Geoscience Frontiers 12 (2021) 101205

Contents lists available at ScienceDirect

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

Asymmetric Atlantic continental margins

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ARTICLE INFO

Article history:
Received 15 February 2021
Revised 8 April 2021
Accepted 20 April 2021
Available online 23 April 2021
Handling Editor: R.D. Nance

Keywords:
Passive continental margin
Asymmetric rift
Moho dip
Continental-ocean transition
Westward drift of the lithosphere

ABSTRACT

We analyze the gross crustal structure of the Atlantic Ocean passive continental margins from north to the south, comparing eleven sections of the conjugate margins. As a general result, the western margins show a sharper continental-ocean transition with respect to the eastern margins that rather show a wider stretched and thinner margin. The Moho is in average about 5.7°±1° dipping toward the interior of the continent on the western side, whereas it is about 2.7°±1° in the eastern margins. Moreover, the stretched continental crust is on average 244 km wide on the western side, whereas it is up to about 439 km on the eastern side of the Atlantic. This systematic asymmetry reflects the early stages of the diachronous Mesozoic to Cenozoic continental rifting, which is inferred as the result of a polarized westward motion of both western and eastern plates, being Greenland, Northern and Southern Americas plates moving westward faster with respect to Scandinavia, Europe and Africa, relative to the underlying mantle.

1. Introduction

The Atlantic Ocean represents the prototype of the passive continental margin formation and related sea-floor spreading (Wilson, 1966; Montadert et al., 1979; Talwani et al., 1983; Hinz et al., 1987; Mutter et al., 1988; Frizon de Lamotte et al., 2015; Nirrengarten et al., 2018). Since the recognition of plate tectonics, rifting and oceanization were considered specular and highly symmetric comparing the two sides (Vine and Matthews, 1963; Sandwell, and Schubert, 1980; Gillard et al., 2016). The Atlantic rifting mostly occurred along pre-existing orogens, i.e., where the lithosphere was thickened by continental collision (Wilson, 1966; Doglioni, 1995; Foulger et al., 2005; Schiffer et al., 2019). However, several studies have shown how the rifting is rather asymmetric, both in terms of bathymetry, geometry, spreading rates and mantle tomography in the oceanic realm and the continental margins (Buck, 1988; Zhang and Tanimoto, 1992; Doglioni et al., 2003; Hopper et al., 2004; Manatschal et al., 2007; Müller et al., 2008; Carminati et al., 2009; Reston, 2009; Panza et al., 2010; Ranero and Pérez-Gussinyé, 2010; Unternehr et al., 2010; Gillard et al., 2016; Biari et al., 2017; Chalot-Prat et al., 2017). For this reason, we compared eleven crustal sections (Figs. 1–11) of the western Atlantic passive continental margins in Greenland, North and South America with their conjugate counterparts in the eastern Atlantic, in Scandinavia, Europe and Africa to highlight their different width and Moho depth dip variation.

2. Methods and analysis

Generally, seismic reflection and refraction profiles, tomography and gravimetric data represent the most crucial data to analyze the crustal structure of a passive margin. The P-waves average propagation speed generates a velocity model constraining the margin structure. Instead, gravimetry allows validating the previous model elucidating the continental crust shape. Several authors (Bauer et al., 2000; Contrucci et al., 2004a,b; Hirsch et al., 2009; Lau et al., 2006; Mjelde et al., 1997, 1998, 2001, 2005; Moulin, 2003; Moulin et al., 2005; Voss and Jokat, 2007) combine these two types of geophysical data. The use of velocity-density conversion (Ludwig et al., 1970; Christensen and Mooney, 1995; Hughes et al., 1998) is essential to develop the models. Another geophysical data useful to analyze margins structure are the magnetic anomalies, which are useful to localize the continental-ocean boundary (COB) and the continental-ocean transition (COT). In the following we describe the gross structure of the crustal geometry of the Atlantic passive continental margins, dividing the ocean basin into three sectors, north, central and southern.

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https://doi.org/10.1016/j.gsf.2021.101205
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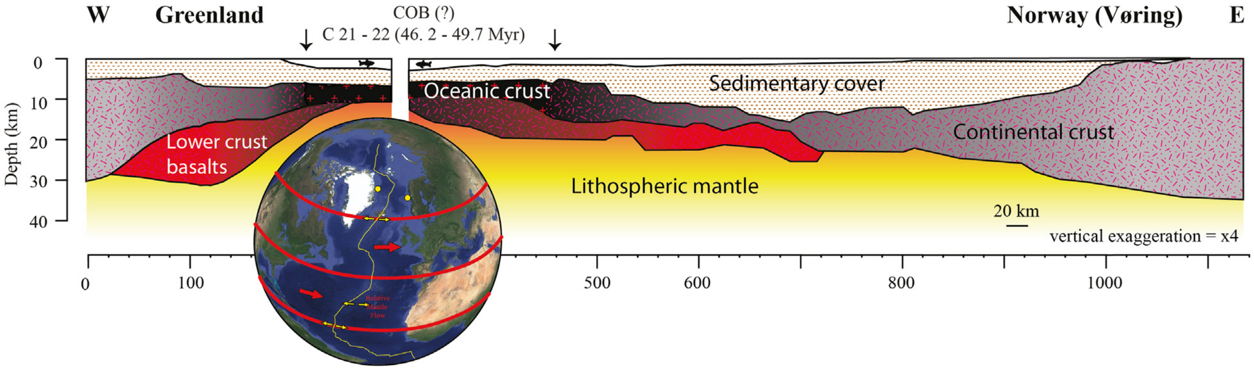


Fig. 1. Comparison of the crustal sections of the passive continental margins of northeast Greenland and Norway with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin in the eastern side. COB, continental-ocean boundary. See text for references.

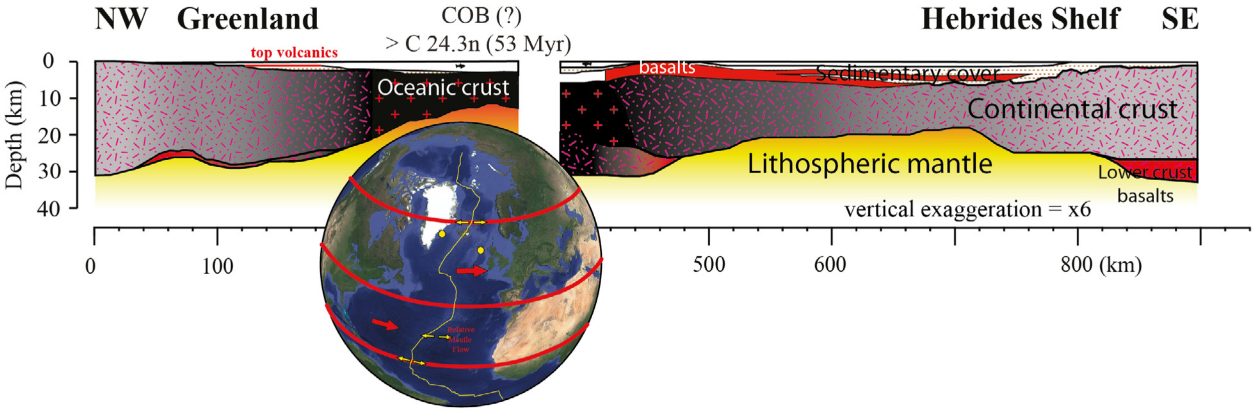


Fig. 2. Comparison of the crustal sections of the passive continental margins of southeast Greenland and Hebrides Shelf with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

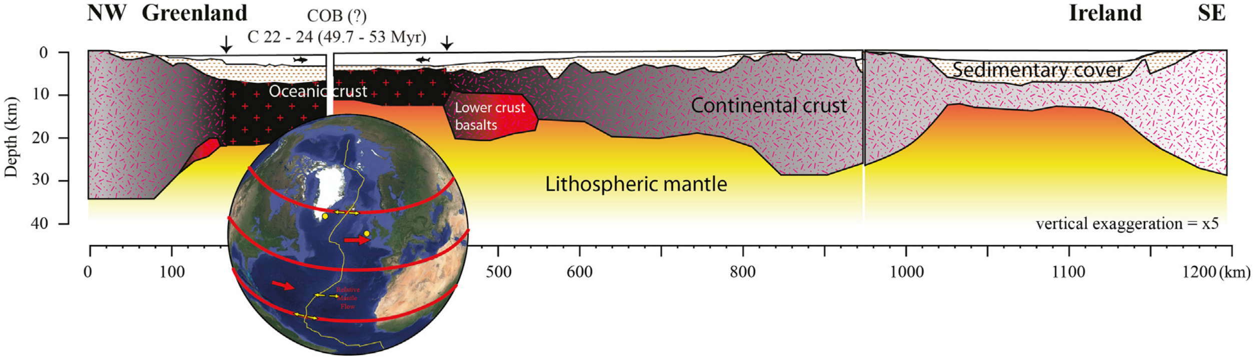


Fig. 3. Comparison of the crustal sections of the passive continental margins of southeast Greenland and Ireland with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

2.1. North Atlantic

In the sections of northeast Greenland and Norway (Fig. 1), the gravimetric field along the Vøring margin shows two strong positive anomalies reaching values between 45 and 80 mGal, which are followed by a negative one of −50 mGal. The crustal thinning develops more to W and S of the Helland Hansen structure. Under the Trøndelag platform, there is a crustal thickness of about 20–25 km (Mjelde et al., 1997, 2001, 2005; Raum et al., 2002), which rise below the Caledonian front to 45 km (Fernandez et al., 2004). All the seismic data define a deep seismic layer with a thickness of 9 km. This shows V_p of 7.0 and 7.4 km/s and a variable density from 2.9 to 3.1 g/cm^3. The Vøring margin (Fernández et al., 2004) has a Moho characterized by a wavy geometry (Raum

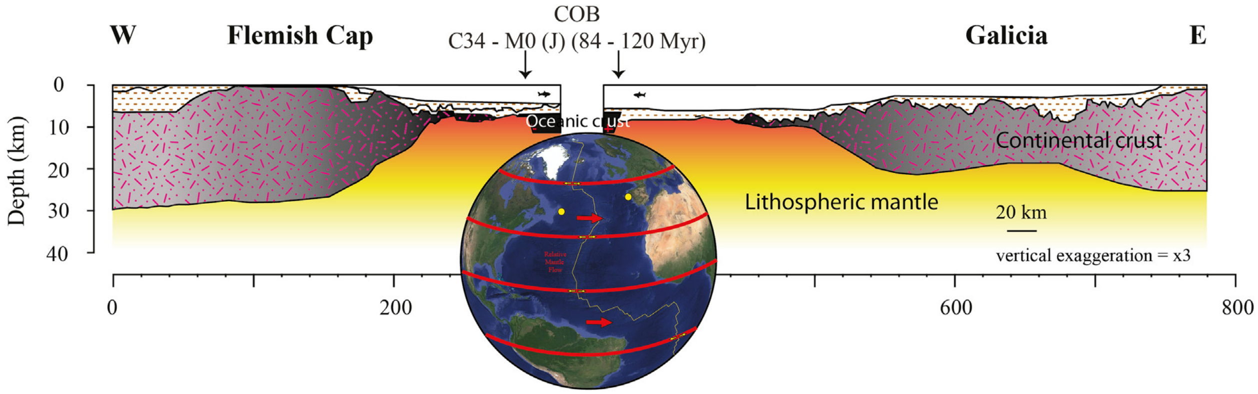


Fig. 4. Comparison of the crustal sections of the passive continental margins of offshore Newfoundland Flemish Cap and Galizia with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

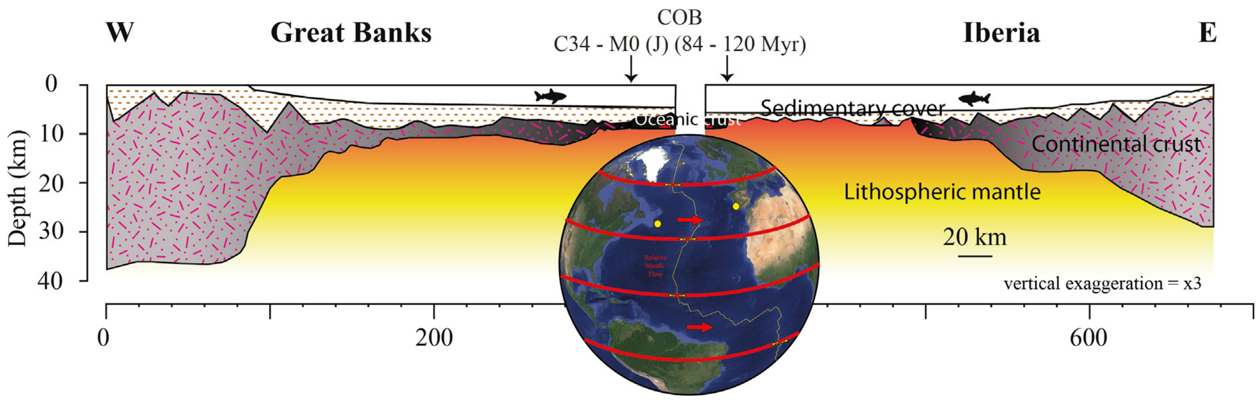


Fig. 5. Comparison of the crustal sections of the passive continental margins offshore Canada of Great Banks and Iberia with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin in the eastern side. COB, continental-ocean boundary. See text for references.

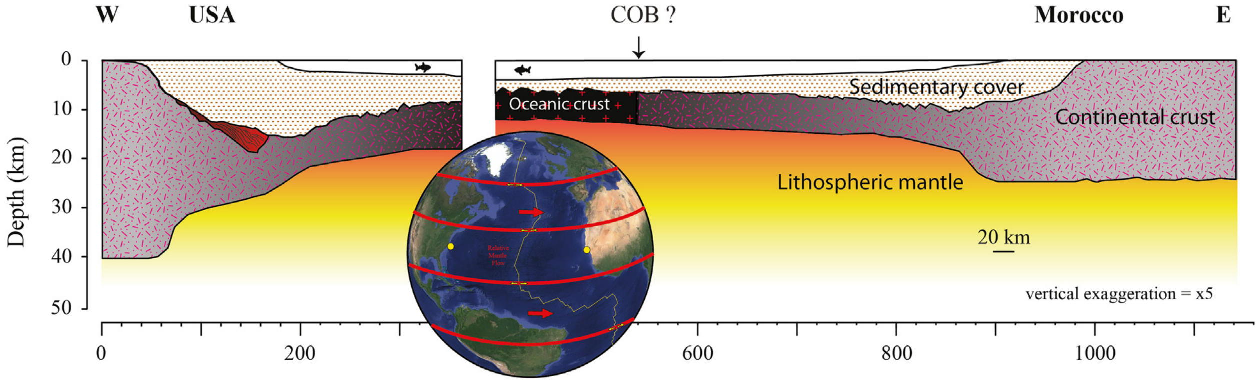


Fig. 6. Comparison of the crustal sections of the passive continental margins offshore eastern US and southern Morocco with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin in the eastern side. COB, continental-ocean boundary. See text for references.

et al., 2002; Mjelde et al., 2005) with a depth ranging between 20 and 23 km below Trøndelag platform and about 15 km to the sea. At ~ 75° N the crustal structure of the East Greenland margin displays a lower continental crust with a high-density value similar to the Vøring margin. This feature seems linked to the Tertiary break-up phase even if its origin is still controversial (Gernigon et al., 2004). Voss and Jokat (2007) suggest a crustal thickness in the proximal domain of 30 km and the Moho evolves from 30 to 18 km depth in a horizontal distance of about 70 km. The COT has an extension of 125 km (Voss and Jokat, 2007), which is wider with respect to the 25–50 km of the Vøring's one (Mjelde et al., 2005). The position of COB is very controversial for these conjugate margins; in fact, Scott (2000), Tsikalas et al. (2002, 2005), Voss and Jokat (2007), Mosar et al. (2002) and Hinz et al. (1987) propose

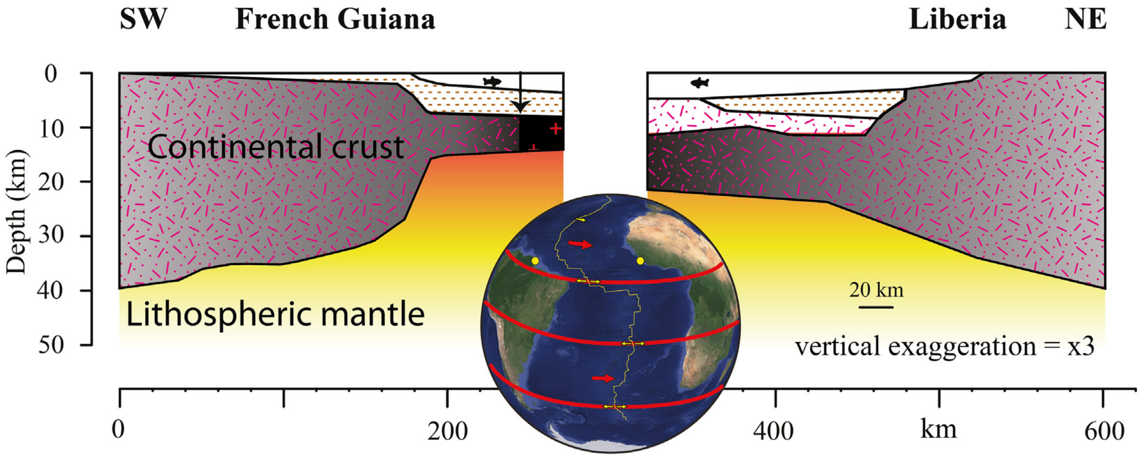


Fig. 7. Comparison of the crustal sections of the passive continental margins of French Guiana and Liberia with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

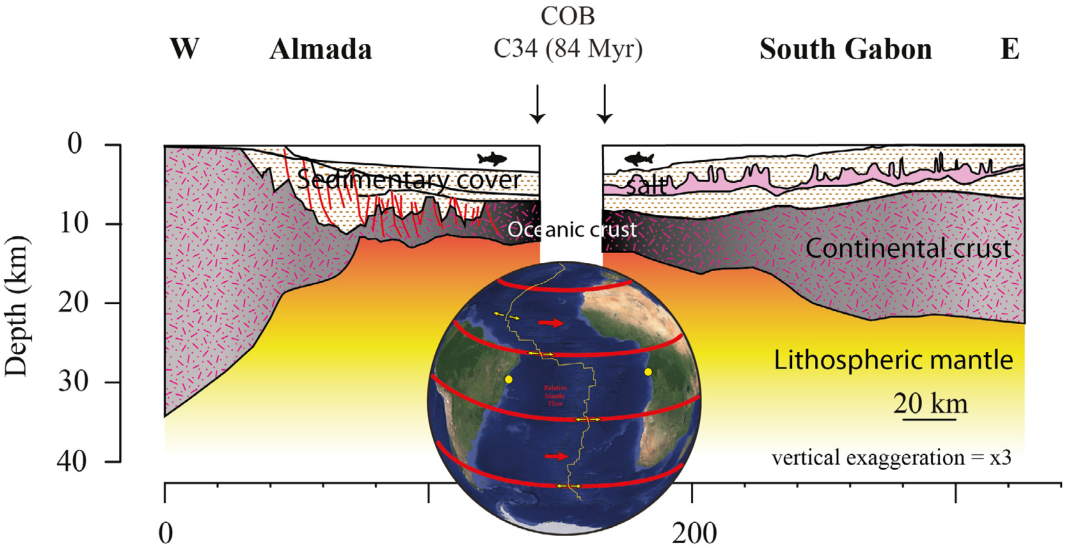


Fig. 8. Comparison of the crustal sections of the passive continental margins of Almada and South Gabon with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

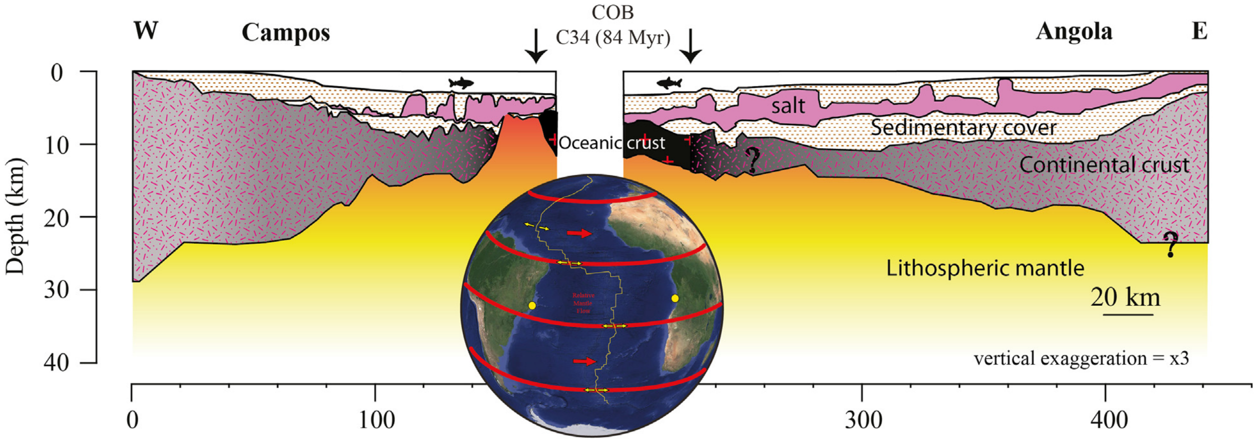


Fig. 9. Comparison of the crustal sections of the passive continental margins of Campos and Angola with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

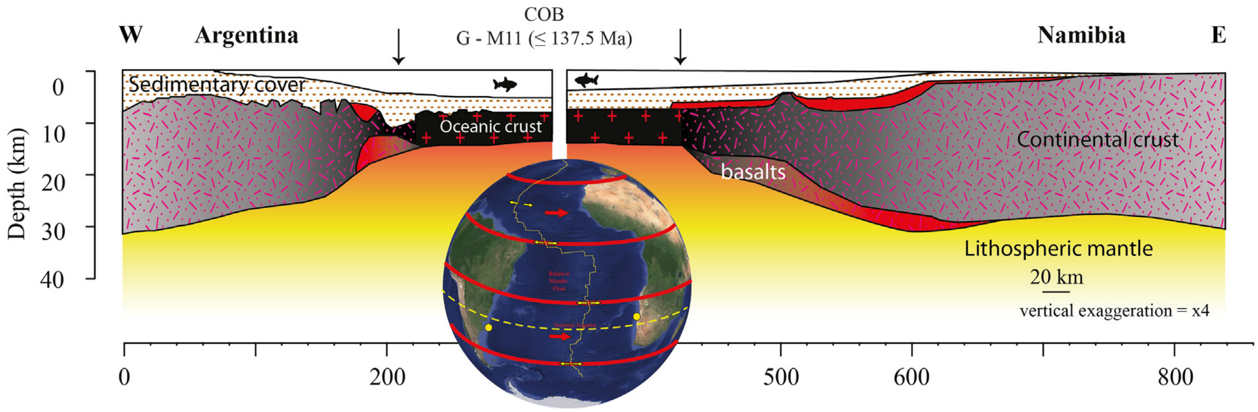


Fig. 10. Comparison of the crustal sections of the passive continental margins of Argentina and Namibia with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

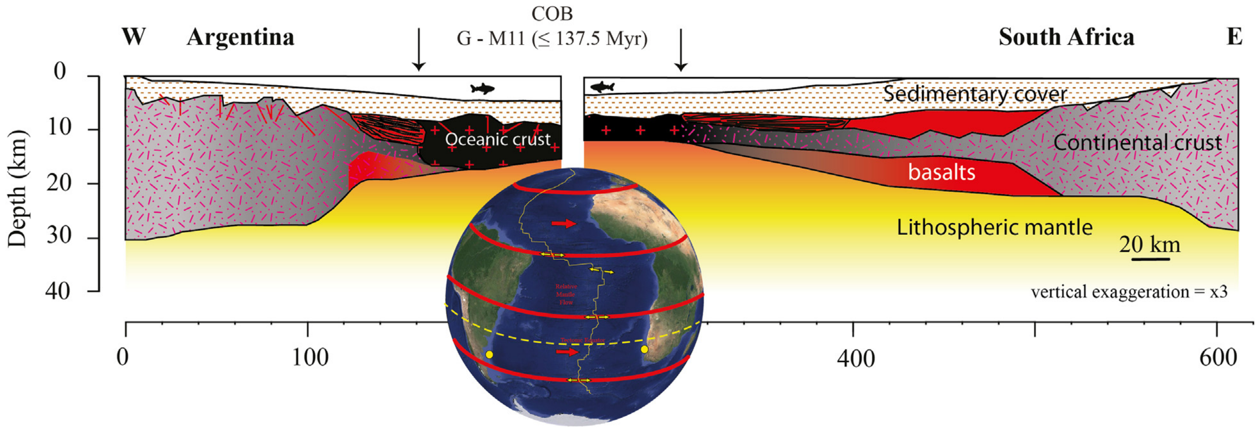
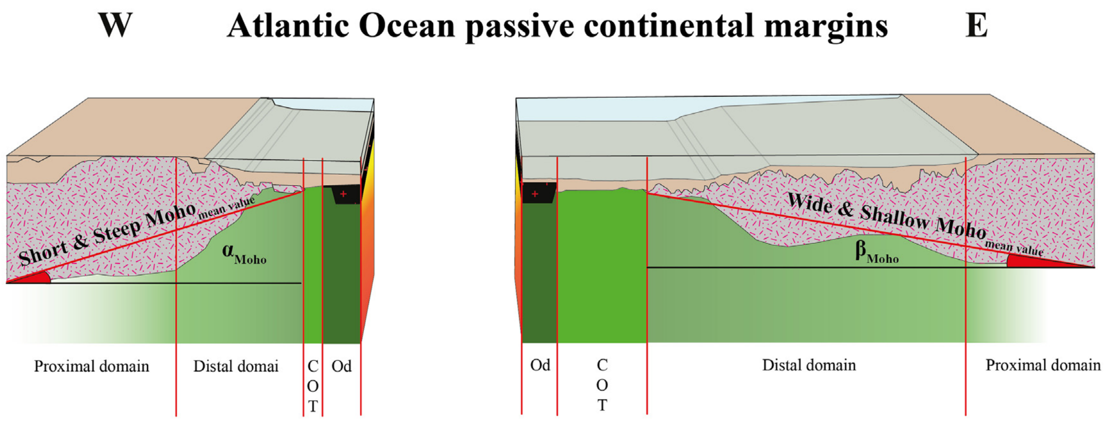


Fig. 11. Comparison of the crustal sections of the passive continental margins of Argentina and South Africa with removed most of the Atlantic oceanic crust. The yellow dots in the globe show the location of the sections. Notice the wider stretched continental margin on the eastern side. COB, continental-ocean boundary. See text for references.

various locations for this structural boundary. Hinz et al. (1987) suggest a COB coincident with the seaward dipping reflectors sequences (SDRs), although Tsikalas et al. (2002, 2005) place it at 50–70 km westward of magnetic anomaly C22. Moreover, Scott (2000) proposes a COB located more towards the continent.

Further south before the Greenland-Iceland-Faroe ridge, it develops the conjugate margins of Greenland and Hebrides (Fig. 2), which are in continuity along strike with the previous margins. The SIGMA line 2 proposed by Korenaga et al. (2000) have detected a crustal thickness of ~30 km, which is very similar to the Hebrides side (Klingelhöfer et al., 2005). The COT for both margins seems to coincide with the extension of basaltic rocks and high velocity lower crusts. In the first approximation, this domain results wider in the Hebrides margin with an extension of 340 km with respect to the ~150 km of the conjugate western margin (Korenaga et al., 2000). In terms of Moho geometry, in the Greenland margin, it develops from 30 to 20 km in the location of the presumed COB, at the end of the seaward dipping volcanic deposits. On the contrary, the eastern conjugate margin shows a more gradual and apparently horizontal geometry. As the Ireland margin, the Hebrides continental margin experimented a rift abortion creating a thinning of crust below the Rockall basin of about 26 km (Klingelhöfer et al., 2005). The position of COB results quite complex but Funck et al. (2017) define this structural boundary landward of Chron C24.3n assuming a break-up phase older than 53 Ma. The complex COB position is also complicated by a potential ridge jump in this region prior to Chron C21 (Funck et al., 2017).

The conjugate margins of East Greenland and Ireland (Fig. 3) shows volcanic features, which are a common characteristic of the North Atlantic passive margins. In the Ireland proximal domain, the crustal thickness is 29 km (Vogt et al., 1998; Funck et al., 2017). The margin is very wide, and it shows a complex shape testified by crustal thicknesses variation, possibly associated with a boudinage of the lithosphere during rifting. These changes are linked to several rift axes located from the break – up position to the Hatton and the Rockall basins. The continental Moho has a great extension and in a general view has a sub-horizontal geometry with respect to the conjugate margin. This develops from 29 km in depth to 12–15 km in the COB location at about 1000 km distance. As suggested by O'Reilly et al. (1996) through wide-angle seismic data, the Rockall basin experienced mantle serpentinization during the rifting process. The COT extends in the Hatton area and has an extension of 25–50 km. On the other hand, the conjugate margin of East Greenland has a shorter extent with respect to the Ireland part; East Greenland shows a short transition from the continent and the ocean. The proximal domain shows thickness values of 35 km (Hopper et al., 2003; White and Smith, 2009; Funck et al., 2017) and the COT is 125 km wide. The resulting Moho is steep and highlights very well the sudden change in the crustal thicknesses from proximal to distal domain



	Proximal domain	Width (km)	**Moho dip (α)**	COT	COT	**Moho dip (β)**	Width (km)	Proximal domain	
Greenland	30 km	215 km	6.7°	125 km	25 - 50 km	2.3°	685 km	35 km	**Norway**
Greenland	30 km	224 km	4.4°	170 km	340 km	2.3°	481 km	30 km	**Hebrides**
Greenland	35 km	169 km	8.5°	125 km	25 - 50 km	1.4°	952 km	29 km	**Ireland**
Flemish Cap	29 km*	320 km	4.4°	80 km	30 km	2.3°	296 km	23 km*	**Galicia**
Great Banks	35 km*	294 km	4.4°	190 - 200 km	120 - 150 km	3.6°	419 km	28 km*	**Iberia**
USA	40 km	362 km	3.4°	-	-	1.3°	601 km	27 km	**Morocco**
French Guiana	35 - 37 km	244 km	6.2°	44 km	> 100 km	3.9°	279 km	40 km	**Liberia**
Almada	34 km	142 km	8.8°	56 km	60 km	3.3°	160 km	25 km	**South Gabon**
Campos	30 - 33 km	167 km	7.9°	37 km	-	2.6°	212 km	27 km	**Angola**
Argentina	28 - 30 km	229 km	6.2°	60 km	200 km	3.3°	429 km	37 km*	**Namibia**
Argentina	28 - 30 km	179 km	4.1°	40 km	135 - 200 km	3.3°	358 km	31.5 km*	**South Africa**

Fig. 12. Overview of the main structural domains analyzed in this work for the conjugate continental margins of the Atlantic Ocean. Below the data of the sections. Data with an asterisk indicate the mean value. COT, continental ocean transition; OD, oceanic domain. See text for references.

approximatively in 300 km. The first oceanic crust is identified by the magnetic anomaly C24 in front of the Hatton margin continental slope (White and Smith, 2009) while Armitage et al. (2008) have proposed a COB coincident with anomaly C22 on the Greenland side.

The Newfoundland margin is subdivided into two principal areas represented by Flemish Cap (49°N) and the Great Banks of Newfoundland (42°N). The central zone of the Flemish Cap shows a 30 km thick continental crust (Fig. 4), which is divided into three layers. Funck et al. (2003) and Hopper et al. (2004) identify a change in the structure of the crust to SE where this area shows only two layers. The upper one has thicknesses of 1–2 km and velocities between 4.7 km/s and 4.9 km/s, whereas the lower one has a maximum thickness of 2 km and seismic velocities from 6.8 km/s to 7.0 km/s. The SCREECH 3 line (Lau et al., 2006) defines a continental crust beneath the Grand Banks having a thickness of ~ 34–37 km and it is structured into upper, middle and lower. These layers define respectively seismic velocities of 5.8–6.25 km/s, 6.3–6.5 km/s and 6.77–6.9 km/s. Moreover, Lau et al. (2006) identified a crustal necking towards the sea, ranging from about 34 km to 10 km deep in about 30 km, implying a Moho slope of ~ 35°. The COT extends for 80 km showing a base divided into two seismic layers. The Iberian margin is subdivided in northern and southern segments, which are respectively the Galicia and the South Iberian abyssal plain (SIAP) zones. Whitmarsh et al. (1996) suggest a Moho depth of 20 km in the proximal domain decreasing to 10 km and increasing to 14 km seaward. The Galicia margin oceanward shows strong positive gravity anomalies that Hopper et al. (2004) and Beslier et al. (1993) link to a peridotite ridge. In addition, Zelt et al. (2003) show seismic data useful to constrain the Moho geometry. This has a variable trend in-depth with a wavy geometry implying a continental crust characterized by two-stage extension, which is spatially separated from about 100 km.

Stanton et al. (2016) propose gravimetric data for Newfoundland and Iberia margins (Fig. 5) and these show important positive gravity anomalies reaching values >60 mGal. The most particular anomalies develop in the Galicia Bank's area with two gravity peaks (~80 mGal) separated by a negative one. They interpret these with two necking zones highlighting the possible abortion of the Permo-Triassic rifting phase. The gravimetric trend varies also along the strike of the Iberian margin. The southern part shows values >80 mGal while there is another strong gravity anomaly on the Iberian side at 33°N, which is correlated with a peridotite ridge. This testifies the mantle exhumation during the continental break–up leading serpentinized peridotite to the surface in the Galician area (Beslier et al., 1993; Whitmarsh et al., 1996, 2001; Whitmarsh and Sawyer, 1996; Henning et al., 2004; Manatschal et al., 2007; Sutra and Manatschal, 2012; Sutra et al., 2013).

The Southern segment of Iberia has a crustal thickness of about 28 km below the continental slope. This depth value shows good correspondence with the seismic data, which offer a value of 6.8 km/s. According to Christensen and Mooney (1995), these data suggest a 25–30 km depth for the base of the continental crust. Pinheiro et al. (1992) propose that the first oceanic crust develops from M11 anomaly or M4 (Russell and Whitmarsh, 2003) along the Iberian margin, whereas Sibuet et al. (2007) and Tucholke and Sibuet (2007) have suggested a seafloor spreading during the Aptian–Albian boundary (Stanton et al., 2016).

Along the Iberia margin, in particular where the continental crust starts thinning westward toward the hyper-extended passive continental margin, the seismicity appears to support the initiation

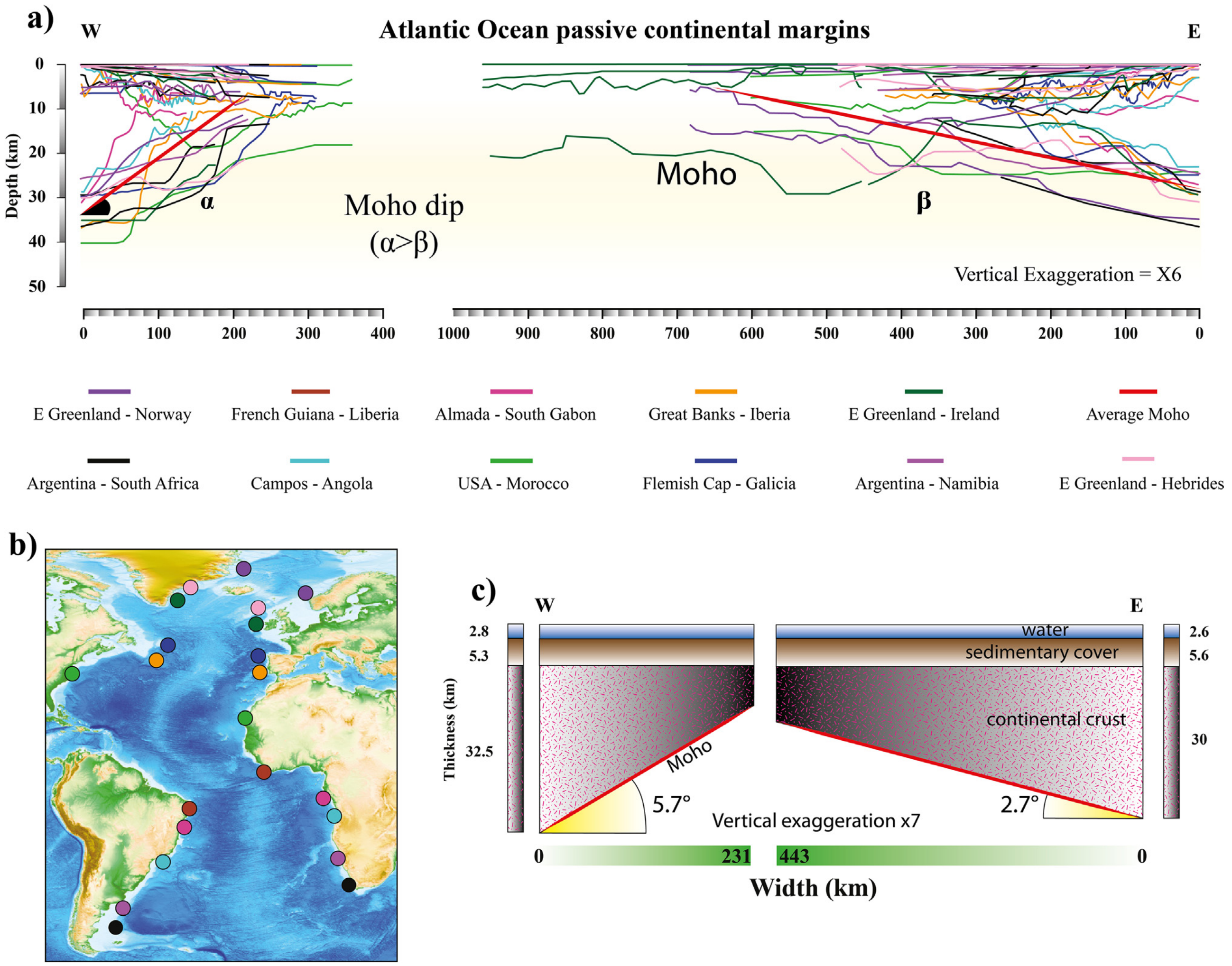


Fig. 13. (a) Schematic diagram showing the outlines of Moho, basins and water columns of reviewed margins along regional transects of the Atlantic conjugate crustal continental margins from geophysical and stratigraphic published data. Transects show the asymmetric geometry of the conjugate crustal structure and basins. The lines define two fundamental trends between western and eastern margins. (b) Location of the analyzed conjugate passive margins. (c) Drawing showing the mean thickness and Moho depth variation for the Western and Eastern Atlantic passive continental margins, moving from the stable continent to the ocean. Notice the different Moho shapes, depth and dip, being steeper and having a shorter continental-ocean transition on the western side. The western margins have a steep Moho with a dip angle in the average of 5.7° with respect to the shallower 2.7° of the eastern margin. The sedimentary cover is on average slightly thinner on the western side. The opposite trend occurs for the water column.

of a new easterly dipping subduction zone (Duarte et al., 2013), inverting the passive margin into an active one.

2.2. Central Atlantic

In the conjugate margins of North America and Morocco (Fig. 6), gravity anomalies reach positive values up to 50–60 mGal and negative ones from −20 to −50 mGal. The Morocco margin has a not thinned continental crust with a thickness of about 27 km, which is divided into two distinct layers represented by an upper layer 12 km thick, and a lower one 15 km thick (Labails et al., 2009, 2010). The Moho develops from 27 to 20 km below the continental slope and then decreases gently to ~13 km in the oceanic domain. A high-velocity layer characterizes the transitional domain defining seismic velocity (7.0–7.4 km/s) higher than typical lower crustal velocity. The Baltimore Canyon Through is interpreted as the conjugate part of the Dakhla segment and presents a crustal thickness of 40 km for the proximal domain (Grow et al., 1983; LASE Study Group, 1986; Watts, 1988). The Moho rises abruptly from 40 to 30 km reaching the depth of 25 km below the continental slope. In the Dakhla margin, a deep layer characterized by seismic lower crustal velocities of 7.2 km/s extends below the margin (Labails and Olivet, 2009). The Central Atlantic shows several magnetic

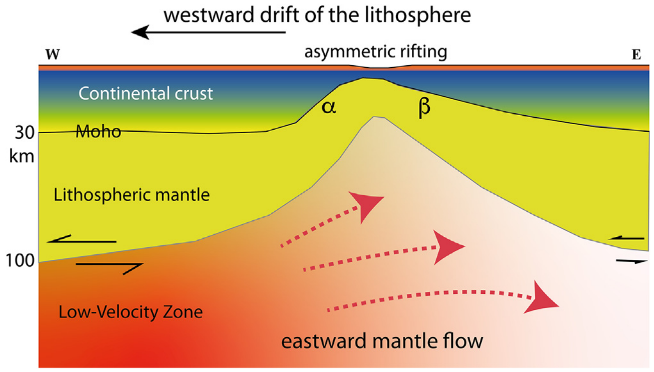


Fig. 14. Sketch illustrating how the asymmetry of the Atlantic passive continental margins can be explained by the early Permo-Mesozoic rifting having a faster westward motion of the western plates with respect to the eastern plates, being both plate pairs moving westward relative to the underlying mantle.

anomalies but the East Coast Magnetic Anomaly (ECMA), Blake Spur Magnetic Anomaly (BSMA) and West African Coast Magnetic Anomaly (WACMA) are the most relevant (Sahabi et al., 2004; Labails and Olivet, 2009). The ECMA is a positive magnetic anomaly developing parallel to the U.S. margin and presenting values of 350 nT. Talwani et al. (1995) interpret this anomaly as the COB and it seems to coincide with the SDRs. The BSMA is another positive magnetic anomaly on the US side. This anomaly indicates an oceanic crust, which has an age of about 165 Ma (Gradstein et al., 2004). Sahabi et al. (2004) identify the WACMA for the Morocco margin and this develops between latitudes 15°N and 20°N. The ECMA and WACMA could represent the COB for these margins.

2.3. South Atlantic

The conjugate margins of French Guiana and Liberia (Fig. 7) develop in the equatorial area of the South Atlantic close to the transform regime. Both margins show strong positive–negative gravity anomalies, which could be related to the edge effect. Besides, the Liberia area has an outer high representing probably the seaward edge of COT. In the proximal domain, the crustal thickness of French Guiana has a value of ~37 km (Greenroyd et al., 2007). The Moho shows a steep dip, which indicates a shorter width of the margin. The COT presents a width of about 44 km, resulting smaller than its conjugate COT of Liberia (>100 km) (Jilinski et al., 2013). The Liberia proximal domain is characterized by a crustal thickness of 40 km, but the Moho is not so steep defining a more gradual necking zone.

The Almada margin (Fig. 8) is part of the northeastern portion of the Brazilian margin where the gravimetric field shows one strong positive anomaly (on average 70 mGal), which is flanked by a negative one developing parallel to the coast for about 350–380 km. This margin has a Moho rising from 35 km to about 20 km in-depth on an average distance of 100 km and with a COT 56 km wide (Blaich et al., 2010). The South Gabon margin develops below the N' Komi Fracture Zone, which divides the Gabon sector into a northern and southern portion (Gordon et al., 2012). Several authors (Wannesson et al., 1991; Meyers et al., 1996; Blaich et al., 2010; Gordon et al., 2012) suggest a continental Moho showing a flat geometry evolving from ~25–27 km deep to ~16 km in about 200 km. The COT is ~60 km wide (Blaich et al., 2010).

The geometries of the conjugate margins of Campos and Angola (Fig. 9) extend to lower latitudes. Moulin (2003), Moulin et al. (2005) and Contrucci et al. (2004a, b) propose a margin division in four regions. Region I corresponds to the continental shelf area, while region II is the continental slope with an extension of 40 to 50 km, where the maximum width of the continental crust develops. It follows region III, which represents the transition zone (e.g., Zalán et al., 2011). Then the region IV indicates the oceanic domain. In region I, the crustal thickness is ~30 km and crustal thinning develops mainly below the continental slope, decreasing from about 30 km to 5 km on 50 km (Moulin et al., 2005). The gravimetric data in the Campos margin area attest strong positive (70–80 mGal) and negative anomalies parallel to the coast. The Moho develops between 7 and 9 sec (TWT) and develops up to 30 km deep to NW and 20 km towards SE (Mohriak et al., 1990). The crustal structure shows a rapid thinning of the crust, from about 32 to 22 km in less than 40 km. Aslanian et al. (2009), which defines a crustal thickness that abruptly diminishes from 32 km to 10 km on a distance less than 70 km. The alleged COT shows a width of 37 km (Zalán et al., 2011). The positioning of the COB for these four margins seems to coincide with the magnetic anomaly C34 defined by Cande and Rabinowitz (1978). This could indicate that the first oceanic crust has formed at about 84 Ma with the opening of the Atlantic Ocean in the central segment during the Late Cretaceous.

Blaich et al. (2009) suggest for the entire Argentinian margin a high-density lower crust (3.2 g/cm^3) developing toward the ocean (Fig. 10). In the proximity of the Colorado basin, the northern part of the margin has a crustal structure with a steep necking zone. The crustal thickness in the proximal domain is about 30 km and decreases to less than 15 km near the COB at a distance of 80 km. In the eastern conjugate passive continental margin of Namibia in southwestern Africa, Bauer et al. (2000) document a more gradual and wide crustal structure; in fact, the Moho is at 30 km depth in the proximal domain, raising to about 15 km along with a distance of ~250 km. The southern Argentine continental margin presents a crustal thickness of ~28–30 km in the proximal zone and a COT of about 60 km in the northern part.

The S-Africa sector (Fig. 11) is widely analyzed by Hirsch et al. (2009), which suggest a crustal partition in three main areas. From west to east, the oceanic crust shows seismic velocities of 4.5–5.0 km/s, 6.2 km/s and 7 km/s corresponding to effusive rocks, volcanic rocks and a gabbroic layer. The following COT displays values of 6.9–7.4 km/s for the middle and lower crust. The continental crust highlights a steady increase of velocities between the upper and lower portions, with seismic velocities of 5.9 to 6.1 km/s up to 6.7 to 7.0 km/s down in the lower crust just above the Moho. In this area, the gravimetric field has a positive anomaly of 50 to 60 mGal followed by a negative (between −25 and −75 mGal). Bauer et al. (2000) and Hirsch et al. (2007, 2009) identify another positive gravimetric anomaly, which only reaches 20 mGal oceanward with respect to COT. The margin has a crustal thickness of about 28 to 35 km in the proximal domain and a COT ranging from 135 to 200 km (Hirsch et al., 2007, 2009; Blaich et al., 2009). The Argentine margin presents COT and COB coinciding with the end of the volcanic wedges interpreted as SDRs (Franke et al., 2006, 2007; Hinz et al., 1999; Blaich et al., 2009) and with magnetic anomaly G, suggested by Rabinowitz and Labrecque (1979). Instead, the COB in the South African area develops more to the west of anomaly G, probably generated by the volcanic wedges (SDRs) (Blaich et al., 2009).

3. Results

The review developed in the previous chapter (Figs. 1–11) has highlighted two different shapes of the Moho beneath the conjugate margins of the Atlantic Ocean. The western margin such as Argentina, Campos, Almada, French Guiana, USA, Newfoundland, and E Greenland displays a short and steep Moho, which is coincident on average with a strictly necking zone. This structural component forms a Moho evolving on average from 32.5 km to less than 15 km. The eastern contrarily, such as Namibia, South Africa, Angola, South Gabon, Liberia, Morocco, Iberia, Ireland, Hebrides and Norway display a gradual Moho resulting on average in a wide crustal framework of the margin. This trend links to a thinner proximal domain (on average 30 km) and the necking zones accommodates more gently the crustal thinning forming with the continental rift process (Fig. 12). These two trends of the continental Moho in the Atlantic Ocean attest to a sort of polarization of the same. To highlight this concept, several regional transects are been constructed for the conjugate margins using geophysical data extrapolated from literature (Figs. 1–11). The results suggest a well-defined orientation of crustal structures through two different Moho shapes below the conjugate margins. The western such as E Greenland, Newfoundland, USA, French Guiana, Almada, Campos and Argentina have a steeper continental Moho, which is on average linked to a thicker proximal domain. On the other hand, the eastern margins such as Norway, Hebrides, Ireland, Iberia, Morocco, South Gabon, Angola, Namibia and South Africa show a more gradual Moho geometry, which is associated with shallower depths and the stretched margin if far wider.

4. Discussion and conclusions

Continental-ocean transition (COT) records the passage from rifting to the drifting stage of passive continental margins. We analysed the main geological and geophysical signatures of the COT bordering the Atlantic Ocean. The western northern and southern American margins are generally characterized by shorter COT, steeper Moho and slightly thicker sedimentary sequences with respect to the eastern European and African conjugate counterparts (Fig. 13).

The western margins have on average a steep continental Moho with a Moho dip of about 5.7°±1°, while the eastern ones show a lower 2.7°±1° Moho dip (Fig. 13). Moreover, the resulting mean structure for Atlantic margins shows distinct differences also for the width of the conjugate margins. The western passive continental margins have a mean width of 231 km, which is considerably lower than the eastern margins that are on average 443 km wide. The analysis highlights also slightly variations in terms of thicknesses for the sedimentary unit and water column. On the western side of the Atlantic Ocean, the margins have a mean basin and water column thickness of 5.3 km and 2.8 km, while the same domains to the east have values of 5.6 km and 2.6 km (Fig. 13).

The asymmetry of the Atlantic passive continental margins can be observed also in most of the oceanic settings worldwide and along backarc basins that show generally sharper width in the western margin and it should be related to the deeper lithosphere-asthenosphere interaction moving along the so-called tectonic equator (Crespi et al., 2007; Cuffaro and Doglioni, 2007, 2018; Panza et al., 2010; Doglioni and Panza, 2015), with an oblique easterly directed mantle upraise beneath rift zones (Chalot-Prat et al., 2017). The analysis reveals also a direct correlation between mantle dynamics proposed for the oceanic rift process by Chalot-Prat et al. (2017) and the crustal structure of the earlier passive margins. An asymmetry detected by mantle tomography, shear wave splitting and electromagnetic surveys is frequently recorded also across all oceanic ridges in the Pacific and Atlantic oceans (Forsyth et al., 1998; Conder et al., 2002; Baba et al., 2006; Johansen et al., 2019). In fact, the crustal asymmetry along continental rifts could suggest similar oblique mantle dynamics during the rifting process leading to the formation of a new oceanic crust as suggested by Doglioni et al. (2003).

An asymmetric rifting is assumed intrinsic to mantle plume impending the continental lithosphere (Koptev et al., 2018). On the other hand, Fromm et al. (2015) have shown how a hotspot plume cannot be the cause of the South Atlantic opening, whereas Will and Frimmel (2018) postulated that far field forces governed the initiation of the Atlantic rift. They also infer that rifting started along pre-existing weakness lithospheric zones. However, the central-northern Atlantic rifting followed the strike of the pre-existing Paleozoic orogens (Doglioni, 1995), whereas in the south Atlantic this rule is apparently not respected (e.g., Frizon de Lamotte et al., 2015), although the deep lithospheric heterogeneities and related weak zones may not be detected at the surface. Alternative popular models would explain the opening of the Atlantic Ocean by mantle convection (e.g., Colli et al., 2018 and references therein). This article rather confirms an asymmetric pattern of plate boundaries that is at odds with simple symmetric spreading associated with poloidal flow and laterally spreading plates dragged by the underlying diverging mantle. Therefore, this analysis supports the geodynamic polarization of the westerly moving lithosphere relative to the underlying mantle (Fig. 14), where all plates move to the "west" relative to the underlying mantle along with the undulate flow of the tectonic equator (Doglioni, 1990, 1993), being the velocity gradients among plates related to the variable viscosity in the low-velocity layer planform (Doglioni and Panza, 2015). This "westerly" directed motion is consistent with the asymmetry of global plate boundaries, both subduction and rift zones that can be fueled by the body tide (Carcaterra and Doglioni, 2018; Ficini et al., 2020; Zaccagnino et al., 2020).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Many thanks for long discussions during the years to Bert Bally, Daniel Bernoulli, Enrico Bonatti, Eugenio Carminati, Françoise Chalot-Prat, Eleonora Ficini and Marco Cuffaro. The critical reading by Dominique Frizon de Lamotte, François Roure and the Handling Editor R. Damian Nance greatly improved the article. The Sapienza University supported this research.

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