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Magma-poor continent-ocean transition zones of the southern North Atlantic: a wide-angle seismic synthesis of a new frontier

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Abstract.

Magma-poor rifted margins, and their corresponding potential zones of exhumed serpentinized mantle, represent a unique class of tectonic boundaries with enormous promise for advancing the energy transition, such as with hydrogen production, carbon sequestration, and in the search for critical minerals. In this study, a synthesis of the results from seismic refraction/wide-angle reflection profiling, and resulting velocity models, across the continent-ocean transitions of the southern North Atlantic Ocean is presented. The models are assessed and compared to understand characteristic basement types and upper mantle behaviour across the region and between conjugate margin pairs. Ultimately, this work highlights the variable nature of continent-ocean transition zones, even within the magma-poor rifted margin end-member case, and points to avenues for future research to fill the knowledge gaps that will accelerate the energy transition.

1 Introduction

The transition from continental to oceanic crust at rifted margins is far more complex than originally conceived during the early development of the theory of plate tectonics (Manatschal et al., 2010; Franke, 2013; Eagles et al., 2015; Péron-Pinvidic et al., 2019). What was once envisioned to simply comprise an abrupt abutting of continental crust against oceanic crust has been revealed to more often consist of variable amounts of magmatic contributions at magma-rich margins (Eldholm et al., 1989; White, 1992) and mantle serpentinization and exhumation at magma-poor margins (Boillot et al., 1980; Whitmarsh et al., 2001; Lavier and Manatschal, 2006; Reston, 2009; Gillard et al., 2019), with the latter hosting promising targets for the energy transition, such as hydrogen production (Albers et al., 2021; Liu et al., 2023; Pérez-Gussinyé et al., 2023), carbon sequestration (Goldberg et al., 2010; Schwarzenbach et al., 2013; Coltat et al., 2021), and critical mineral exploration (Hannington et al., 2017; Patten et al., 2022).

A key component of the theory of plate tectonics was founded on the concept of the Wilson Cycle (Wilson, 1966), which involves the repeated opening and closing of successive ocean basins over geological time. This concept originated based on evidence collected around the modern Atlantic Ocean (Argand, 1922; Wilson, 1966; Williams, 1984), which revealed that the Paleozoic Iapetus Ocean existed before the Atlantic, with rifting having been seeded within the deformation zones from earlier Rodinian rifting and breakup as well as subsequent Appalachian-Caledonian and Variscan orogenic episodes (Thomas, 2005).

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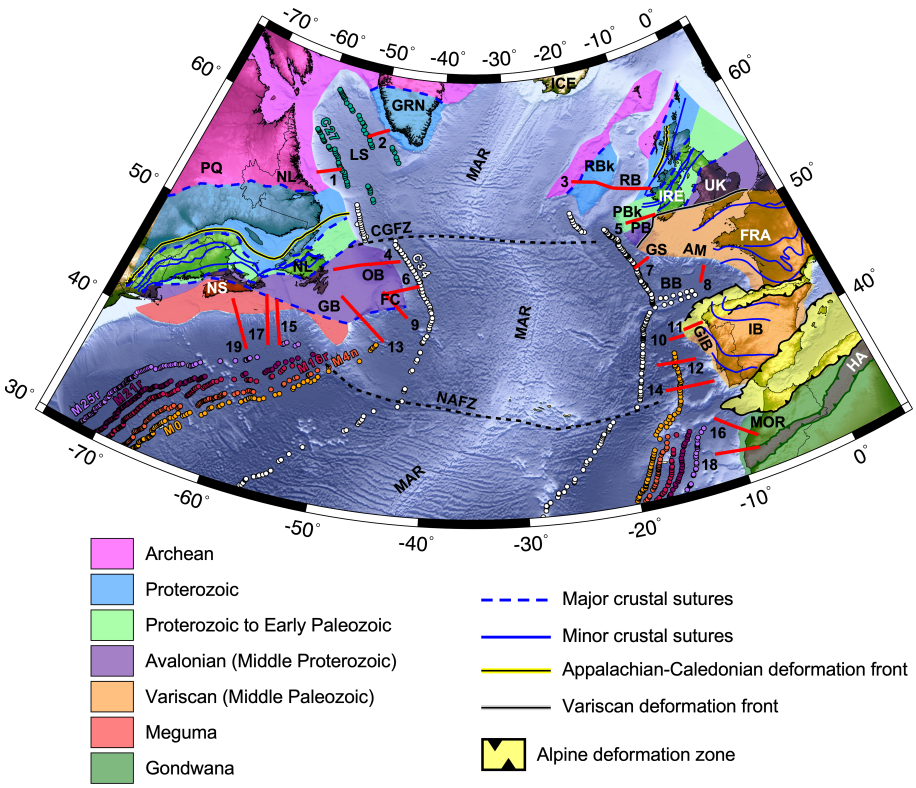

Figure 1. Topographic/bathymetric map from ETOPO1 (Amante and Eakins, 2009) of the study area of the southern North Atlantic Ocean subdivided by inferred basement affinity of continental crust, adapted from Jolivet et al. (2021), Tyrrell et al. (2007), Waldron et al. (2022), and Ziegler and Dèzes (2006). The numbered solid red lines correspond to the seismic refraction/wide-angle reflection (RWAR) profiles for which velocity models are reproduced in this work. The corresponding survey names and citations are provided in Table 1. Fracture zones are delimited by dashed black lines. Select magnetic chron anomalies from Seton et al. (2014) are plotted as coloured circles (M25r, M21r, M16r, M4n, M0, C34, C27). Abbreviations: AM, Armorican Margin; BB, Bay of Biscay; CGFZ, Charlie-Gibbs Fracture Zone; FC, Flemish Cap; GB, Grand Banks; GIB, Galicia Interior Basin; GRN, Greenland; GS, Goban Spur; HA, High Atlas; IB, Iberia; IRE, Ireland; LS, Labrador Sea; MAR, Mid-Atlantic Ridge; MOR, Morocco; NAFZ, Newfoundland-Azores Fracture Zone; NL, Newfoundland & Labrador; NS, Nova Scotia; OB, Orphan Basin; PB, Porcupine Basin; PBk, Porcupine Bank; RB, Rockall Basin; RBk, Rockall Bank; UK, United Kingdom.

In this contribution, I present a review of seismic refraction/wide-angle reflection velocity models across continent-ocean transition zones of magma-poor margins of the southern North Atlantic Ocean (Fig. 1). Furthermore, the resulting interpretations for basement type variations and upper mantle type variations are investigated with a view to reconciling conflicting interpretations and tracking regional trends.

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2 Geological background

Opening of the modern Atlantic Ocean resulted from the breakup and dispersal of the supercontinent Pangea (Schettino and Turco, 2009; Buiter and Torsvik, 2014; Frizon de Lamotte et al., 2015; Whalen et al., 2015; Müller et al., 2016; Peace et al., 2020), which itself formed through multiple orogenies from the end of the Neoproterozoic to the Triassic (Cawood and Buchan, 2007; Stampfli et al., 2013; Chenin et al., 2015), with closure of the Palaeozoic Iapetus Ocean during the Appalachian-Caledonide Orogen (Haworth and Keen, 1979; Williams, 1984, 1995). This zone of orogenesis ultimately corresponded to the eventual locus of Mesozoic rifting of the southern North Atlantic. Palaeozoic closure of the adjacent Rheic Ocean due to collision of northern Africa with southern Europe resulted in the Variscan Orogen, which mostly affected the European margins south of Ireland (Nance et al., 2010; Kroner and Romer, 2013; Chenin et al., 2015).

For the northernmost portion of the central Atlantic (Fig. 1), NW-SE-oriented rifting began in the Late Triassic ($\sim$230 Ma; Schettino and Turco (2009)) and breakup between Nova Scotia and Morocco occurred at $\sim$175 Ma (Klitgord and Schouten, 1986). Northward rift migration into the southern North Atlantic Ocean between Newfoundland and Iberia, with a reoriented W-E extension direction, occurred from the Late Jurassic to Early Cretaceous, achieving breakup at $\sim$115 Ma (Eddy et al., 2017). A final reorientation of the rifting to SW-NE in the Late Cretaceous (de Graciansky and Poag, 1985; Tucholke et al., 1989; Hopper et al., 2006; Tucholke et al., 2007) saw the migration of rifting to between Newfoundland and Ireland and then eventually the Labrador Sea between Labrador and Greenland from 130 Ma (Roest and Srivastava, 1989), with breakup and seafloor spreading inferred to coincide with creation of magnetic chron 27 ($\sim$62 Ma; Gradstein et al. (2012)) in the Labrador Sea (Fig. 1; Chalmers and Laursen (1995)).

3 Characterization of rifted margins

Rifted margins are commonly described in terms of rift domains, which typically progress oceanward from the landward-most proximal domain, to the necking domain, to the distal domain, to the enigmatic outer domain, and ultimately to the oceanic domain (Péron-Pinvidic et al., 2013). These domains correspond to specific evolutionary stages in the rift-to-drift transition and mapping their distributions allows for direct comparison of margin structures both along strike of rifted margins and across conjugate margin pairs. When considering the rifted margin end-members of magma-poor versus magma-rich margins, the main differences are typically manifest in the distal domain. Magma-poor margins in particular commonly have distal domains comprising hyperextended continental crust and potentially wide tracts of exhumed serpentinized mantle (Whitmarsh et al., 2001; Reston, 2009), while magma-rich margins have distal domains dominated by magmatic products like seaward-dipping reflectors and intrusives in the lower crust (Eldholm et al., 2000; Planke et al., 2000). Continent-ocean transition zones typically correspond to these distal domains and can also include embryonic oceanic crust, accreted prior to the initiation of classic seafloor spreading.

While magma-poor margins are less common than magma-rich margins worldwide (Reston, 2009), they do represent the dominant margin type in the southern North Atlantic, from Nova Scotia to Labrador on the eastern Canadian margin, and from Morocco to the Irish Atlantic margin on the European side. These particular margins resulted from the propagation of rifting

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through ancient Appalachian-Caledonian orogenic terranes, with inheritance likely driving the development of continental ribbons (e.g. Flemish Cap, Porcupine Bank, Rockall Bank; Péron-Pinvidic and Manatschal (2010)) and possibly setting up the necessary conditions for exhumation of serpentinized mantle within their distal domains. The development of continent-ocean transition zones for these margins, encompassing the final stages of rifting and the initiation of seafloor spreading, remains an area of active research, hampered by sparser data availability compared to more proximal domains, and challenged by the non-uniqueness inherent to geophysical methods in the absence of drilling. In this study, we focus on identifying the transitions from extended continental crust (encompassing proximal, necking, and portions of the distal domains) to exhumed serpentinized mantle (a component of the distal domain), where present, to oceanic crust, whether anomalously thin, anomalously thick, or of normal thickness (5-8.5 km; White et al. (1992)).

4 Geophysical Methods

For studying continent-ocean transition zones, seismic refraction/wide-angle reflection (RWAR) techniques arguably represent the best geophysical method for determining their crustal and upper mantle velocity structures, as well as delineating fundamental lithospheric boundaries such as the Mohorivičić discontinuity (Moho), which separates the lower crust from the upper mantle. In the marine environment, these surveys involve the deployment of ocean bottom seismometers (OBS) that record arrivals from airgun sources deployed at the sea surface.

Data from RWAR surveys consist of seismic waveforms recorded as a function of time, from which traveltimes for both refracted and reflected seismic phases between the sources and the OBS can be identified and picked. The waveforms themselves contain information about the velocity variations both within layers and across subsurface interfaces. Traditionally, forward modelling using ray tracing, with localized inversion, has been used to derive velocity models from OBS traveltime data (Červený et al., 1977; McMechan and Mooney, 1980; Červený and Pšenčík, 1981, 1984; Zelt and Smith, 1992), such as for the majority of the RWAR profiles included in this study (indicated by the FMRT label in the fourth column of Table 1). More recently, tomographic inversion methods have begun to replace and complement the forward modelling approaches (Van Avendonk et al., 1998; Zelt and Barton, 1998; Korenaga et al., 2000, 2001; Van Avendonk et al., 2004; Meléndez et al., 2015; Begović, 2020). These are less time-consuming to develop and arguably less biased. The simplest form of tomographic inversion involves reproducing the picked seismic phase traveltimes (both refracted and possibly reflected), and the velocity models that were developed using this technique in the study area are indicated by the TTI label in the fourth column of Table 1. The most computationally expensive approach to modelling RWAR data involves Full-Waveform Inversion (FWI), which attempts to reproduce both the observed traveltimes as well as the seismic waveforms themselves (Pratt and Worthington, 1990; Pratt et al., 1996, 1998; Pratt, 1999; Ravaut et al., 2004; Brenders and Pratt, 2007; Virieux and Operto, 2009). As FWI requires much more closely spaced OBS than used in conventional RWAR surveys, there has not yet been widespread use of this technique offshore (Sears et al., 2008; Kamei et al., 2013; Morgan et al., 2013; Górszczyk et al., 2021), particularly in the Atlantic Ocean (Minshull and Singh, 1993; Davy et al., 2017; Guo et al., 2020; Boddupalli et al., 2021, 2022), and only one FWI-generated partial profile is considered in this synthesis (Jian et al. (2021); line 15b in Table 1).

5 Geophysical Constraints

Across the southern North Atlantic Ocean, a large number of RWAR surveys have been deployed (see Fig. 1 and Table 1 for the profiles included in this study), from which crustal and upper mantle variations have been revealed and continent-ocean transition zones have been interpreted. However, unlike for the northern reaches of the North Atlantic Ocean (Funck et al., 2017), no detailed synthesis of the southern North Atlantic Ocean, with models plotted at comparable scales and with comparable colour palettes, has yet been produced, despite a few regional profiles appearing in a pan-Atlantic synthesis (Biari et al., 2021). Herein, across Figs. 2 to 6, the velocity models from the profiles highlighted in Fig. 1 are reproduced and compared.

5.1 Labrador - Greenland margins

The Labrador Sea is bordered by the rifted passive margins of Labrador in the WSW and Greenland in the ENE, with the densest concentration of RWAR surveys acquired on the Labrador margin (van der Linden, 1975; Chian et al., 1995; Reid, 1996; Funck and Louden, 1998, 1999, 2000; Funck et al., 2001a, b; Hall et al., 2002; Funck et al., 2008), although these are focused primarily on the proximal domain. While the Greenland margin has received less attention, select studies do exist (Chian and Louden, 1992; Gohl and Smithson, 1993; Chian and Louden, 1994; Funck et al., 2007) to allow a conjugate margin comparison.

Figure 2 shows the comparison of RWAR derived velocity models from either side of the Labrador Sea, resulting from the work of Chian and Louden (1994) and Chian et al. (1995) (profiles 1 and 2 in Fig. 1). Landward, these models demonstrate a fundamental asymmetry, with a wider zone of thinned continental crust for the Labrador margin relative to the Greenland margin. Moving outboard toward the continent-ocean transition zone (COTZ), greater symmetry is observed. On both margins, extensive sub-crustal 100 km-wide zones of serpentinized mantle are modelled, with 80 km and 70 km of those zones exhumed on the Labrador and Greenland margins, respectively. The seaward extents of both models show normal oceanic crust abutting these zones of exhumation, which is consistent with their correspondence with magnetic chron 27 (Fig. 2a), interpreted as undisputed oceanic crust by Chalmers and Laursen (1995). While linear magnetic anomalies have been identified landward of chron 27 (not shown; Seton et al. (2014)), these are inferred to correspond to magnetite generated during the serpentinization process (Nazarova, 1994; Oufi et al., 2002; Sibuet et al., 2007a).

5.2 Orphan Basin - northern Irish Atlantic margins

The NE margin of Newfoundland, corresponding to the Orphan Basin, and the conjugate northern Irish Atlantic margin once lay within the thickened terranes of the Appalachian-Caledonide Orogen, with the resulting inherited structures strongly influencing subsequent rifting and the formation of multiple continental ribbons (e.g., Flemish Cap, Rockall Bank, Porcupine Bank; Fig. 1). While RWAR profiling has been undertaken in the Orphan Basin (Keen and Barrett, 1981; Chian et al., 2001; Lau et al., 2015; Welford et al., 2020), only the studies by Chian et al. (2001) and Welford et al. (2020) allowed for characterization of a portion of the COTZ (profile 4 in Fig. 1). Meanwhile, on the conjugate northern Irish Atlantic margin, there is a

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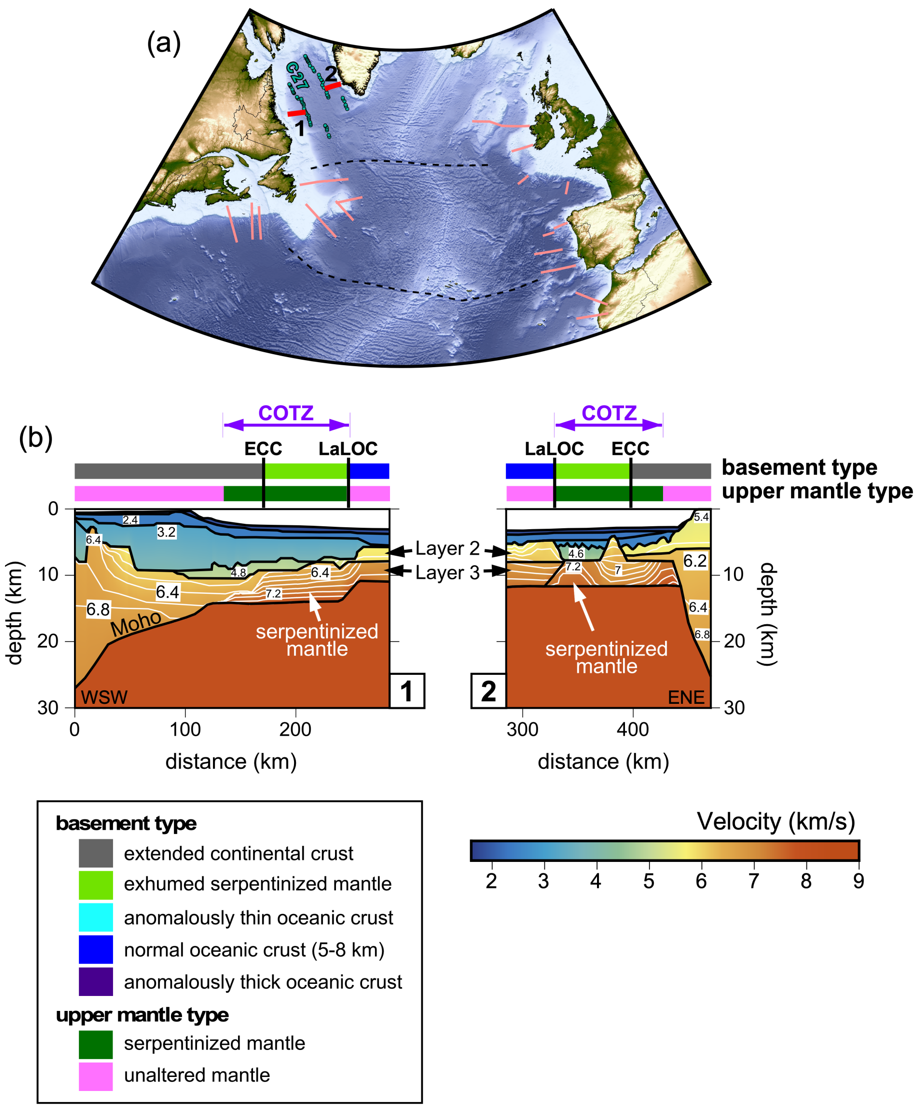

Figure 2. (a) Topography/bathymetry map with location of velocity models in (b) highlighted in red, and all other considered velocity model locations in this study shown in pink. (b) Velocity models reproduced from 1: Chian et al. (1995) and 2: Chian and Louden (1994). In (a), the dashed black lines are fracture zones and magnetic chron anomaly C27 picks from Seton et al. (2014) are plotted as coloured circles. In (b), model boundaries are shown as solid black lines and velocity contours (with a contour interval of 0.2 km s^{-1}) are shown as solid white lines within the crust. Interpreted basement types and upper mantle types are plotted above each velocity model with colours explained in the legend. Abbreviations: COTZ, continent-ocean transition zone; ECC, edge of continental crust; LaLOC, landward limit of oceanic crust.

lack of modern RWAR studies across the continent-ocean transition, with older surveys with sparse OBS revealing simplistic abrupt continent-ocean boundaries (COB; Makris et al. (1988); Hauser et al. (1995)). As such, only inboard surveys crossing

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the Rockall Basin, the Porcupine Basin, and their respective flanking banks are included in this study in order to capture the velocity structures where rifting failed to achieve breakup and seafloor spreading (profiles 3 and 5 in Fig. 1).

Figure 3 shows the comparison between the velocity model from Welford et al. (2020) across the Orphan Basin, and velocity models that lie inboard of the COTZ on the northern Irish Atlantic margin (Funck et al., 2017; Prada et al., 2017). These profiles are dominated by either thinned continental crust across multiple failed rifts, or by thicker continental crust in the form of continental ribbons. Across all of these failed rifts, low velocities in the upper mantle are consistent with some degree of serpentinization (Hauser et al., 1995; O'Reilly et al., 1996; Reston et al., 2004; O'Reilly et al., 2006; Prada et al., 2017). At the COTZ, outboard of the Orphan Basin, the nature of the basement cannot be uniquely defined due to non-unique velocities but it may correspond to either exhumed mantle or anomalously thin oceanic crust, consistent with its location inboard of magnetic chron 34, the locus of undisputed oceanic crust in this part of the southern North Atlantic Ocean (Fig. 3a; Srivastava et al. (1990)).

5.3 Flemish Cap - southern Irish and Armorican margins

Southeast of the Orphan Basin on the Newfoundland margin lies the Flemish Cap, a continental ribbon that is interpreted to have been rotated and translated during Mesozoic rifting (Sibuet et al., 2007b), leading to the formation of the Orphan Basin itself. Ignoring this rotation, early studies proposed the Goban Spur, on the southern Irish margin, as the conjugate margin to the Flemish Cap (Keen and Dehler, 1993; Gerlings et al., 2012). More recent work however suggests a closer link between the Flemish Cap and the Porcupine Bank (Peace et al., 2019; Sandoval et al., 2019; Yang and Welford, 2022).

Two RWAR profiles cross the NE margin of the Flemish Cap, the 460 km-long FLAME 1 survey (profile 6 in Figs. 1 and 4; Gerlings et al. (2011)) and a shorter coincident 80 km-long experiment involving four OBS (Reid and Keen, 1990). The FLAME 1 velocity model comprises basement with a very narrow 20 km-wide transitional zone of exhumed serpentinized mantle, with a more expansive 80 km-wide zone of serpentinized mantle underlying thinned continental crust. An abrupt transition from exhumed mantle to normal oceanic crust in the model is consistent with the intersection of the seawardmost portion of the FLAME 1 model (profile 6) with the magnetic chron 34 anomaly (Fig. 4a), the locus of undisputed oceanic crust along this portion of the southern North Atlantic (Srivastava et al., 1990).

On the southern Irish margin, the Goban Spur and regions immediately to the south have seen the greatest number of RWAR experiments (Ginzburg et al., 1985; Whitmarsh et al., 1986; Horsefield et al., 1994; Bullock and Minshull, 2005), with the most recent model by Bullock and Minshull (2005) corresponding to profile 7 in Figs. 1 and 4. In this model, the transitional crust spans 120 km and is subdivided into an inboard 70 km wide zone of serpentinized mantle peridotites with subdued relief, and an oceanward 50 km wide zone of possibly exhumed serpentinized basement ridges, similar to ones identified on the Iberian margin to the south (Boillot et al., 1980; Beslier et al., 1993; Shipboard Scientific Party, 1998; Dean et al., 2000; Henning et al., 2004).

South of the Goban Spur, along the northern margin of the Bay of Biscay lies the Armorican margin. The Norgasis 14 RWAR line (profile 8 in Fig. 1) was modelled by Thinon et al. (2003), revealing an 80 km-wide zone of transitional exhumed mantle,

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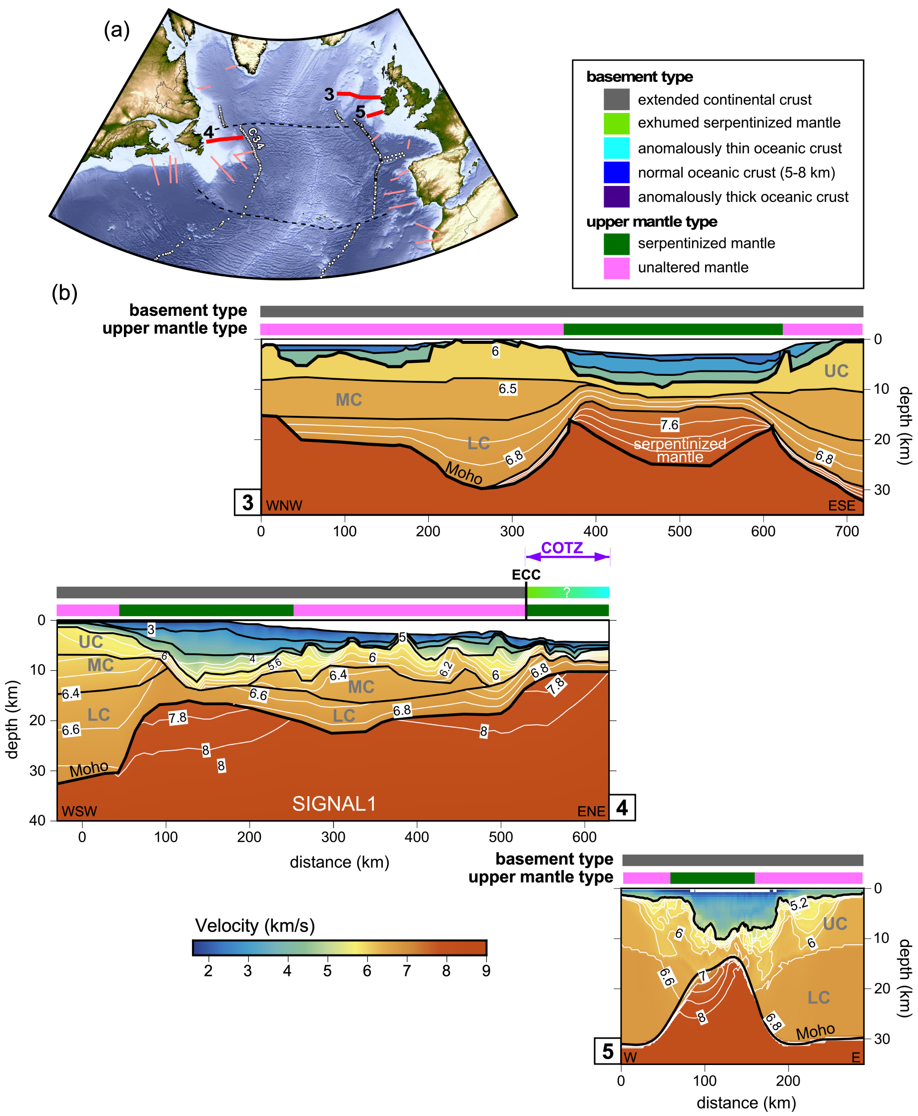

Figure 3. (a) Topography/bathymetry map with location of velocity models in (b) highlighted in red, and all other considered velocity model locations in this study shown in pink. (b) Velocity models reproduced from 3: Funck et al. (2017), 4: Welford et al. (2020), and 5: Prada et al. (2017). In (a), the dashed black lines are fracture zones and magnetic chron anomaly C34 picks from Seton et al. (2014) are plotted as white circles. In (b), model boundaries are shown as solid black lines and velocity contours (with a contour interval of 0.2 km s^{-1}) are shown as solid white lines within the crust. Interpreted basement types and upper mantle types are plotted above each velocity model with colours explained in the legend. Abbreviations: COTZ, continent-ocean transition zone; ECC, edge of continental crust; LC, lower crust; MC, middle crust; UC, upper crust.

bordered oceanward by an abrupt transition to normal thickness oceanic crust. A more extensive unexhumed sub-crustal 130 km-wide zone of serpentinized mantle was shown to extend beneath that normal oceanic crust.

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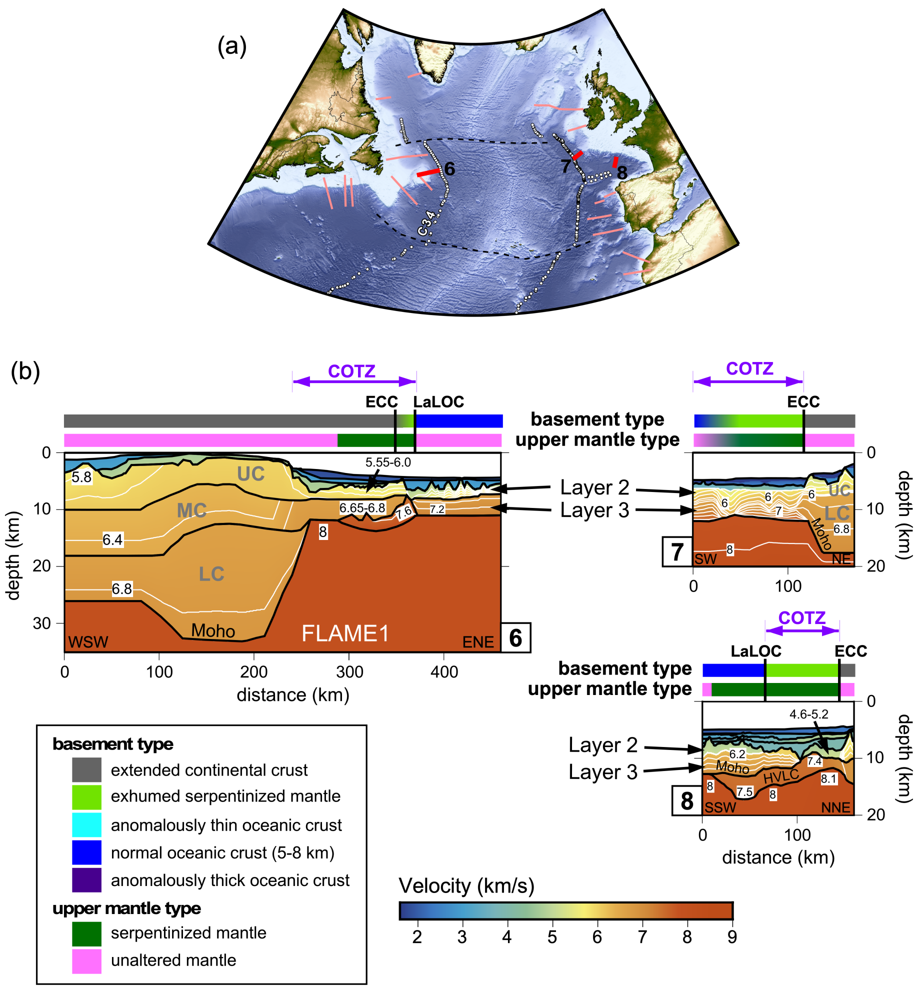

Figure 4. (a) Topography/bathymetry map with location of velocity models in (b) highlighted in red, and all other considered velocity model locations in this study shown in pink. (b) Velocity models reproduced from 6: Gerlings et al. (2011), 7: Bullock and Minshull (2005), and 8: Thinon et al. (2003). In (a), the dashed black lines are fracture zones and magnetic chron anomaly C34 picks from Seton et al. (2014) are plotted as white circles. In (b), model boundaries are shown as solid black lines and velocity contours (with a contour interval of 0.2 km s^{-1}) are shown as solid white lines within the crust. Interpreted basement types and upper mantle types are plotted above each velocity model with colours explained in the legend. Abbreviations: COTZ, continent-ocean transition zone; ECC, edge of continental crust; HVLC, high-velocity lower crust; LaLOC, landward limit of oceanic crust; LC, lower crust; MC, middle crust; UC, upper crust.

5.4 Southeast Newfoundland-Iberia margins

165 The southeast Newfoundland and northwest Iberian margins arguably represent the best studied conjugate margin pair in the world (Louden and Chian, 1999; Srivastava et al., 2000; Manatschal et al., 2007; Péron-Pinvidic et al., 2007; Sibuet et al., 2007a; Tucholke et al., 2007; Crosby et al., 2008; Péron-Pinvidic and Manatschal, 2009; Manatschal et al., 2010; Soares

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et al., 2012; Péron-Pinvidic et al., 2013; Sutra et al., 2013; Mohn et al., 2015; Stanton et al., 2016; Brune et al., 2017; Eddy et al., 2017; Alves and Cunha, 2018; Causer et al., 2020; Liu et al., 2022). Herein, we focus on two RWAR surveys on the Newfoundland margin (profiles 9 and 13 in Fig. 1) and four profiles on the Iberian side (profiles 10, 11, 12, and 14 in Fig. 1). Profiles 10 and 11 combined provide almost continuous coverage from east to west across the Galicia Interior Basin, the outboard Galicia Bank continental ribbon, and the COTZ beyond (Fig. 5).

The two presented SCREECH profiles along the southeast Newfoundland margin (Fig. 5; Funck et al. (2003); Lau et al. (2006)) both show abrupt oceanward crustal necking, with outboard thinned continental crust underlain by serpentinized mantle. Southeast of Flemish Cap, the thinned continental crust only extends for 20 km (profile 9) before being replaced by anomalously thin oceanic crust (60 km-wide zone). Conversely, the SCREECH 3 profile off the Grand Banks shows a 90 km-wide zone of thinned continental crust transitioning into a 95 km-wide zone of exhumed serpentinized mantle, with an abrupt transition into normal oceanic crust overlying unaltered mantle.

Across the Galicia margin, making up the northwestern Iberian margin, a failed rift corresponding to the Galicia Interior Basin consists of thinned continental crust overlying serpentinized mantle (profile 11 in Fig. 5 Pérez-Gussinyé et al. (2003)). At the oceanward end of profile 10 (Sibuet et al., 1995; Druet et al., 2017), abrupt crustal necking of the Galicia Bank transitions to an exhumed serpentinized ridge, confirmed through drilling (Shipboard Scientific Party, 1987) and dredging (Boillot et al., 1980), and then anomalously thin oceanic crust over a further distance of approximately 20 km (Whitmarsh et al., 1996; Druet et al., 2017). The thin oceanic crust overlies serpentinized mantle (Sibuet et al., 1995).

Along the mid-Iberian margin, a recent tomographic inversion of densely spaced OBS (10 to 12 km spacing) along the FRAME-p3 line (profile 12 in Fig. 1) by Grevemeyer et al. (2022) reveals an even split between exhumed serpentinized mantle landward, and normal oceanic crust oceanward. These two segments are split by the J anomaly, a prominent magnetic anomaly from the southern North Atlantic Ocean that is the subject of much controversy as to its significance (or not) as a seafloor spreading isochron (Russell and Whitmarsh, 2003; Srivastava et al., 2000; Bronner et al., 2011; Nirrengarten et al., 2016; Stanton et al., 2016). Grevemeyer et al. (2022) conclude that it is not an isochron and so should not be used to constrain plate reconstructions but that it does mark the onset of seafloor spreading at this location along the Iberian margin.

The Tagus Abyssal Plain within the southwest Iberian margin has been sampled by the least amount of RWAR surveys, and until recently, only with widely spaced OBS (30 to 40 km spacing for Afilhado et al. (2008)). A recent velocity model from Merino et al. (2021) shows the highest resolution and highest degree of complexity for a model in this region, achieved using a dense OBS spacing (approximately 14 km) and co-located with a 300 km-long multichannel seismic (MCS) reflection line. Thinned continental crust in the east abuts a 60 km-wide zone of exhumed serpentinized mantle oceanward, before a 50 km-wide rafted segment of thinned continental crust, possibly intruded by melts, is encountered. Merino et al. (2021) hypothesize that the rafted continental block was originally part of the Newfoundland margin and was orphaned on the Iberian margin due to an abrupt westward jump in the localization of extension. Immediately oceanward of the rafted continental block, a 60 km-wide zone of anomalously thick oceanic crust over unaltered mantle is revealed, transitioning to an 80 km-wide zone of anomalously thin oceanic crust, and finally normal oceanic crust. The magnetic J anomaly lies within the zone of thickened oceanic crust and is interpreted to correspond to the onset of seafloor spreading, as was also interpreted to the north along profile 12 (Grevemeyer et al., 2022).

5.5 Nova Scotia-Morocco margins

The Nova Scotia and Moroccan conjugate margin pair were the first to experience rifting during the late Triassic and subsequent breakup during the Jurassic within the study region (Schettino and Turco, 2009; Sibuet et al., 2012), with Morocco acting as an independent small plate detached from mainland Africa (Beauchamp et al., 1996; Piqué et al., 1998; Labails et al., 2010). Three RWAR surveys on the Nova Scotia margin (profiles 15, 17, and 19) are presented here, with the oceanwardmost half of profile 15 covered by both a forward modelled ray traced velocity model (model 15a in Fig. 6; Lau et al. (2018)) as well as a Full-Waveform Inversion model (model 15b in Fig. 6; Jian et al. (2021)) derived using the same OBS data. On the Moroccan side, two RWAR surveys (profiles 16 and 18 in Fig. 1) are used for comparison, corresponding to the SISMAR 4 (Contrucci et al., 2004) and MIRROR 1 (Biari et al., 2015) surveys.

For all three long Nova Scotian profiles (5a, 17, and 19 in Fig. 6), gradual continental necking zones are observed, thinning from 30 km to less than 10 km over a lateral distance of approximately 200 km. The two southern profiles (SMART 1 and SMART 2; profiles 17 and 19 in Fig. 6) reveal thinned continental crust beyond the necking zone extending 60 to 80 km oceanward over serpentinized mantle. Meanwhile, the OETR profile (profile 15a in Fig. 6) has a more restricted extent of thinned continental crust beyond the necking zone, but it overlies unaltered mantle. Profiles 15a, 15b, and 17 show evidence of 40 to 80 km-wide zones of exhumed serpentinized mantle while the southernmost SMART 2 line (profile 19 in Fig. 6) shows thinned continental crust transitioning to an 80 km-wide zone of anomalously thin oceanic crust and eventually normal oceanic crust. There is disagreement along the OETR line in terms of the nature of the oceanwardmost basement type. While Lau et al. (2018) modelled normal oceanic crust outboard of the zone of exhumed serpentinized mantle, the FWI work by Jian et al. (2021) argued for anomalously thin oceanic crust.

The two Moroccan profiles (SISMAR 4 and MIRROR 1, profiles 16 and 18 in Fig. 6) show similar velocity structures, with a slightly more abrupt continental necking zone compared to the conjugate Nova Scotian profiles, with crustal thinning from 30 km to less than 10 km occurring over a lateral distance of approximately 160 km. Both Moroccan models comprise very narrow 30 to 40 km-wide COTZ with extended continental crust transitioning to normal ocean crust. There is no evidence of serpentinized mantle or of exhumed mantle in the basement along the Moroccan margin based on models generated to date (Biari et al., 2015; Klingelhoefer et al., 2016).

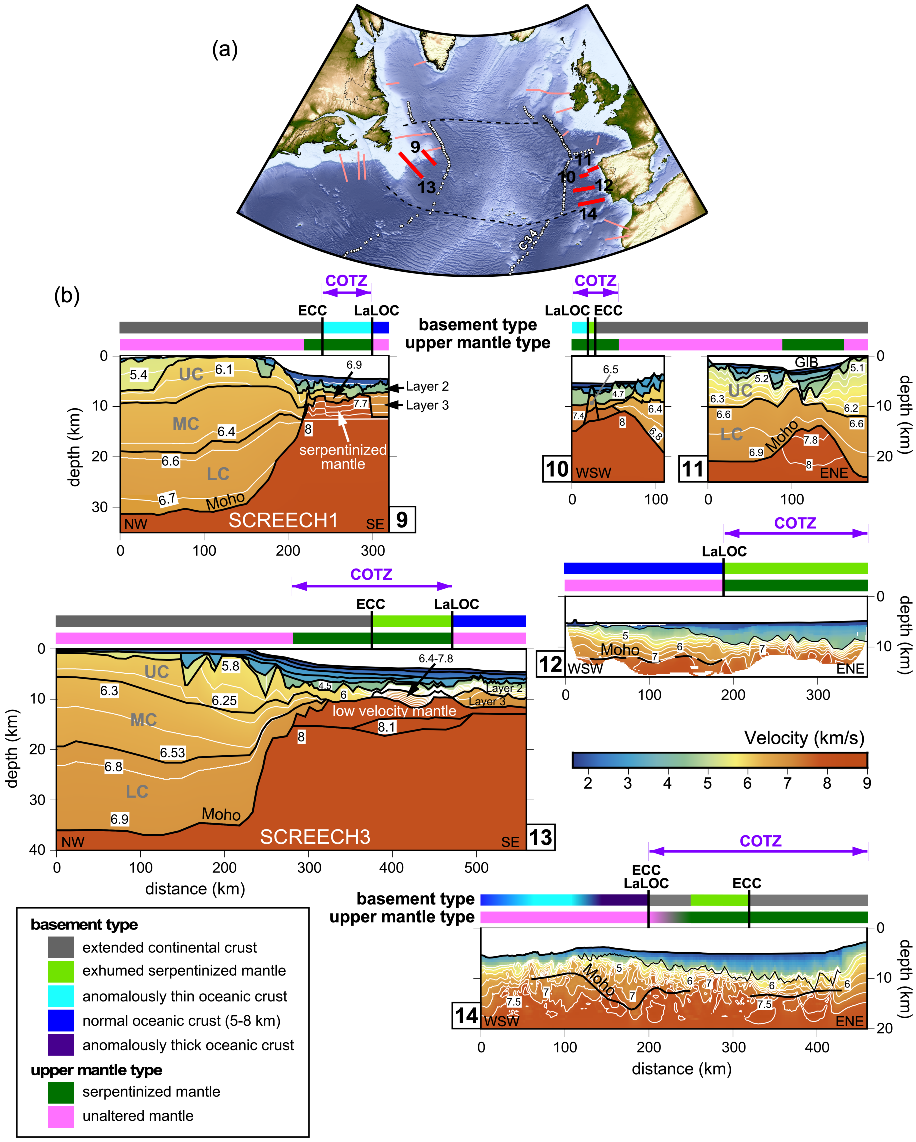

Figure 5. (a) Topography/bathymetry map with location of velocity models in (b) highlighted in red, and all other considered velocity model locations in this study shown in pink. (b) Velocity models reproduced from 9: Funck et al. (2003), 10: Sibuet et al. (1995) and Druet et al. (2017), 11: Pérez-Gussinyé et al. (2003), 12: Grevemeyer et al. (2022), 13: Lau et al. (2006), and 14: Merino et al. (2021). In (a), the dashed black lines are fracture zones and magnetic chron anomaly C34 picks from Seton et al. (2014) are plotted as white circles. In (b), model boundaries are shown as solid black lines and velocity contours (with a contour interval of 0.2 km s^{-1}) are shown as solid white lines within the crust. Interpreted basement types and upper mantle types are plotted above each velocity model with colours explained in the legend. Abbreviations: COTZ, continent-ocean transition zone; ECC, edge of continental crust; GIB, Galicia Interior Basin; LaLOC, landward limit of oceanic crust; LC, lower crust; MC, middle crust; UC, upper crust.

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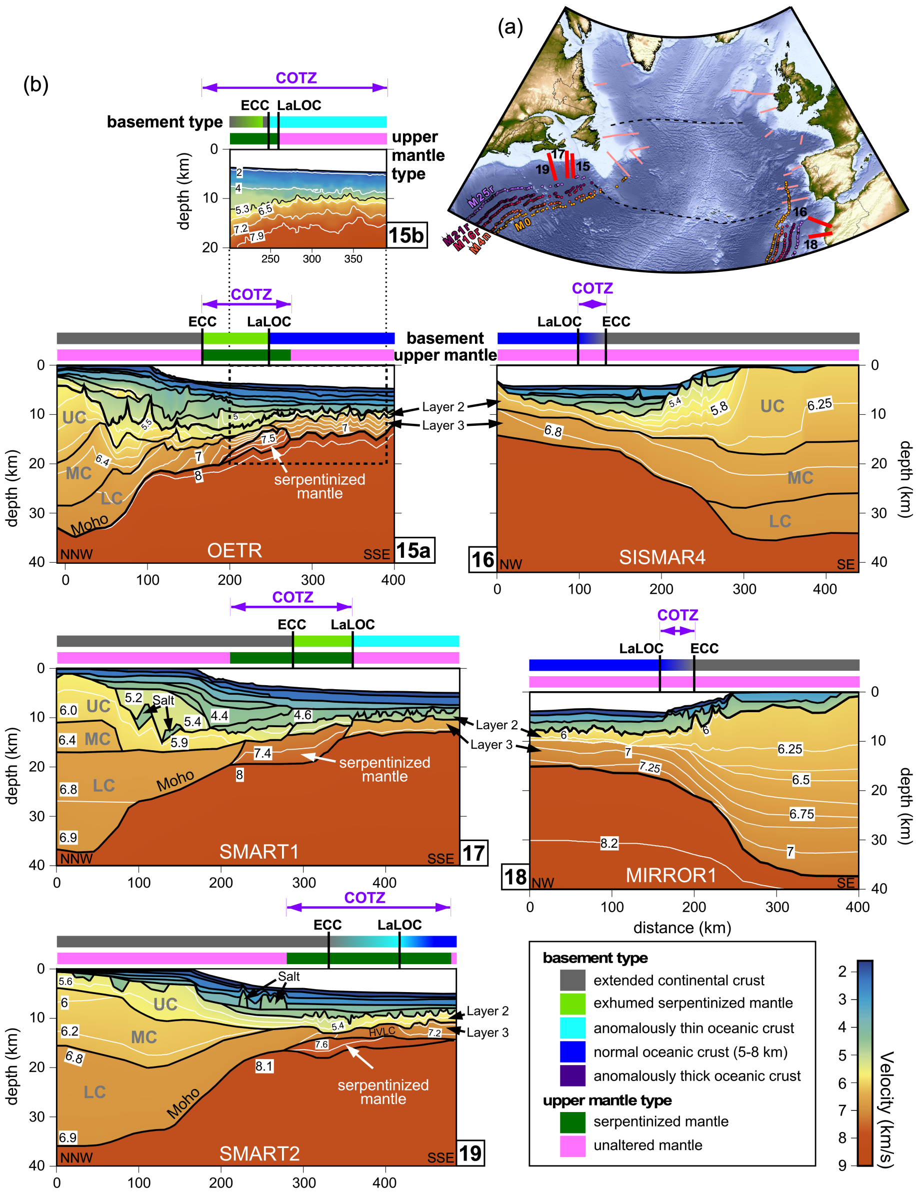

Figure 6. (a) Topography/bathymetry map with location of velocity models in (b) highlighted in red, and all other considered velocity model locations in this study shown in pink. (b) Velocity models reproduced from 15a: Lau et al. (2018), 15b: Jian et al. (2021), 16: Contrucci et al. (2004), 17: Funck et al. (2004), 18: Biari et al. (2015), and 19: Wu et al. (2006). In (a), the dashed black lines are fracture zones and magnetic chron anomalies from Seton et al. (2014) are plotted as coloured circles (M25r, M21r, M16r, M4n, M0). In (b), model boundaries are shown as solid black lines and velocity contours are shown as solid white lines within the crust. Interpreted basement types and upper mantle types are plotted above each velocity model with colours explained in the legend. Abbreviations: COTZ, continent-ocean transition zone; ECC, edge of continental crust; LaLOC, landward limit of oceanic crust; LC, lower crust; MC, middle crust; UC, upper crust.

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6 Discussion

The basement types and upper mantle types interpreted in the velocity models presented in Figs. 2 to 6 are summarized in the maps presented in Fig. 7 and in the diagram in Fig. 8. The map views allow for easier regional interpretations and correlations, while the diagram allows for side by side and conjugate margin comparisons. The widths of the individual basement and upper mantle components, as well as the interpreted COTZ along each profile, are also listed in Table 2.

For the interpreted basement types (Fig. 7a, and Fig. 8), the greatest variations are observed with regards to the presence/absence, and extent if present, of exhumed serpentinized mantle, and with regards to the nature of the oceanic crust (thin versus thick versus normal). The widths of these respective zones are listed in the first two columns of Table 2.

On the North American margins (Fig. 8, left side), exhumed serpentinized mantle is modelled on all of the profiles other than profile 9 across Flemish Cap and the southernmost profile along the Nova Scotian margin (profile 19). The widths of the exhumed zones vary from 20 km (profile 6) to 95 km (profile 13). On the European margins (Fig. 8, right side), south of the northern Irish margin, which lacks RWAR constraints, exhumed serpentinized mantle is ubiquitous down through Iberia, ranging in width from 10 km (profile 10) to 160 km (profile 12), with the narrowest zone outboard of the Galicia Bank continental ribbon. Offshore Morocco, no exhumed serpentinized mantle has been observed, revealing a fundamental asymmetry with its Nova Scotian conjugate margin pair (Fig. 8).

The nature of the oceanic crust outboard of the North American margins varies between anomalously thin oceanic crust (profiles 4, 9, 15b, 17, and 19 in Fig. 7a) and normal oceanic crust (profiles 1, 6, 13, 15a in Fig. 7a). Given this seemingly random variablity, it is unclear whether the thickness variations represent variable seafloor spreading processes acting at the local scale or simply modelling variations (e.g., OBS spacing, modelling methodology). On the European margins, only two models (profiles 10 and 14) reveal zones of anomalously thin oceanic crust, with the latter model also exhibiting a 60 km-wide zone of anomalously thick oceanic crust immediately inboard of the thin oceanic crust. Merino et al. (2021) interpret this significant lateral variation as corresponding to the J anomaly.

For the interpreted upper mantle types (Fig. 7b and Fig. 8), sub-crustal serpentinized mantle appears ubiquitous to all but the Moroccan profiles investigated in this study, with significant variations in terms of the lateral extent of serpentinized mantle within the COTZ of individual models, from 55 km (profile 10) to 230 km (profile 14). In addition, wherever failed rifts have been interpreted in the presented profiles (Orphan Basin, Rockall Basin, Porcupine Basin, Galicia Interior Basin; profiles 3, 4, 5, and 11 in Fig. 7b; see Table 2), serpentinized mantle is always detected, varying in width from 70 km (profile 11) to 260 km (profile 3). It should be noted though that another RWAR profile across the Orphan Basin but away from the COTZ (not shown; Lau et al. (2015)), oblique to profile 4, did not show evidence for mantle serpentinization despite revealing failed rifts.

Regardless of whether mantle exhumation is achieved or not, serpentinization of mantle requires the complete embrittlement of the crust (Pérez-Gussinyé and Reston, 2001), which couples the crustal deformation with the upper mantle deformation and allows for the formation of throughgoing crustal faults that tranport fluids into the mantle. This process necessitates an extended period of ultraslow rifting in order to allow sufficient cooling of the lithosphere to lead to embrittlement. The widespread distribution of serpentinized mantle throughout the study region (other than for the Moroccan margin) is consistent with lengthy ultraslow rifting for the early stages of the southern North Atlantic opening.

6.1 COTZ regional trends and the role of inheritance

Figures 7 and 8 ultimately reveal the challenges associated with defining continent-ocean transition zones (COTZ) even within the magma-poor margin end member category. Basement types (Figs. 7a and 8) show a range of transition zone components (e.g., thinned continental crust, exhumed serpentinized mantle, anomalously thin/thick oceanic crust) with variable widths, often with conflicting interpretations in close proximity to each other. Complicating matters further is the fact that these margins often comprise extensive zones of sub-crustal and unexhumed serpentinized mantle, that extend laterally beyond the interpreted ECC and LaLOC, which are defined solely based on basement types (Fig. 7b). Furthermore, unexhumed serpentinized mantle is often found far inboard of the present day COTZ due to the presence of failed rifts (Fig. 7a).

By extrapolating the regional extents of modelled zones of exhumed serpentinized mantle, as well as the broader serpentinized mantle zones that underlie thinned continental crust and occasionally oceanic crust according to RWAR surveys, the interplay between inheritance and serpentinization can be investigated (Fig. 9), subject to the variable RWAR profile coverage. To first order, the resulting map highlights that, while inferred mantle serpentinization is pervasive on all of the interrogated margins in this synthesis (other than the Moroccan margin; Klingelhoefer et al. (2016)), exhumation of that serpentinized mantle only occurs in proximity to the locus of eventual seafloor spreading. There is also an indication, albeit biased by the available RWAR coverage, that exhumation is greatest in proximity to major fracture zones (NAFZ and CGFZ in Fig. 9), with diminished exhumation towards the Bay of Biscay extinct triple point, at least for Flemish Cap and the northwest Iberian margin.

In terms of inheritance, there is no direct spatial correlation between particular basement terranes and a propensity for mantle exhumation (Fig. 9). This signifies that while the proximal, necking, and hyperextension rifting processes might vary according to inherited structures and crustal fabrics, as argued by Manatschal et al. (2015) and modelled by Jammes and Lavier (2019), mantle serpentinization and exhumation, which occur at the later stages of rifting, do not appear to be influenced by the nature of their continental basement. Instead, the mantle serpentinization and exhumation are more likely controlled by the formation of detachment faults (Jammes and Lavier, 2019) and fundamental rifting parameters such as rift velocity (Huismans and Beaumont, 2007; Tetreault and Buiter, 2018). According to Brune et al. (2016), rifting velocities tend to be slow for the first two thirds of the rift evolution and then speed up for the last third, with the fast phase starting approximately 10 Myr before breakup is achieved. This piece-wise acceleration, which is thought to result from a feedback loop where strain softening processes increase non-linearly over time as deformation continues, may be sufficient to explain why unexhumed mantle serpentinization is so widespread, presumably occuring during slower rifting even within failed rifts, but that the exhumation requires the rift acceleration, and so is only observed immediately prior to breakup (Huismans and Beaumont, 2007).

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6.2 Avenues for future research and potential rewards

Based on the available RWAR profiling of the southern North Atlantic Ocean, and the highly variable nature of the modelled continent-ocean transition zones revealed therein, it is abundantly clear that significant research is still needed in order to properly understand the rift-to-drift evolution along magma-poor margins. Several key avenues for future research are proposed.

Given the unmatched and crucial value of RWAR profiling for determining crustal and mantle velocities, as well as delimiting key horizontal boundaries like the Moho and lateral variations attributable to continent-ocean transitions, clearly more geophysical surveys are needed to fill coverage gaps (particularly across continent-ocean transition zones) and to ensure that margins are being compared using similar data acquisition parameters and modelling approaches. As clearly demonstrated by Grevemeyer et al. (2022), a dense spacing of OBS (10-12 km) is pivotal for high resolution characterization of continent-ocean transition zones. The resulting models allow for improved correlations with independent and co-located geophysical constraints such as shipboard magnetic data, and increase confidence in posited interpretations. Furthermore, as demonstrated by the direct comparison of models generated by conventional FMRT modelling (Lau et al., 2018) and FWI (Jian et al., 2021) using the exact same input data but yielding different models and interpretations (models 15a and 15b in Fig. 6), comparable modelling approaches need to be used in order to reliably identify velocity model features that can be attributed to real geological phenomena. To this end, synthetic modelling of RWAR acquisition parameters to determine optimal OBS spacings and their influence on modelling outputs are needed.

Where high resolution velocity structural models do now exist, such as for southwest Iberia (Merino et al., 2021; Grevemeyer et al., 2022), significant variations in mantle exhumation and the onset of oceanic crustal accretion are revealed over relatively short spatial scales. To explain these variations, an enhanced need for numerical modelling efforts now exists, to complement existing work (Bowling and Harry, 2001; Pérez-Gussinyé et al., 2001; Pérez-Gussinyé and Reston, 2001; Pérez-Gussinyé et al., 2006; Huismans and Beaumont, 2007; Theunissen and Huismans, 2022; Liu et al., 2023), with particular emphasis placed on which key parameters (e.g., rift velocity, thermal structure, magmatic contributions, hydrothermal circulation, mantle fertility) control and/or influence localized rifting processes and seafloor spreading mechanisms. While these parameters can be more effectively isolated and their impacts quantified using 2-D numerical models, their incorporation into 3-D models is the ultimate goal if the complexities of the southern North Atlantic are to be properly explained.

Continent-ocean transition zones hold great potential for advancing the energy transition, with serpentinized mantle representing an important global source of geologic hydrogen (Albers et al., 2021; Milkov, 2022; Liu et al., 2023), and ultramafic rocks serving the role of both effective carbon sequestration reservoirs (Goldberg et al., 2010; Schwarzenbach et al., 2013; Picazo et al., 2020; Coltat et al., 2021) as well as sources of critical minerals (Hannington et al., 2017; Patten et al., 2022). An improved understanding of the processes involved in their formation and the key controlling parameters is essential for characterizing these zones offshore and explaining their occurences in subsequent orogenesis onshore.

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7 Conclusions

In this study, the continent-ocean transition zones (COTZ) of the southern North Atlantic Ocean have been synthesized using seismic refraction/wide-angle reflection (RWAR) profiling in order to elucidate variations in both interpreted basement types and upper mantle types, as well as to extract regional trends in COTZ components and distributions. The main findings are:

- COTZ in the southern North Atlantic Ocean are generally associated with zones of exhumed serpentinized mantle, of variable width, with most margins (other than Morocco) comprising extensive zones of unexhumed sub-crustal serpentinized mantle.
- Variations in oceanic crustal thicknesses within COTZ may reflect localized seafloor spreading processes or may simply show that different OBS spacings and methodological approaches can generate conflicting results at the oceanward limits of the RWAR profiles.
- Significant RWAR data gaps exist, particularly for the northern Irish Atlantic margins, and a clearer understanding of optimal data acquisition and modelling approaches is needed to properly characterize continent-ocean transition zones using these methods.
- A more profound understanding of continent-ocean transition zones offshore is needed to identify the key parameters that drive their evolution. This groundwork is essential for evaluating the incorporation of these zones into later orogenesis revealed onshore.

Author contributions. JKW developed the concept for the contribution. JKW prepared the figures and the manuscript.

Competing interests. The author declares that they have no conflict of interest.

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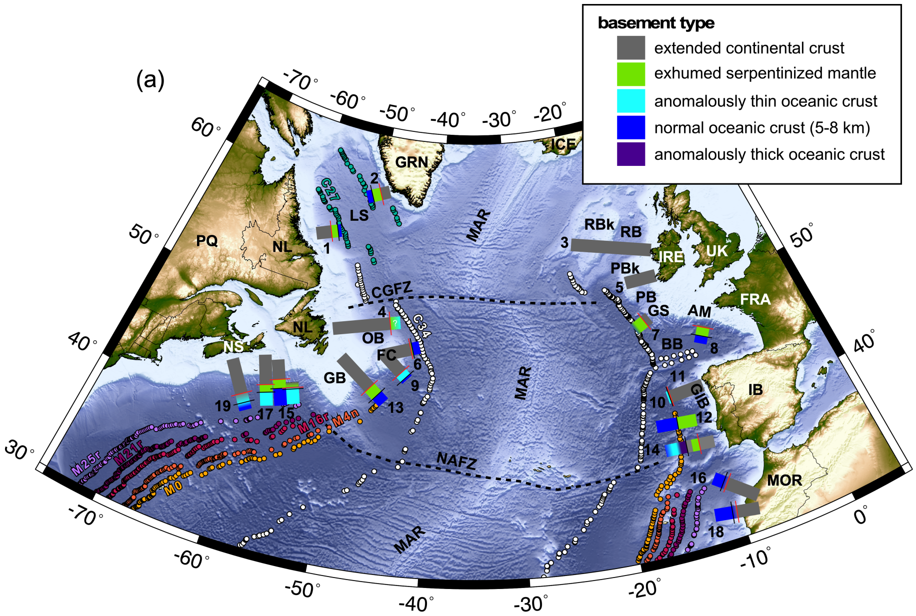

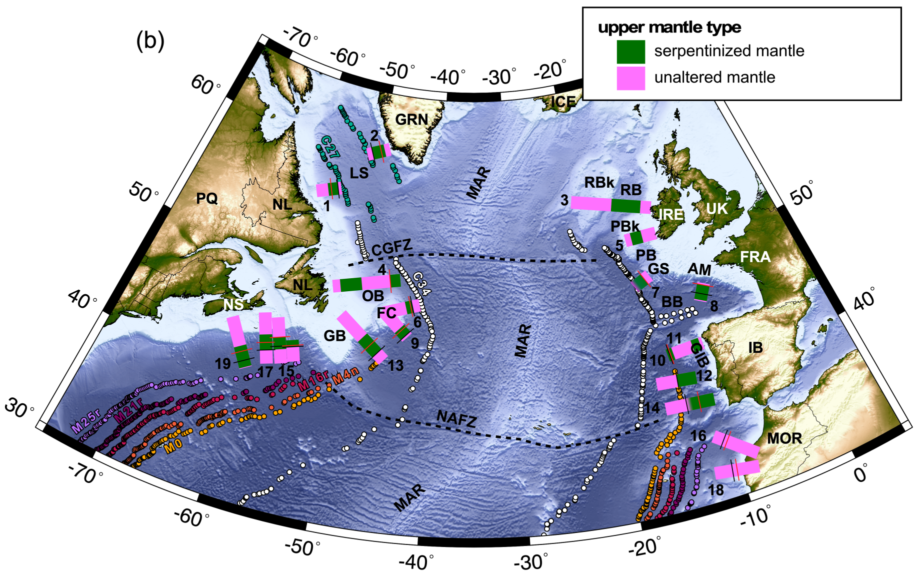

Figure 7. Topographic/bathymetric maps from ETOPO1 (Amante and Eakins, 2009) of the study area of the central and north Atlantic Ocean, with (a) showing the interpreted basement types summarized in this work, and (b) showing the interpreted upper mantle types summarized in this work. The numbered interpretations in both plots correspond to the seismic refraction/wide-angle reflection (RWAR) profiles described in Table 1. The solid red and black lines intersecting the interpreted polygons correspond to the ECC (edge of continental crust) and LaLOC (landward limit of oceanic crust) boundaries, respectively, highlighed in Figs. 2 to 6. Fracture zones are delimited by dashed black lines. Select magnetic chron anomalies from Seton et al. (2014) are plotted as coloured circles (M25r, M21r, M16r, M4n, M0, C34, C27) on both plots. Abbreviations: AM, Armorican Margin; BB, Bay of Biscay; CGFZ, Charlie-Gibbs Fracture Zone; FC, Flemish Cap; GB, Grand Banks; GIB, Galicia Interior Basin; GRN, Greenland; GS, Goban Spur; IB, Iberia; IRE, Ireland; LS, Labrador Sea; MAR, Mid-Atlantic Ridge; MOR, Morocco; NAFZ, Newfoundland-Azores Fracture Zone; NL, Newfoundland & Labrador; NS, Nova Scotia; OB, Orphan Basin; PB, Porcupine Basin; PBk, Porcupine Bank; RB, Rockall Basin; RBk, Rockall Bank; UK, United Kingdom.

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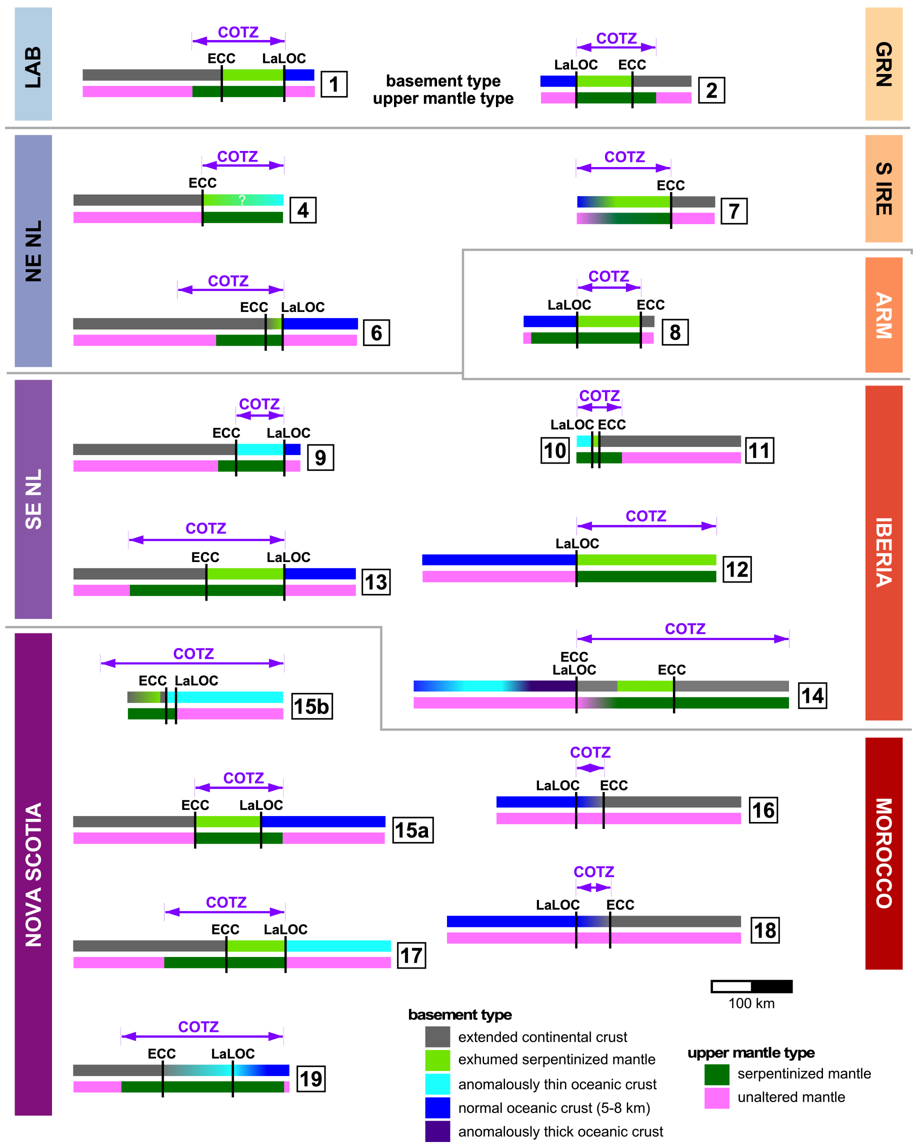

Figure 8. Summary diagram capturing the continent-ocean transition zone (COTZ) variations along the North American margins (left side; purple tone labels) and the European/Morrocan margins (right side; orange tone labels). Landward portions of some of the sections have been truncated to conserve space. Conjugate margin pairs are roughly delimited by the gray horizontal lines. Basement types are plotted above and upper mantle types are plotted below for each profile (labelled by the numbered squares). Abbreviations: ARM, Armorican Margin; ECC, edge of continental crust; GRN, Greenland; LaLOC, landward limit of oceanic crust; LAB, Labrador; NE NL, northeast Newfoundland; SE NL, southeast Newfoundland; S IRE, southern Ireland.

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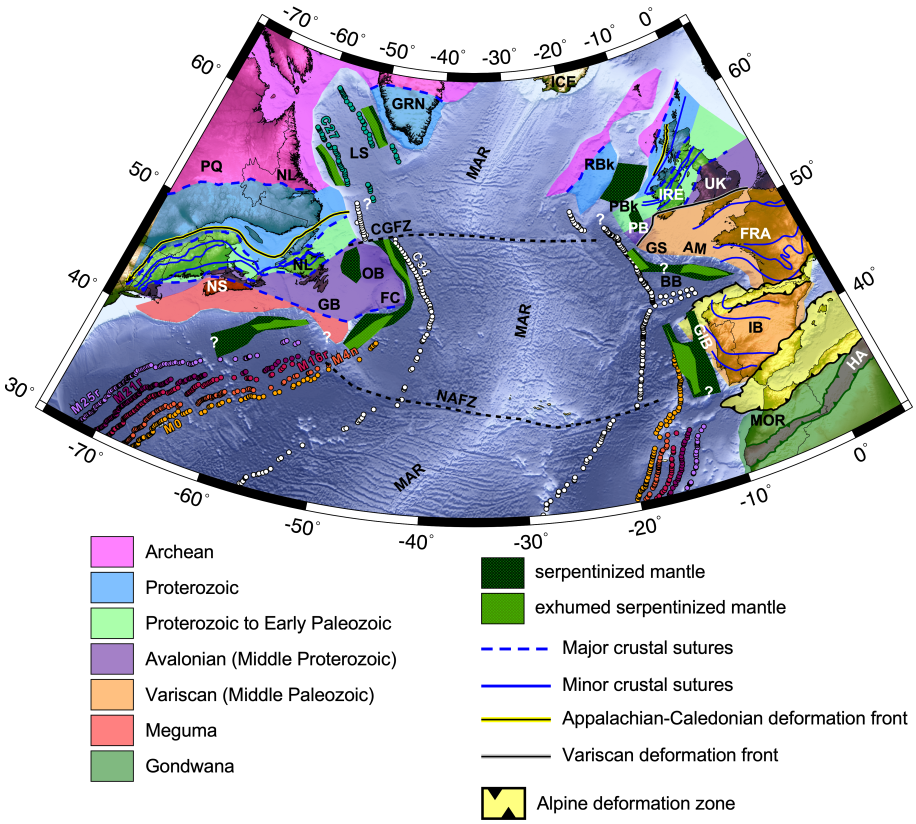

Figure 9. Topographic/bathymetric map from ETOPO1 (Amante and Eakins, 2009) of the study area of the southern North Atlantic Ocean subdivided by inferred basement affinity of continental crust, adapted from Jolivet et al. (2021), Tyrrell et al. (2007), Waldron et al. (2022), and Ziegler and Dèzes (2006). Interpreted extents of serpentinized mantle (hashed green polygons) with zones of exhumed serpentinized mantle (hashed light green polygons), extrapolated from Fig. 7, are overlain (areas marked with white question marks lack RWAR coverage). Fracture zones are delimited by dashed black lines. Select magnetic chron anomalies from Seton et al. (2014) are plotted as coloured circles (M25r, M21r, M16r, M4n, M0, C34, C27). Abbreviations: AM, Armorican Margin; BB, Bay of Biscay; CGFZ, Charlie-Gibbs Fracture Zone; FC, Flemish Cap; GB, Grand Banks; GIB, Galicia Interior Basin; GRN, Greenland; GS, Goban Spur; HA, High Atlas; IB, Iberia; IRE, Ireland; LS, Labrador Sea; MAR, Mid-Atlantic Ridge; MOR, Morocco; NAFZ, Newfoundland-Azores Fracture Zone; NL, Newfoundland & Labrador; NS, Nova Scotia; OB, Orphan Basin; PB, Porcupine Basin; PBk, Porcupine Bank; RB, Rockall Basin; RBk, Rockall Bank; UK, United Kingdom.

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Table 1. Labelled refraction lines in Fig. 1, the source of the velocity models presented herein, and how those models were derived (FMRT, forward model ray tracing; TTI, tomographic traveltime inversion; FWI, full waveform inversion).

Label no.	Survey line name	Citation	Source	Modelling type
1	90R1	Chian et al. (1995)	Digitized	FMRT
2	88R2	Chian and Louden (1994)	Digitized	FMRT
3	RAPIDS 1	Funck et al. (2017)	Digitized	FMRT
4	SIGNAL 1	Welford et al. (2020)	Original file	FMRT
5	P03	Prada et al. (2017)	Original file	TTI
6	FLAME 1	Gerlings et al. (2011)	Digitized	FMRT
7	-	Bullock and Minshull (2005)	Digitized	FMRT
8	Norgasis 14	Thinon et al. (2003)	Digitized	FMRT
9	SCREECH 1	Funck et al. (2003)	Original file	FMRT
10	-	Sibuet et al. (1995) and Druet et al. (2017)	Digitized	FMRT
11	-	Pérez-Gussinyé et al. (2003)	Digitized	FMRT
12	FRAME-p3	Grevemeyer et al. (2022)	Original file	TTI
13	SCREECH 3	Lau et al. (2006a)	Digitized	FMRT
14	FRAME-2	Merino et al. (2021)	Original file	TTI
15	OETR-2009	(a) Lau et al. (2018) and (b) Jian et al. (2021)	(a) Original file and (b) Digitized	(a) FMRT and (b) FWI
16	SISMAR 4	Contrucci et al. (2004)	Digitized	FMRT
17	SMART 1	Funck et al. (2004)	Digitized	FMRT
18	MIRROR 1	Biari et al. (2015)	Digitized	FMRT
19	SMART 2	Wu et al. (2006)	Digitized	FMRT

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Table 2. Labelled refraction lines in Fig. 1, width of exhumed serpentinized mantle zone, width of anomalous oceanic crust zone (thin or thick), width of sub-crustal serpentinized mantle zone, and width of full COTZ (as delimited in Figs. 2 to 6).

Label no.	Exhumed mantle	Anomalous oceanic crust	Sub-crustal serpentinized mantle	Interpreted COTZ
1	80 km	-	110 km (within COTZ)	115 km
2	70 km	-	100 km (within COTZ)	100 km
3	-	-	260 km (failed rift)	-
4	50 km ??	50 km ?? (thin)	210 km (failed rift) and 100 km (within COTZ)	100 km
5	-	-	100 km (failed rift)	-
6	20 km	-	80 km (within COTZ)	130 km
7	70 to 120 km	-	70 to 120 km (within COTZ)	120 km
8	80 km	-	130 km (within COTZ)	80 km
9	-	60 km	80 km (within COTZ)	60 km
10	10 km	20 km (thin)	55 km (within COTZ)	55 km
11	-	-	70 km (failed rift)	-
12	160 km	-	160 km (within COTZ)	160 km
13	95 km	-	190 km (within COTZ)	190 km
14	60 km	80 km (thin) and 60 km (thick)	230 km (within COTZ)	260 km
15a	40 km	140 km (thin)	60 km (within COTZ)	225 km
15b	80 km	-	110 km (within COTZ)	110 km
16	-	-	-	30 km
17	70 km	130 km (thin)	150 km (within COTZ)	150 km
18	-	-	-	40 km
19	-	80 km (thin)	200 km (within COTZ)	200 km