Northwest-African margin on the regional bathymetry and topography map [*Maruyama et al.*, 1999; *Ryan et al.*, 2009]. Crustal structure modified after (b) SISMAR-4 [*Contrucci et al.*, 2004b], (c) MIRROR-1 [*Biari et al.*, 2015], and (d) DAKHLA Nord profiles [*Klingelhoefer et al.*, 2009]. HVOC = high-velocity oceanic crust, CUC = crust of unknown composition, and NOC = normal oceanic crust. Numbers represent seismic layer velocities in km/s. Graphs located underneath the profiles represent 1-D vz profiles extracted from the original velocity models below the top of the basement, from the domain where they are situated. Red lines represent mean vz profiles, the blue shaded area bounds a compilation of velocity profiles of typical Atlantic oceanic crust [*White et al.*, 1992], and bold dark gray profiles correspond to mean velocity profiles for thinned continental crust [*Christensen and Mooney*, 1995].

5. Discussion

Two pairs of conjugate deep seismic lines in the central Atlantic can be compared to better understand the mechanisms of crustal thinning, initial breakup and the start of oceanic accretion. These pairs are the

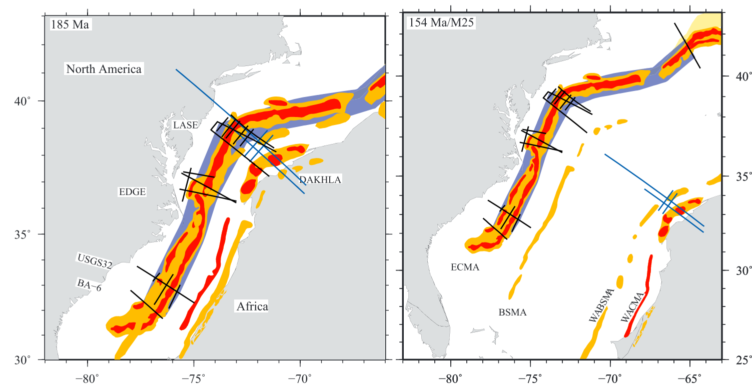

Figure 6. Plate kinematic reconstruction of the northern central Atlantic (poles from *Seton et al.* [2012]). Magnetic anomalies are marked in two colors (red and orange) depending on its amplitude, the extent of the underplate is shown in blue, and the extent of the salt basins is indicated in yellow. Wide-angle seismic profiles located along present day African continent are shown by blue lines and those on the American margin by green lines.

SMART-1-MIRROR-1 profiles in the northern and the LASE-DAKHLA-Nord profiles in the southern central Atlantic. The northern profiles are located in a zone of little to no volcanism during break-up, and salt basins are imaged as well as the presence of only the WACMA and ECMA anomalies. The southern profiles are located in the zone in which strong volcanic influence is observed along the American margin, no salt basins were imaged, and two additional magnetic anomalies, the BSMA and the ABSMA, are present. These differences seem to indicate that rifting styles were different between the two conjugate margin pairs. As the LASE profile is modeled from six expanding spread profiles only and does not include the thickness of unthinned continental crust, constraints are weaker in the south; nevertheless, some conclusions can also be drawn for the southern region.

5.1. Southern Central Atlantic: DAKHLA and LASE Profiles

The southern conjugate pair consists of the 750 km long DAKHLA Nord profile reaching about 150 km seaward of M25 and the 450 km long LASE profile, which extends up to about 30 km from the BSMA and was acquired without extension by land stations (Figure 6). Data quality differs between both profiles. On the African side 28 marine and 11 terrestrial seismic stations were used to image the margin from unthinned continental crust up to true oceanic crust, whereas the deeper structures on the American side were modeled based on six large aperture marine profiles running parallel to the margin (Figure 6) with limited constraints on the structure of unthinned continental crust and the landward extent of the underplate layer.

5.1.1. Geometry of the Continental Domains

A comparison of both profiles shows that the sedimentary thickness is up to 10 km higher on the American side (Figure 7). This probably results from climatic differences after separation of the continents leading to a higher sedimentation rate at the American continental margin. A carbonate bank was imaged along both profiles; however, it is thinner on the African side than on the American side. Carbonates develop in shallow water and grow with increasing subsidence of the margin. Along the LASE profile, the carbonate bank is emplaced on a prerift or synrift layer of SDRs expression of the magmatism during breakup. On the conjugate margin, no SDRs were identified along the DAKHLA profile, probably partly explaining the lower amplitude of the WACMA in this region compared to the ECMA. Along the DAKHLA profile the WACMA is located in the region of thinned continental crust, which is proposed to be intruded by volcanic products such as dikes and sills leading to elevated velocities (7.2–7.3 km/s) [*Klingelhoefer et al.*, 2009]. In contrast, along the LASE profile, the ECMA is located on heavily intruded crust of oceanic origin (Figure 7). The unthinned continental crustal thickness is not constrained along the LASE profile, so no direct comparison to the DAKHLA profile can be made, but unthinned continental crust imaged along the remaining U.S. margin shows a thickness of 32–34 km (Figure 8). The fact that the crustal thickness is lower along the DAKHLA profiles than those to the north and on the conjugate margin can be explained by the presence of the Reguibat Ridge [*Klingelhoefer et al.*, 2009; *Labails and Olivet* [2009]; *Benabdellouahed et al.*, 2016]. The Precambrian Reguibat Shield is proposed to have remained stable during the Hercynian orogeny and the central Atlantic opening, which led to the formation of the Tarfaya-Laayoune and Mauritanian-Senegal basins. The

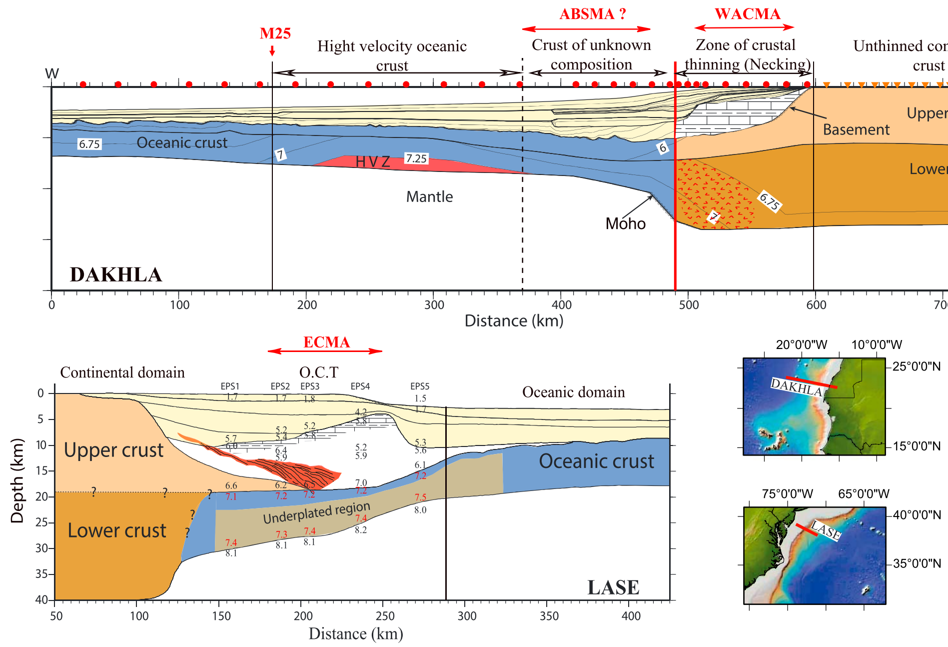

Figure 7. Interpreted depth sections along the conjugate DAKHLA [*Klingelhoefer et al.*, 2009] and LASE [*LASE Study Group*, 1986] profiles. HVZ = high-velocity zone (mixture of lower crustal material with upper mantle peridotites), numbers represent seismic layer velocities (km/s). Location of the wide-angle seismic profiles acquired during the DAKHLA and LASE surveys on the regional bathymetry and topography map [*Ryan et al.*, 2009].

DAKHLA profile is located between these two basins, and thus, the crustal thickness is not a direct result of rifting only. Similarity in the Mauritanian Basin, a 30 km thick continental crust was imaged by seismic reflection profiles in the Mauritanian Basin [*Weigel et al.*, 1982].

5.1.2. Oceanic Accretion and Underplating

The seismic velocities in the ocean-continent transition zone are higher on the American side than on the African margin (Figure 8). The higher velocities are probably related to the presence of intrusions and volcanic products along the U.S. margin. Based on the wide-angle seismic profiles, one main difference between the two margins in the southern central Atlantic is the presence of thick layers of underplate and SDRs, both associated to synrift volcanism on the American margin. No SDRs and no underplate were imaged on the conjugate African margin [*Labails and Olivet*, 2009, *Klingelhoefer et al.*, 2009]. It has been proposed that these volcanic products form part of the CAMP (central Atlantic magmatic province), which spans four continents and is of Triassic-Jurassic age, associated to opening of the central Atlantic [*Marzoli et al.*, 1999; *Jourdan et al.*, 2009; *Blackburn et al.*, 2013]. However, SDRs were also identified on deep reflection seismic data offshore the Blake Plateau, and there are situated on top of the CAMP flood basalts and therefore of a younger age

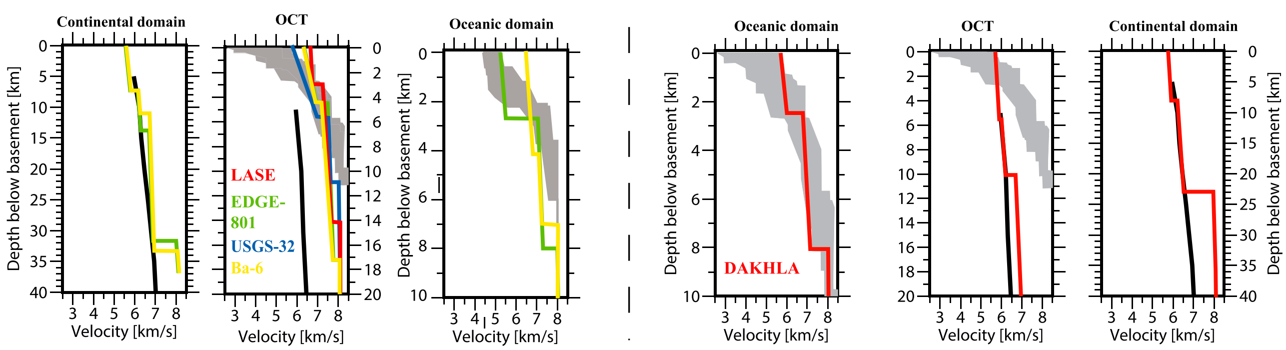

Figure 8. Comparison of vz profiles underneath the basement in the continental, OCT, and oceanic domains between the U.S. profiles and the DAKHLA profile. Colored lines represent mean vz profiles, the gray area bounds a compilation of vz profiles for typical Atlantic oceanic crust [*White et al.*, 1992], and the bold black lines correspond to mean vz profiles for thinned continental crust [*Christensen and Mooney*, 1995].

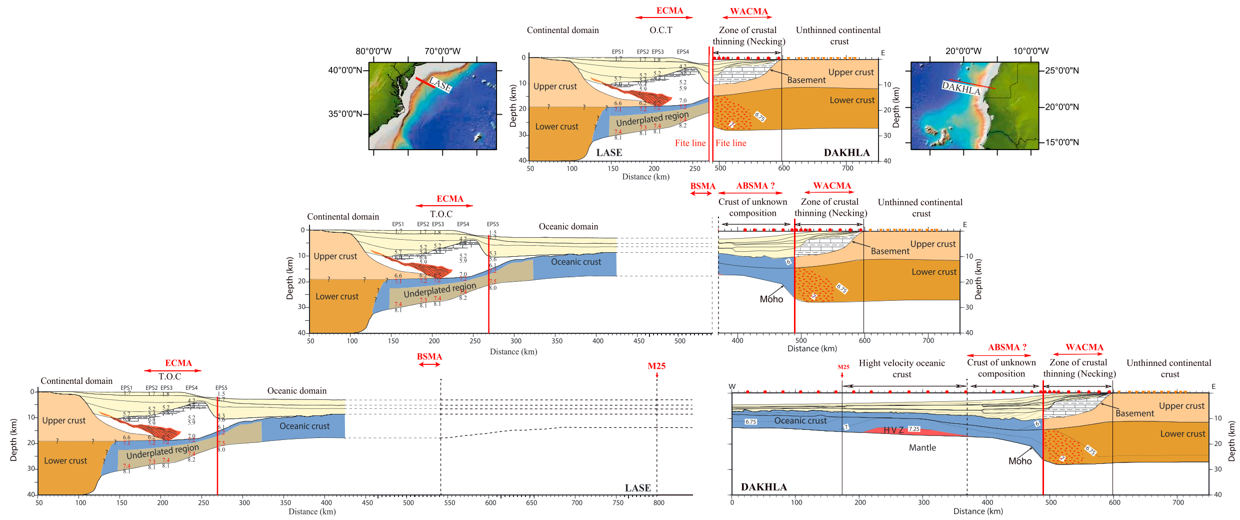

Figure 9. Reconstruction of the U.S.-Mauritania margin pair. (a) After initial extension, (b) accretion of highly intruded and underplated oceanic crust and seaward dipping reflector sequences on the western margin and slightly intruded oceanic crust on the eastern margin, and (c) accretion of thin normal oceanic crust.

[*Oh et al*., 1995]. On land the volcanic products are distributed equally along the American and the African margin. The asymmetry of this volcanism in the offshore can be explained by two different hypotheses: (a) an asymmetry in a second phase of continental breakup leading to updaming of hot mantle material preferably along the American margin and (b) a jump of the rift axis along the southern central Atlantic margin. The fact that a magnetic anomaly (ABSMA) conjugate to the BSMA has been identified along the African margin seems to rule out the second hypothesis [*Labails et al*., 2010]. Analogue to the fact that the WACMA is of lower amplitude than the ECMA, the ABSMA is of much weaker amplitude than the BSMA. This fact additionally favors the hypothesis that hot mantle was rising up mainly underneath the American margin. One possible explanation would be that this asymmetry is related to the presence of the Caledonian arc on the American margin [*Müntener and Manatschal*, 2006]. The first oceanic crust on both margins margin is about 10 km thick and characterized by elevated velocities ($>$7.4 km/s), probably due to the volcanic activity during opening. On the African margin oceanic crust accreted after the M25 magnetic anomaly is thinner around 6 km, but oceanic crust younger than the M25 anomaly was not sampled on the American side, so no comparison is possible (Figure 9).

5.1.3. Opening History of the Southern Central Atlantic

On the basis of this study, we propose that the southern central Atlantic opened symmetrically. The originally thicker African continental crust was thinned by the formation of the Tarfaya-Laayoune and Mauritanian-Senegal basins, probably during the Carnian [*Le Roy and Piqué*, 2001]. While crust on the African side was probably intruded by a moderate amount of volcanic material, the American margin experienced strong magmatic activity, with thick SDR sequences deposited on the margin and a several kilometers thick ultramafic layer underplated underneath the crust. Protooceanic crust was probably slightly thickened by the volcanic activity during opening of the ocean basin.

5.2. Northern Central Atlantic: MIRROR-SMART Profiles

In this segment the deep crustal structure is constrained by the SMART-1 and MIRROR-1 conjugate profiles. Interpretations can be extended using the CONRAD data set on the Moroccan margin [*Holik et al*., 1991] and the SMART-2 and OETR lines along the Canadian margin [*Wu et al*., 2006; *Luheshi et al*., 2012] (Figure 10).

5.2.1. Geometry of the Continental Crust

The plate kinematic reconstruction at 185 Ma with a slightly open fit confirms that the SMART-1 profile is conjugate to the MIRROR-1 profile, with only a minor offset from a difference in strike angle (Figure 2). The crustal geometry of unthinned continental crust along both profiles is comparable and includes three distinct layers. Crustal thickness at the continent is 37 km on both margins, and the width of the necking zone is ~170 km on the Canadian side compared to 150 km on the African side. Several tilted blocks can be identified at the

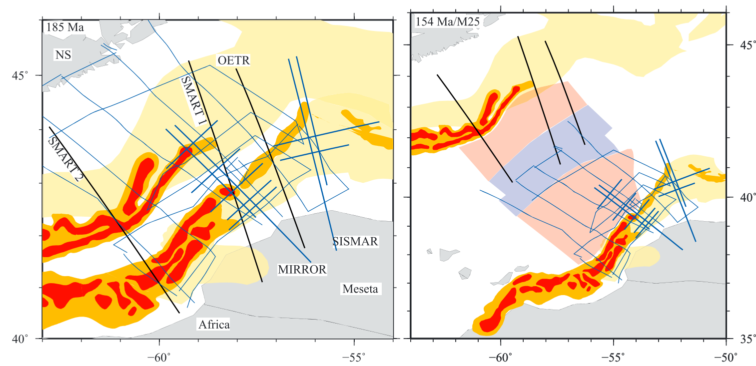

Figure 10. Plate kinematic reconstruction after *Seton et al.* [2012] of the northern central Atlantic. Magnetic anomalies are marked in two colors (red and orange) depending on its amplitude; extent of the salt basins in yellow. Wide-angle seismic profiles located along the present-day African continent are shown by blue lines and those on the American margin by green lines. Light red shaded region shows the extent of the zone with high lower crustal velocities and the light blue shaded region the extent of thin oceanic crust. NS = Nova Scotia.

continental slope along both profiles. Their spacing is up to 25 km along the MIRROR-1 profile and slightly larger up to 30 km on the Canadian profile (Figure 11). However, individual blocks vary in size. A comparison of vz profiles from all profiles available for this segment shows that unthinned continental crust is nearly identical along all profiles between 33 and 35 km indicating that the original crustal thickness was not modified after rifting (Figure 12).

The crustal structure and the geometry of the zone of crustal thinning are similar along both margins, with a width of 120–130 km and a two layered crust. The ratio of upper to lower crustal thickness to unthinned continental crust is similar indicating a symmetric rifting mode, rather than rifting along a lithospheric shear fault. Older work proposing asymmetric rifting of the margin considered the SISMAR-4 profile as conjugate part [e.g., *Sibuet et al.*, 2012; *Maillard et al.*, 2006; *Tari and Molnar*, 2005]. The SISMAR-4 profile is located in the northern Moroccan salt basin at the intersection of the Atlantic margin with the northern Moroccan margin, which opened in a geodynamic setting differing from the Atlantic passive margin, by highly oblique rifting between the Iberian and African plates [*Frizon de Lamotte et al.*, 2011; *Sallarès et al.*, 2011].

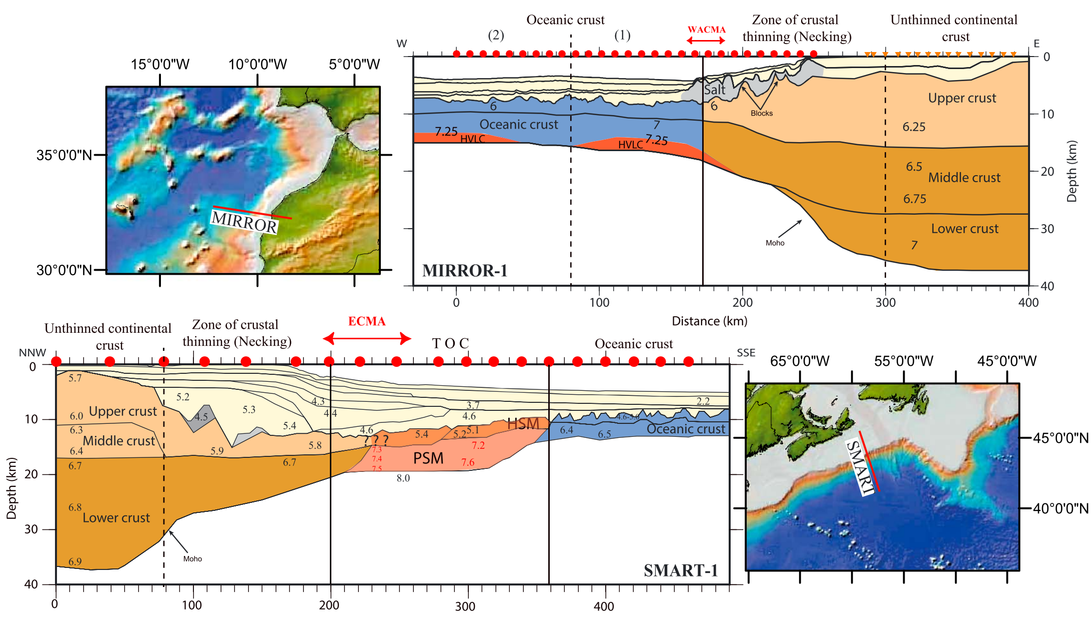

Figure 11. Interpreted depth sections along the conjugate SMART-1 [*Funck et al.*, 2004] and MIRROR-1 [*Biari et al.*, 2015] profiles. PSM = partially serpentinized mantle, HSM = highly serpentinized mantle, and HVLC = high-velocity lower crust. Numbers represent seismic layer velocities (km/s). Location of the wide-angle seismic profiles acquired during MIRROR and SMART surveys on the regional bathymetry and topography map [*Ryan et al.*, 2009].

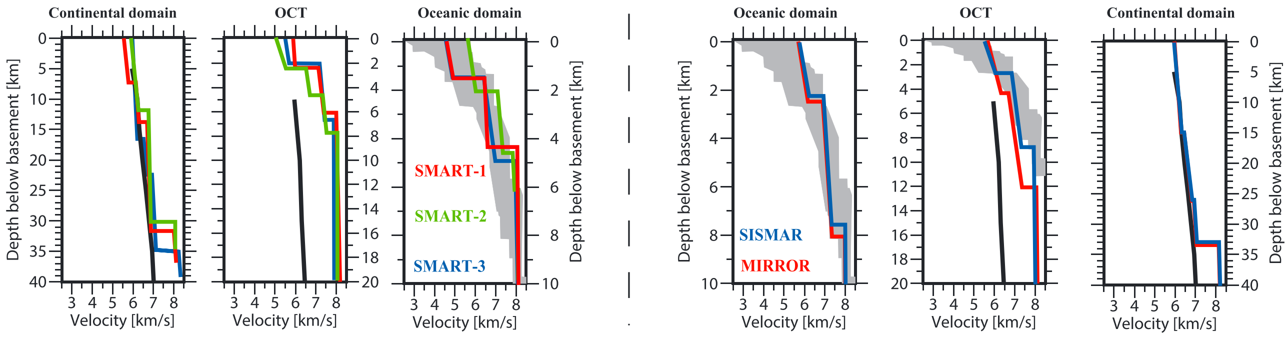

Figure 12. Comparison of vz profiles in the continental, OCT, and oceanic domains between the SMART profiles, SISMAR, and MIRROR profiles. Colored lines represent mean vz profiles, the gray shaded area bounds a compilation of vz profiles for typical Atlantic oceanic crust [*White et al.*, 1992], and the bold black profiles correspond to mean vz profiles for thinned continental crust [*Christensen and Mooney*, 1995].

5.2.2. Oceanic Accretion and Mantle Exhumation

The existence of a region of serpentinized upper mantle material on the Canadian margin which has no counterpart along the Moroccan margin is one of the major differences between the two margins. In plate kinematic reconstructions, this region of serpentinized upper mantle material located oceanward of the ECMA was created at the same time as a zone of a 7–8 km thick crust with velocities as high as 7.25 km/s located seaward of WACMA (Figure 13b). The thickness is above the average of 7.1 km and the velocities slightly higher than in normal Atlantic crust [*White et al.*, 1992]. *Biari et al.* [2015] interpret this crust either as oceanic crust with some small pockets of serpentinite included into the lower crust at an early accretionary center [*Biari et al.*, 2015] or as thin oceanic crust thickened after accretion by the volcanic underplate between 60 Ma and 30 Ma associated with the Canary hot spot [*Holik et al.*, 1991].

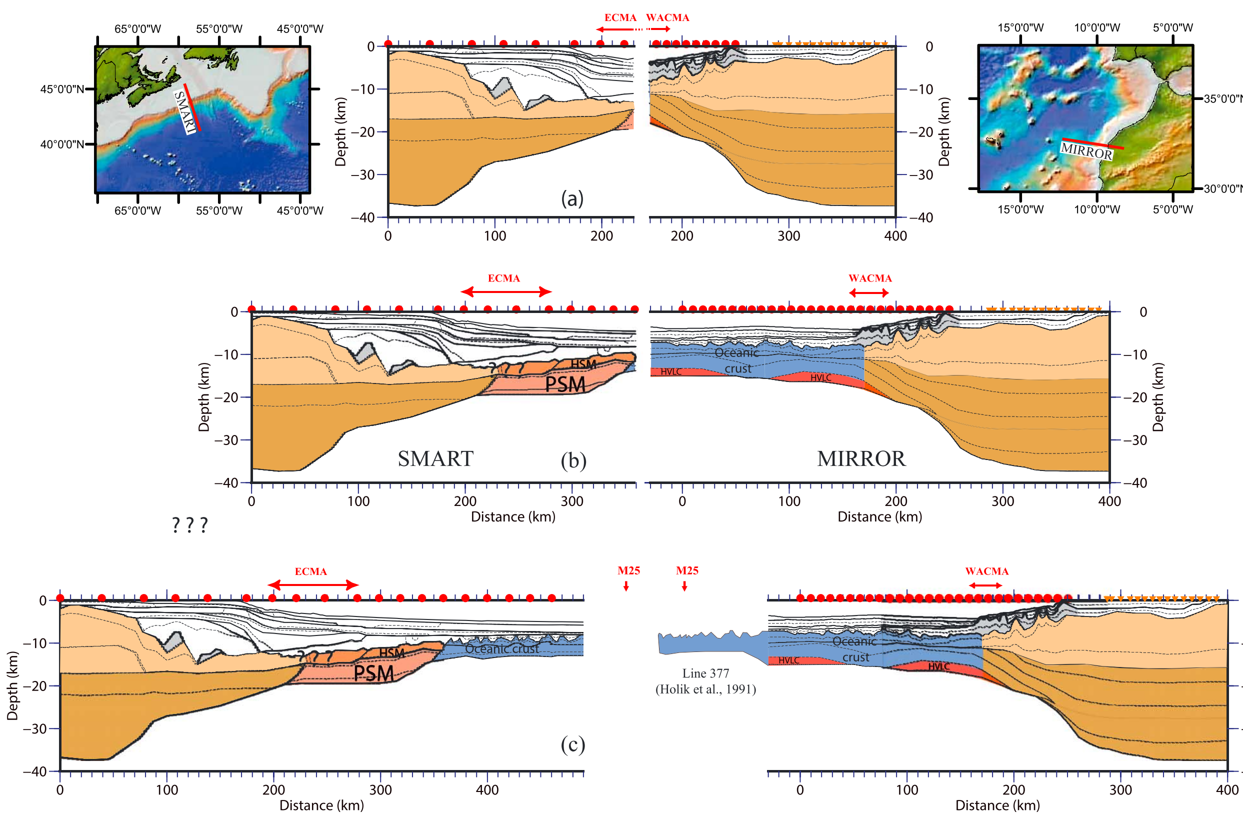

Figure 13. Reconstruction of the Nova-Scotia-Moroccan margin pair. (a) After initial extension, (b) asymmetric seafloor spreading, with exhumation to the west and magmatic accretion to the east, and (c) accretion of thin magmatic oceanic crust.

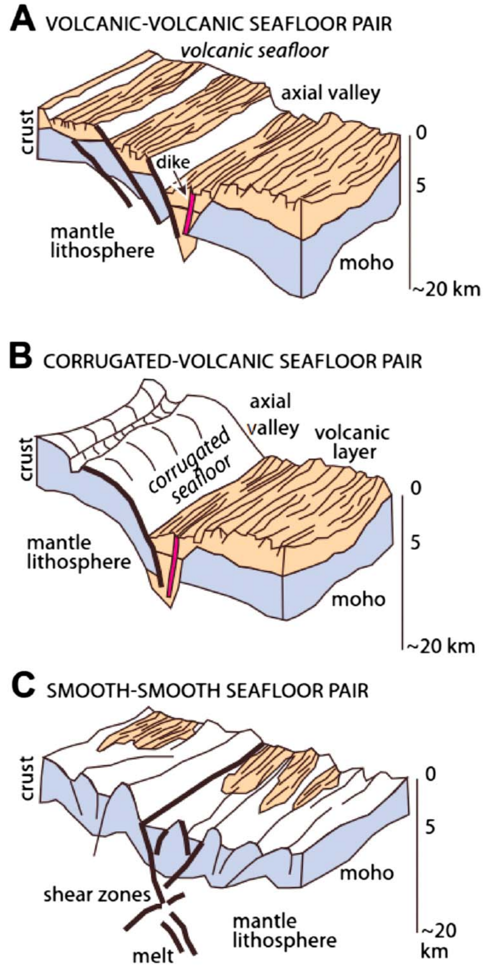

Figure 14. Lithosphere-scale sketches of the axial region for three proposed modes of magma-poor ultraslow spreading, shown in order of decreasing melt supply. Modes A (volcanic-volcanic) and B (corrugated-volcanic) also develop at faster spreading sections of the Mid-Atlantic Ridge and in more magmatically robust regions of ultraslow ridges. Mode C (smooth-smooth or smooth-volcanic), with little to no axial volcanism, appears specific to magma-poor ultraslow ridges [after *Cannat et al.*, 2006; *Dean et al.*, 2015].

Results from recent studies of slow and ultraslow spreading ridges allow us to reconcile observations of the thickness and lithology of crust bordering the opening anomalies oceanward along the conjugate profiles [*Whitmarsh et al.*, 2001; *Cannat et al.*, 2006]. Based on bathymetric data and dredging along the ultraslow spreading Southwest Indian Ridge (full spreading rate ~14 mm/yr), it was shown that mantle derived rocks can be continuously exhumed for at least 11 Ma [*Cannat et al.*, 2006; *Sauter et al.*, 2013; *Smith*, 2013]. Dredges from these regions show a high percentage of serpentinite and lack the hummocky morphology which is characteristic for magmatic oceanic crust. These mantle-derived serpentinites form broad patches of smooth seafloor, several tens of kilometers across, characteristic for amagmatic spreading with a high percentage of serpentinite incorporated into the crust. At spreading rates up to 40 mm/yr, new crust can be accreted in an asymmetrical manner. Volcanic flows are emplaced on one side of the ridge axis, while the existing oceanic lithosphere is cut by a detachment fault and mantle material is exhumed on the opposite flank [*Smith*, 2013; *Sauter et al.*, 2013]. Smooth seafloor forms at portions of the ridge where volcanism is scarce to absent [*Cannat et al.*, 2006; *Sauter et al.*, 2013]. This type of accretion might be analogous to the processes that led to the formation of crust imaged along the ocean-continent transition zone of magma-poor continental margins [*Whitmarsh et al.*, 2001; *Cannat et al.*, 2006]. According to this hypothesis, serpentinite ridges imaged in the ocean-continent transition zone in West Iberia were proposed to correspond to oceanic core complexes created during initial amagmatic seafloor spreading [*Dean et al.*, 2015]. Also, oceanic crust accreted at very slow spreading rates might be asymmetric with igneous crust generated in one direction and predominantly amagmatic crust in the opposite direction [*Cannat et al.*, 2006] (Figure 14).

In the light of this new work, we propose that the region of mainly serpentinized upper mantle on the Canadian margin and the initial oceanic crust at the Moroccan margin are conjugates and resulted from asymmetric spreading creating seafloor by faulting the existing lithosphere on the Canadian side and magmatic oceanic crust including pockets of serpentinite on the Moroccan margin.

Recent investigations on the slow spreading Mid-Atlantic ridge lead to the proposition that periods of low melt production and production of amagmatic oceanic crust are interspersed with phases of production of magmatic crust and that periods of low melt production resulting directly from depleted mantle might trigger the transition from magmatic to amagmatic spreading [*Wilson et al.*, 2013]. Serpentinized mantle peridotites drilled along the Newfoundland margin drilled during Ocean Drilling Program Leg 210 show a highly

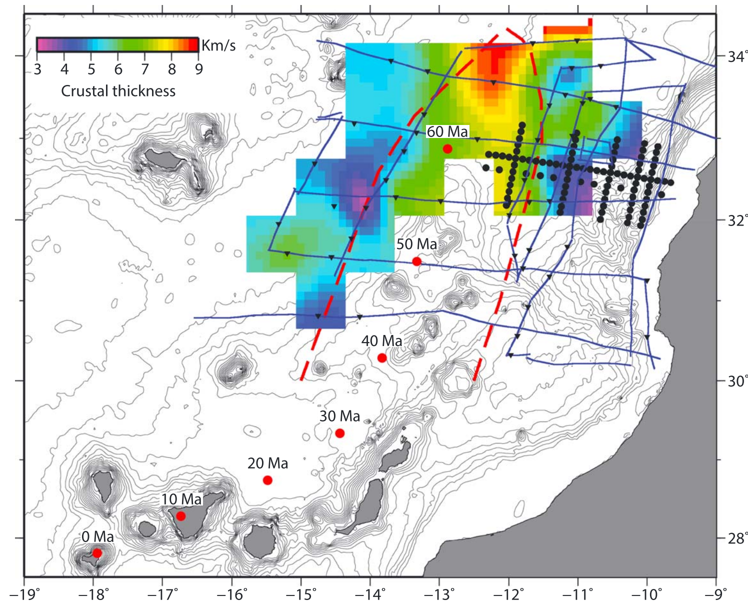

Figure 15. Lower crustal thickness in the southern segment from sonobuoy and ocean bottom seismometer (OBS) deployments [*Holik et al*., 1991; *Biari et al*., 2015]. Background contoured bathymetry from satellite altimetry [*Smith and Sandwell*, 1997]. Positions of sonobuoys are marked by inverted triangles [*Holik et al*., 1991] and OBS [*Biari et al*., 2015] by black circles. Blue lines mark the position of multichannel seismic (MCS) profiles, the red dashed line marks the extent of the basement bulge from *Holik et al*. [1991], and red dots show the reconstructed position of the Canary hot spot over time [*Carracedo et al*., 1998].

depleted composition, corresponding to 14 to 20–25% melting [*Müntener and Manatschal*, 2006]. The authors therefore proposed that they may represent inherited (e.g., Caledonian) subarc mantle that was exhumed close to the ocean floor during the rifting evolution of the Atlantic. The peridotites from the conjugate Iberian margin are less depleted which can either be explained by a different inherited composition or refertilizing by local melt impregnation of previously depleted, arc-related peridotite [*Müntener and Manatschal*, 2006]. An alternative explanation is a subcontinental origin of this part of the upper mantle [*Chazot et al*., 2005]. We propose that the inherited state of depletion of the mantle from its position under the Caledonian volcanic arc might have suppressed the formation of magmatic oceanic crust during the early opening of the Atlantic.

The slightly elevated crustal thickness along the African margin can then further be explained by the presence of the Canary hot spot between 60 Ma and 30 Ma in the study region. A 200 km wide basement high has been identified and mapped in this region based on analysis of MCS data and sonobuoy recordings [*Holik et al*., 1991] (Figure 15). It is associated with volcanic products in the sedimentary column and with a region of high lower crustal velocities and slightly (1–2 km) thickened crust [*Holik et al*., 1991]. Comparison of the shape of the basement high with the track of the Canary hot spot led to the proposition that the volcanism was linked to the presence of the Canary hot spot in this region, which created magmatic layers and modified the crust by intrusions and volcanic underplate [*Holik et al*., 1991]. An alternative interpretation is that it corresponds to a region of anomalously high lower crustal velocities imaged between the WACMA and magnetic anomaly M25 along the entire margin [*Klingelhoefer et al*., 2009; *Biari et al*., 2015]. At M25 times, seafloor spreading rates changed and a more typical but thin oceanic crust was produced.

5.2.3. Thin Crust Accreted After Anomaly M25

On the SMART-1 profile, anomalously thin oceanic crust characterized by seismic velocities between 5 km/s and 6.5 km/s is identified oceanward of 350 km model distance (Figure 3a). This is proposed to result from very slow spreading at the onset of seafloor accretion [*Funck et al*., 2004]. The plate kinematic reconstruction for M25 shows that all oceanic crust along the MIRROR-1 profile had already been produced and that the thin oceanic crust observed along the Canadian margin dates after M25 (Figure 11). Oceanic crust corresponding to the same age as that imaged at the SMART-1 profile, however, is constrained by sonobuoy data from the CONRAD survey. Indeed, oceanic crust imaged in the prolongation of the MIRROR-1 profile along profile

CONRAD-377 thin from 8 km to 5 km in thickness with a decrease of lower crustal velocities from 7.32 km/s to 6.82 km/s. These values are closer to those modeled along the SMART-1 profile and nearly identical to those modeled along SMART-2.

6. Conclusions

Comparison of deep sounding seismic profiles from one of the oldest passive conjugate continental margin pairs in the world offers insight into the mechanism of rifting, breakup, and initial seafloor spreading. The opening of an ocean basin can be influenced by local processes, such as late crustal thinning (as imaged along the continental part of the DAKHLA profile) as well as thickening (as imaged due to the Canary Hot spot along the Mirror profile).

Therefore, each conjugate margin pair can only be discussed in the context of its geological history. Crustal thinning and beta-factor calculations can therefore only to be used with caution and after evaluation of the later processes eventually modifying the margin structure.

In the southern central Atlantic, the U.S. continental margin is characterized by thick layers of volcanic underplate and SDR sequences, which are thinner and more rare on the African side, where they seem to be mostly related to the presence of the Canary hot spot. Rifting was symmetric, and the thinner continental crustal thickness imaged by the African profiles is probably due to the formation of the Tarfaya-Laayoune basin during the Carnian. Initial oceanic crust is slightly thicker than normal Atlantic oceanic crust and characterized by elevated seismic velocities, probably due to the volcanism at rifting. Oceanic crust younger than the M25 anomaly is normal thickness along the African side.

In the north, crustal geometry of the unthinned continental crust and the necking zone is nearly symmetric and does affect upper and lower crustal layers in a similar manner along both margins. A region including seismic velocities too high to be explained by either continental or oceanic crust is observed on the Canadian side, whereas on the African side an oceanic crust with slightly elevated velocities is imaged. Plate kinematic reconstructions indicate that these zones were created at the same time, and we propose that they result from asymmetric spreading creating amagmatic crust on the Canadian side and magmatic oceanic crust including pockets of serpentinite on the Moroccan margin. Oceanic crust in the study area might have been modified and thickened by the presence of the Canary hot spot between 60 and 30 Ma. In the north as well as in the south, oceanic crust oceanward of the WACMA anomaly and up to the M25 isochron is characterized by high velocities in the lower crust, probably related to serpentinites included into the crust during very slow seafloor spreading. After isochron M25, a widespread plate reorganization led to an increase in spreading velocity and the production of thin magmatic crust on both sides of the spreading center, however, with the African margin accreting a 1–2 km thicker crust.

Acknowledgments
The GPlates software was used to create the plate-tectonic reconstructions (http://gplates.org/contact.html). The GMT software package [*Wessel and Smith*, 1995] was used in the preparation of this paper. We would like to thank two anonymous reviewers and the Associate Editor for their constructive reviews which greatly helped improve the manuscript. No new data was used in producing this manuscript. All data for this paper are properly cited and referred to in the reference list.

References

Aslanian, D., and M. Moulin (2012), Palaeogeographic consequences of conservational models in the South Atlantic Ocean, *Geol. Soc. Lond. Spec. Publ.*, *369*, 75–90, doi:10.1144/SP369.5.

Aslanian, D., et al. (2009), Brazilian and African passive margins of the central segment of the South Atlantic Ocean: Kinematic constraints, *Tectonophysics*, *468*, 98–112, doi:10.1016/j.tecto.2008.12.016.

Austin, J. A., P. L. Stoffa, J. D. Phillips, J. Oh, D. S. Sawyer, G. M. Purdy, E. Reiter, and J. Makris (1990), Crustal structure of the Southeast Georgia embayment-Carolina trough: Preliminary results of a composite seismic image of a continental suture(?) and a volcanic passive margin, *Geology*, *18*, 1023–1027, doi:10.1130/0091-7613(1990)018<1023:CSOTSG>2.3.CO;2.

Benabdellouahed, M., A. Baltzer, M. Rabineau, D. Aslanian, M. Sahabi, F. Germond, B. Loubrieu, and Y. Biari (2016), Slope morphologies offshore DAKHLA (SW Moroccan margin), *Bull. Soc. Geol. Fr.*, *187*(1), 27–39, doi:10.2113/gssgfbull.187.1.27.

Benabdellouahed, M., et al. (2017), Recent uplift of the Atlantic Atlas (offshore West Morocco): Tectonic arch and submarine terraces, *Tectonophysics*, *706–707*, 46–58, doi:10.1016/j.tecto.2017.03.024.

Biari, Y., et al. (2015), Deep crustal structure of the north-west African margin from combined wide-angle and reflection seismic data (MIRROR seismic survey), *Tectonophysics*, *656*, 154–174, doi:10.1016/j.tecto.2015.06.019.

Blackburn, T. J., P. E. Olsen, S. A. Bowring, N. M. McLean, D. V. Kent, J. Puffer, G. McHone, E. T. Rasbury, and M. Et-Touhami (2013), Zircon U-Pb geochronology links the end-Triassic extinction with the central Atlantic magmatic province, *Science*, *340*, 941–945, doi:10.1126/science.1234204.

Bown, J. W., and R. S. White (1994), Variation with spreading rate of oceanic crustal thickness and geochemistry, *Earth Planet. Sci. Lett.*, *121*, 435–449, doi:10.1016/0012-821X(94)90082-5.

Cande, S. C., J. M. Stock, R. D. Müller, and T. Ishihara (2000), Cenozoic motion between East and West Antarctica, *Nature*, *404*(6774), 145–150.

Cannat, M., D. Sauter, V. Mendel, E. Ruellan, K. Okino, J. Escartin, V. Combier, and M. Baala (2006), Modes of seafloor generation at a melt-poor ultraslow-spreading ridge, *Geology*, *34*, 605–608, doi:10.1130/G22486.1.

Carracedo, J. C., S. Day, H. Guillou, E. Rodríguez Badiola, J. A. Canas, and F. J. Pérez Torrado (1998), Hotspot volcanism close to a passive continental margin: The Canary Islands, *Geol. Mag.*, *135*, 591–604.

Chazot, G., S. Charpentier, J. Kornprobst, R. Vannucci, and B. Luais (2005), Lithospheric mantle evolution during continental break-up: The West Iberia non-volcanic passive margin, *J. Petrol.*, *46*, 2527–2568, doi:10.1093/petrology/egi064.

Christensen, N. I., and W. D. Mooney (1995), Seismic velocity structure and composition of the continental crust: A global view, *J. Geophys. Res.*, *100*, 9761–9788, doi:10.1029/95JB00259.

Contrucci, I., L. Matias, M. Moulin, L. Géli, F. Klingelhoefer, H. Nouzé, D. Aslanian, J.-L. Olivet, J.-P. Réhault, and J.-C. Sibuet (2004a), Deep structure of the West African continental margin (Congo, Zaïre, Angola), between 5°S and 8°S, from reflection/refraction seismics and gravity data, *Geophys. J. Int.*, *158*, 529–553, doi:10.1111/j.1365-246X.2004.02303.x.

Contrucci, I., F. Klingelhofer, J. Perrot, R. Bartolome, M.-A. Gutscher, M. Sahabi, J. Malod, and J.-P. Rehault (2004b), The crustal structure of the NW Moroccan continental margin from wide-angle and reflection seismic data, *Geophys. J. Int.*, *159*, 117–128, doi:10.1111/j.1365-246X.2004.02391.x.

Davison, I. (2005), Central Atlantic margin basins of north West Africa: Geology and hydrocarbon potential (Morocco to Guinea), *J. African Earth Sci.*, *43*, 254–274, doi:10.1016/j.jafrearsci.2005.07.018.

Dean, S. L., D. S. Sawyer, and J. K. Morgan (2015), Galicia Bank ocean–continent transition zone: New seismic reflection constraints, *Earth Planet. Sci. Lett.*, *413*, 197–207, doi:10.1016/j.epsl.2014.12.045.

Diebold, J., and P. Stoffa (1981), The traveltime equation, tau-p mapping, and inversion of common midpoint data, *Geophysics*, *46*, 238–254, doi:10.1190/1.1441196.

Dillon, W. P., and P. Popenoe (1988), The Blake plateau basin and Carolina trough, *Geol. N. Am.*, *2*, 291–328.

Evain, M., A. Afilhado, C. Rigoti, A. Loureiro, D. Alves, F. Klingelhoefer, P. Schnurle, A. Feld, R. Fuck, and J. Soares (2015), Deep structure of the Santos Basin-São Paulo plateau system, SE Brazil, *J. Geophys. Res. Solid Earth*, *120*, 5401–5431, doi:10.1002/2014JB011561.

Frizon de Lamotte, D., C. Raulin, N. Mouchot, J.-C. Wrobel-Daveau, C. Blanpied, and J.-C. Ringenbach (2011), The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: Initial geometry and timing of the inversion processes, *Tectonics*, *30*, TC3002, doi:10.1029/2010TC002691.

Funck, T., H. R. Jackson, K. E. Louden, S. A. Dehler, and Y. Wu (2004), Crustal structure of the northern Nova Scotia rifted continental margin (eastern Canada), *J. Geophys. Res.*, *109*, B09102, doi:10.1029/2004JB003008.

Hellinger, S. J. (1981), The uncertainties of finite rotations in plate tectonics, *J. Geophys. Res.*, *86*(B10), 9312–9318.

Holbrook, W. S., and P. B. Kelemen (1993), Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup, *Nature*, *364*, 433–436, doi:10.1038/364433a0.

Holbrook, W. S., G. M. Purdy, R. E. Sheridan, L. Glover, M. Talwani, J. Ewing, and D. Hutchinson (1994a), Seismic structure of the U.S. Mid-Atlantic continental margin, *J. Geophys. Res.*, *99*, 17871–17891, doi:10.1029/94JB00729.

Holbrook, W. S., E. C. Reiter, G. M. Purdy, D. Sawyer, P. L. Stoffa, J. A. Austin, J. Oh, and J. Makris (1994b), Deep structure of the U.S. Atlantic continental margin, offshore South Carolina, from coincident ocean bottom and multichannel seismic data, *J. Geophys. Res.*, *99*, 9155–9178, doi:10.1029/93JB01821.

Holik, J. S., P. D. Rabinowitz, and J. A. Austin (1991), Effects of Canary hotspot volcanism on structure of oceanic crust off Morocco, *J. Geophys. Res.*, *96*, 12,039–12,067, doi:10.1029/91JB00709.

Huismans, R., and C. Beaumont (2011), Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins, *Nature*, *473*, 74–78, doi:10.1038/nature09988.

Jaffal, M., F. Klingelhoefer, L. Matias, F. Teixeira, and M. Amrhar (2009), Crustal structure of the NW Moroccan margin from deep seismic data (SISMAR cruise), *C. R. Geosci.*, *341*, 495–503, doi:10.1016/j.crte.2009.04.003.

Jagoutz, O., O. Müntener, G. Manatschal, D. Rubatto, G. Péron-Pinvidic, B. D. Turrin, and I. M. Villa (2007), The rift-to-drift transition in the North Atlantic: A stuttering start of the MORB machine?, *Geology*, *35*, 1087–1090, doi:10.1130/G23613A.1.

Jansa, L. F., J. P. Bujak, and G. L. Williams (1980), Upper Triassic salt deposits of the western North Atlantic, *Can. J. Earth Sci.*, *17*, 547–559.

Jourdan, F., A. Marzoli, H. Bertrand, S. Cirilli, L. H. Tanner, D. J. Kontak, G. McHone, P. R. Renne, and G. Bellieni (2009), $^{40}Ar/^{39}Ar$ ages of CAMP in North America: Implications for the Triassic–Jurassic boundary and the ^{40}K decay constant bias, *Lithos*, *110*, 167–180, doi:10.1016/j.lithos.2008.12.011.

Keen, C. E., and D. P. Potter (1995a), Formation and evolution of the Nova Scotian rifted margin: Evidence from deep seismic reflection data, *Tectonics*, *14*, 918–932, doi:10.1029/95TC00838.

Keen, C. E., and D. P. Potter (1995b), The transition from a volcanic to a nonvolcanic rifted margin off eastern Canada, *Tectonics*, *14*, 359–371.

Kirkwood, B. H., J.-Y. Royer, T. C. Chang, and R. G. Gordon (1999), Statistical tools for estimating and combining finite rotations and their uncertainties, *Geophys. J. Int.*, *137*(2), 408–428.

Klingelhoefer, F., C. Labails, E. Cosquer, S. Rouzo, L. Géli, D. Aslanian, J.-L. Olivet, M. Sahabi, H. Nouzé, and P. Unternehr (2009), Crustal structure of the SW-Moroccan margin from wide-angle and reflection seismic data (the DAKHLA experiment) part A: Wide-angle seismic models, *Tectonophysics*, *468*, 63–82, doi:10.1016/j.tecto.2008.07.022.

Klingelhoefer, F., et al. (2015), Imaging proto-oceanic crust off the Brazilian continental margin, *Geophys. J. Int.*, *200*, 471–488, doi:10.1093/gji/ggu387.

Klingelhoefer, F., et al. (2016), Crustal structure variations along the NW-African continental margin: A comparison of new and existing models from wide-angle and reflection seismic data, *Tectonophysics*, *674*, 227–252, doi:10.1016/j.tecto.2016.02.024.

Klitgord, K., and H. Schouten (1986), Plate kinematics of the central Atlantic, *Geol. N. Am.*, *1000*, 351–378.

Labails, C. (2007), La marge sud-marocaine et les premières phases d'ouverture de l'océan Atlantique Central, 135 pp., Univ. de Bretagne Occidentale. [Available at http://tel.archives-ouvertes.fr/tel-00266944/fr/.]

Labails, C., and J.-L. Olivet (2009), Crustal structure of the SW Moroccan margin from wide-angle and reflection seismic data (the DAKHLA experiment). Part B—The tectonic heritage, *Tectonophysics*, *468*, 83–97, doi:10.1016/j.tecto.2008.08.028.

Labails, C., J.-L. Olivet, D. Aslanian, and W. R. Roest (2010), An alternative early opening scenario for the central Atlantic Ocean, *Earth Planet. Sci. Lett.*, *297*, 355–368, doi:10.1016/j.epsl.2010.06.024.

LASE Study Group (1986), Deep structure of the US East Coast passive margin from large aperture seismic experiments (LASE), *Mar. Pet. Geol.*, *3*, 234–242, doi:10.1016/0264-8172(86)90047-4.

Lau, K. W. H., K. E. Louden, T. Funck, B. E. Tucholke, W. S. Holbrook, J. R. Hopper, and H. Christian Larsen (2006), Crustal structure across the Grand Banks–Newfoundland Basin continental margin—I. Results from a seismic refraction profile, *Geophys. J. Int.*, *167*, 127–156, doi:10.1111/j.1365-246X.2006.02988.x.

Le Roy, P., and A. Piqué (2001), Triassic–Liassic western Moroccan synrift basins in relation to the central Atlantic opening, *Mar. Geol.*, *172*(3), 359–381.

Lizarralde, D., and W. S. Holbrook (1997), US Mid-Atlantic margin structure and early thermal evolution, *J. Geophys. Res.*, *102*, 22,855–22,875.

Lizarralde, D., W. S. Holbrook, and J. Oh (1994), Crustal structure across the Brunswick magnetic anomaly, offshore Georgia, from coincident ocean bottom and multi-channel seismic data, *J. Geophys. Res.*, *99*, 21,741–21,757, doi:10.1029/94JB01550.

Louden, K. E., K .W. H. Lau, and M. Nedimovic (2010), Chapter 2: Plate tectonics. PLAY FAIRWAY Analysis Offshore Nova Scotia Canada Atlas.

Luheshi, M., D. G. Roberts, K. Nunn, J. Makris, B. Colletta, H. Wilson, F. Monnier, G. Rabary, and M. Dubille (2012), The impact of conjugate margins analysis on play fairway evaluation—An analysis of the hydrocarbon potential of Nova Scotia, *First Break*, *30*, 61–72, doi:10.3997/1365-2397.2011037.

Maillard, A., J. Malod, E. Thiébot, F. Klingelhoefer, and J.-P. Réhault (2006), Imaging a lithospheric detachment at the continent–ocean crustal transition off Morocco, *Earth Planet. Sci. Lett.*, *241*, 686–698, doi:10.1016/j.epsl.2005.11.013.

Manatschal, G. (2004), New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and Alps, *Int. J. Earth Sci.*, *93*, 432–466, doi:10.1007/s00531-004-0394-7.

Maruyama, H., H. Masaharu, P. Holland, J. Payne, N. A. Bryant, T. L. Logan, J. P. Muller, G. Schreier, and J. S. MacDonald (1999), The global land one-kilometer base elevation (GLOBE) digital elevation model, version 1.0. Natl. Ocean. Atmospheric Adm. Natl. Geophys. Data cent. Boulder CO digit. Data Base World Wide Web URL HttpwwwNgdcNoaaGovmggtopoglobe Html.

Marzoli, A., P. R. Renne, E. M. Piccirillo, M. Ernesto, G. Bellieni, and A. De Min (1999), Extensive 200-million-year-old continental flood basalts of the central Atlantic magmatic province, *Science*, *284*(5414), 616–618.

Moulin, M., D. Aslanian, and P. Unternehr (2010), A new starting point for the south and equatorial Atlantic Ocean, *Earth Sci. Rev.*, *98*, 1–37, doi:10.1016/j.earscirev.2009.08.001.

Müntener, O., and G. Manatschal (2006), High degrees of melt extraction recorded by spinel harzburgite of the Newfoundland margin: The role of inheritance and consequences for the evolution of the southern North Atlantic, *Earth Planet. Sci. Lett.*, *252*, 437–452, doi:10.1016/j.epsl.2006.10.009.

Oh, J., J. A. Austin, J. D. Phillips, M. F. Coffin, and P. L. Stoffa (1995), Seaward-dipping reflectors offshore the southeastern United States: Seismic evidence for extensive volcanism accompanying sequential formation of the Carolina trough and Blake plateau basin, *Geology*, *23*, 9–12, doi:10.1130/0091-7613(1995)023<0009:SDROTS>2.3.CO;2.

Olivet, J. L., J. Bonnin, P. Beuzart, and J.-M. Auzende (1984), Cinématique de l'Atlantique Nord et Central, *Publ. CNEXO Sér. Rapp. Sci. Tech.*, *54*, 1–108.

Péron-Pinvidic, G., and G. Manatschal (2008), The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: A new point of view, *Int. J. Earth Sci.*, *98*, 1581–1597, doi:10.1007/s00531-008-0337-9.

Roeser, H. A., C. Steiner, B. Schreckenberger, and M. Block (2002), Structural development of the Jurassic magnetic quiet zone off Morocco and identification of Middle Jurassic magnetic lineations, *J. Geophys. Res.*, *107*(B10), 2207, doi:10.1029/2000JB000094.

Ryan, W. B. F., et al. (2009), Global multi-resolution topography synthesis, *Geochem., Geophys., Geosyst.*, *10*, Q03014, doi:10.1029/2008GC002332.

Sahabi, M., D. Aslanian, and J.-L. Olivet (2004), Un nouveau point de départ pour l'histoire de l'Atlantique central, *C. R. Geosci.*, *336*, 1041–1052, doi:10.1016/j.crte.2004.03.017.

Sallarès, V., A. Gailler, M.-A. Gutscher, D. Graindorge, R. Bartolomé, E. Gràcia, J. Díaz, J. J. Dañobeitia, and N. Zitellini (2011), Seismic evidence for the presence of Jurassic oceanic crust in the central Gulf of Cadiz (SW Iberian margin), *Earth Planet. Sci. Lett.*, *311*, 112–123, doi:10.1016/j.epsl.2011.09.003.

Sauter, D., et al. (2013), Continuous exhumation of mantle-derived rocks at the Southwest Indian Ridge for 11 million years, *Nat. Geosci.*, *6*, 314–320, doi:10.1038/ngeo1771.

Seton, M., et al. (2012), Global continental and ocean basin reconstructions since 200 Ma, *Earth Sci. Rev.*, *113*, 212–270, doi:10.1016/j.earscirev.2012.03.002.

Sheridan, R., D. Musser, L. Glover, M. Talwani, J. Ewing, W. S. Holbrook, G. Purdy, R. Hawman, and S. Smithson (1993), Deep seismic reflection data of EDGE U.S. mid-Atlantic continental-margin experiment: Implications for Appalachian sutures and Mesozoic rifting and magmatic underplating, *Geology*, *21*, 563–567, doi:10.1130/0091-7613(1993)021<0563:DSRDOE>2.3.CO;2.

Sheridan, R. E., et al. (1982), Early history of the Atlantic Ocean and gas hydrates on the Blake Outer Ridge: Results of the Deep Sea Drilling Project Leg 76, *Geol. Soc. Am. Bull.*, *93*, 876–885, doi:10.1130/0016-7606(1982)93<876:EHOTAO>2.0.CO;2.

Shillington, D. J., W. S. Holbrook, H. J. A. Van Avendonk, B. E. Tucholke, J. R. Hopper, K. E. Louden, H. C. Larsen, and G. T. Nunes (2006), Evidence for asymmetric nonvolcanic rifting and slow incipient oceanic accretion from seismic reflection data on the Newfoundland margin, *J. Geophys. Res.*, *111*, B09402, doi:10.1029/2005JB003981.

Shimeld, J. (2014), A comparison of salt tectonic subprovinces beneath the Scotian slope and Laurentian fan, in *Salt-sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century. Proceedings of the 24th Annual Bob F. Perkins Research Conference*, edited by P. Post, pp. 502–532, Gulf Coast Soc. of the Soc. of Econ. Paleontol. and Miner.

Sibuet, J.-C., S. Rouzo, and S. Srivastava (2012), Plate tectonic reconstructions and paleogeographic maps of the central and North Atlantic oceans [1]This article is one of a series of papers published in this CJES special issue on the theme of Mesozoic–Cenozoic geology of the Scotian Basin. [2]Earth Sciences sector contribution 20120172, *Can. J. Earth Sci.*, *49*, 1395–1415, doi:10.1139/e2012-071.

Smith, W., and D. Sandwell (1997), Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956–1962.

Smith, D. (2013), Tectonics: Mantle spread across the sea floor, *Nat. Geosci.*, *6*, 247–248, doi:10.1038/ngeo1786.

Tari, G., and J. Molnar (2005). Correlation of syn-rift structures between Morocco and Nova Scotia, Canada, in *Transactions GCSSEPM Foundation, 25th Ann. Res. Conf. SEPM*, pp. 132–150.

Tari, G., D. Brown, H. Jabour, M. Hafid, K. Louden, and M. Zizi (2012), 8—The conjugate margins of Morocco and Nova Scotia, in *Regional Geology and Tectonics: Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps*, edited by D. G. Roberts and A. W. Bally, pp. 284–323, Elsevier, Boston.

Tréhu, A. M., A. Ballard, L. M. Dorman, J. F. Gettrust, K. D. Klitgord, and A. Schreiner (1989), Structure of the lower crust beneath the Carolina trough, U.S. Atlantic continental margin, *J. Geophys. Res.*, *94*, 10,585–10,600, doi:10.1029/JB094iB08p10585.

Van Avendonk, H. J. A., W. S. Holbrook, G. T. Nunes, D. J. Shillington, B. E. Tucholke, K. E. Louden, H. C. Larsen, and J. R. Hopper (2006), Seismic velocity structure of the rifted margin of the eastern Grand Banks of Newfoundland, Canada, *J. Geophys. Res.*, *111*, B11404, doi:10.1029/2005JB004156.

Vogt, P. R. (1973), Early events in the opening of the North Atlantic, *Implic. Cont. Drift Earth Sci.*, *2*, 693–712.

Wade, J. A., and B. C. MacLean (1990), Aspects of the geology of the Scotian Basin from recent seismic and well data; the geology of the southeastern margin of Canada, in *Geology of the Continental Margin of Eastern Canada*, edited by M. J. Keen, and G. J. Williams, No. 2, pp. 190–238, The Geol. of North Am., Geol. Soc. of Am.

Weigel, W., G. Wissmann, and P. Goldflam (1982), Deep seismic structure (Mauritania and central Morocco), in *Geology of the Northwest African Continental Margin*, edited by D. U. von Rad et al., pp. 132–159, Springer, Berlin.

Welsink, H. J., J. D. Dwyer, and R. J. Knight (1989), Tectono-stratigraphy of the passive margin off Nova Scotia, *Extensional Tecton. Stratigr. N. Atl. Margins AAPG Mem.*, *46*, 215–231.

Wessel, P., and W. H. F. Smith (1995), New version of the Generic Mapping Tools, *EOS Trans. Am. Geophys. Union*, *76*, 460–465, doi:10.1029/95EO00198.

White, R. S., D. McKenzie, and R. K. O'Nions (1992), Oceanic crustal thickness from seismic measurements and rare earth element inversions, *J. Geophys. Res.*, *97*, 19683–19715, doi:10.1029/92JB01749.

White, R., and D. McKenzie (1989), Magmatism at rift zones: The generation of volcanic continental margins and flood basalts, *J. Geophys. Res.*, *94*, 7685–7729, doi:10.1029/JB094iB06p07685.

Whitmarsh, R. B., G. Manatschal, and T. A. Minshull (2001), Evolution of magma-poor continental margins from rifting to seafloor spreading, *Nature*, *413*, 150–154, doi:10.1038/35093085.

Wilson, S. C., B. J. Murton, and R. N. Taylor (2013), Mantle composition controls the development of an oceanic core complex, *Geochem., Geophys., Geosyst.*, *14*, 979–995, doi:10.1002/ggge.20046.

Withjack, M. O., R. W. Schlische, and P. E. Olsen (2012), Development of the passive margin of eastern North America: Mesozoic rifting, igneous activity, and breakup, in *Regional Geology and Tectonics*, edited by D. G. Roberts and A. W. Bally, pp. 301–335, Phanerozoic Rift Systems and Sedimentary Basins, Elsevier, New York.

Wu, Y., K. E. Louden, T. Funck, H. R. Jackson, and S. A. Dehler (2006), Crustal structure of the central Nova Scotia margin off eastern Canada, *Geophys. J. Int.*, *166*, 878–906, doi:10.1111/j.1365-246X.2006.02991.x.

Zelt, C. A., and R. B. Smith (1992), Seismic traveltime inversion for 2-D crustal velocity structure, *Geophys. J. Int.*, *108*, 16–34, doi:10.1111/j.1365-246X.1992.tb00836.x.