“CONJUGATE MARGINS” – AN OVERSIMPLIFICATION OF THE COMPLEX SOUTHERN NORTH ATLANTIC RIFT AND SPREADING SYSTEM?

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ABSTRACT

The prevalence of conjugate margin terminology and studies in the scientific literature is testimony to the contribution that this concept and approach has made to the study of passive margins, and more broadly extensional tectonics. However, when applied to the complex rift, transform and spreading system of the southern North Atlantic (i.e. the passive margins of Newfoundland, Labrador, Ireland, Iberia and southern Greenland), it becomes obvious that at these passive continental margin settings additional geological phenomena complicate this convenient description. These aspects include: 1) the preservation of relatively undeformed continental fragments, 2) formation of transform systems and oblique rifts, 3) triple junctions (with both rift and spreading-axes), 4) multiple failed rift axes, 5) post-breakup processes such as magmatism, 6) localised subduction, and 7) ambiguity in identification of oceanic isochrons. Comparison of different published reconstructions of the region show ambiguity in conducting conjugate margin studies. This demonstrates the need for a more pragmatic approach to the study of continental passive margin settings where a greater emphasis is placed on the inclusion of these possibly complicating features in palinspastic reconstructions, plate tectonic, and evolutionary models.

INTRODUCTION

Passive margins represent a first-order plate tectonic feature, formed as a result of rifting followed by continental breakup whereby new oceanic crust is produced at a spreading axis (Eldholm and Sundvor, 1979; Bradley, 2008). This process leaves a complex, and highly variable, transition from relatively undeformed continental crust, sometimes called the proximal zone/domain, through necking and possibly exhumed domains, to oceanic crust (Lundin et al., 2018; Nirrengarten et al., 2018; Peron-Pinvidic and Manatschal, 2019). Passive margins are structurally diverse, but are typically classified as either magma-rich or magma-poor, in reference to the volume of widespread rifting and breakup-related magmatism (Geoffroy, 2005; Franke, 2013; Guan et al., 2019).

Numerous tactics have been deployed to research passive margins, including a wide array of both geological and geophysical methodologies. However, irrespective of the individual methods used, one approach that has contributed significantly to our understanding of rift systems and passive margins is the notion of 'conjugate margins' (Wilson et al., 2001). A conjugate margin pair comprises two passive margins now located on different tectonic plates, separated by oceanic crust (including a spreading axis), that were once adjoined in the rift system that preceded breakup. Conjugate margin studies have been conducted globally, for example in the NE Atlantic (Skogseid and Eldholm, 1987; Kvarven et al., 2015; Gernigon et al., 2015, 2019), the southern North Atlantic (Welford et al., 2012; Sandoval et al., 2019), the Labrador Sea (Chian et al., 1995; Peace et al., 2016), the South Atlantic (Blaich et al., 2009), the Nova Scotia-Morocco margins (Tari et al., 2012; Louden et al., 2013), the South China Sea (Pichot et al., 2014; Song et al., 2019), the Gulf of Aden (Nonn et al., 2019), as well as Antarctica and its conjugates during the breakup of Gondwana (Williams et al., 2011; Veevers, 2012; Ball et al., 2013). Conjugate margin studies allow us to appreciate the large-scale structure of the rift system, and also to extrapolate concepts derived on one margin to its conjugate. This is useful in areas of limited data coverage where acquiring additional data may not be feasible.

At some geographical locations, near-orthogonal spreading, with minimal geological complications, makes it relatively easy to conduct conjugate margin studies. However, numerous complicating geological aspects often make such reconstructions problematic. In this article, we outline geological phenomena that introduce complications into conjugate margin studies, and thus palinspastic and plate tectonic reconstructions. We then test the influence of these aspects on the passive margins of the southern North Atlantic (i.e. the passive margins of

Newfoundland, Labrador, Ireland, Iberia and southern Greenland) (Figure 1), and relevant nearby regions, using published plate models for the region (Matthews et al., 2016; Nirrengarten et al., 2018). We find that conjugate margin studies are sometimes overly simplistic, ignoring aspects that could have significant implications for such models.

GEOLOGICAL SETTING

Opening of the North Atlantic Ocean represents one of the final stages of the dispersal of Pangaea (Frizon De Lamotte et al., 2015; Peace et al., 2019a). As such, the Atlantic Ocean is nearly entirely surrounded by passive continental margins, which effectively provides a continuous record from continental rifting to current oceanic accretion at the active Mid-Atlantic Ridge spreading centre (Nirrengarten et al., 2018) (Figure 1). This aspect makes it an ideal location to conduct this type of study. In addition, although conjugate margin studies have been conducted globally, the present study area was chosen as this region has been intensively studied, yet understanding of some principle aspects of the geodynamic evolution remain elusive (Hansen et al., 2009). For example, the rift/breakup kinematics and processes (Nirrengarten et al., 2018), the relationship between tectonics and magmatism (Hansen et al., 2009; Peace et al., 2019a), and regional structure (Foulger et al., 2019). Thus, a fundamental reappraisal of the conjugate margins approach that underpins much of the regional understanding is appropriate and timely.

The structure and evolution of many of the passive margins of the southern North Atlantic are known in detail from decades of work (Shannon et al., 1995; Hitchen, 2004; Naylor and Shannon, 2005; Tucholke et al., 2007; Sibuet et al., 2007a; Welford et al., 2012; Magee et al., 2014; Gouiza et al., 2015, 2016; Dafoe et al., 2017; Roberts et al., 2018; Sandoval et al., 2019). As a result, some of the best-studied passive margins are located in this region, such as the Grand Banks, offshore Newfoundland, and the Iberian margin (Eddy et al., 2017) (Figure

1). However, the region also contains less-well-studied margins such as the northern Newfoundland Margin (i.e. the Orphan Basin; Figures 1 and 2), parts of the Irish Margin (i.e. the Rockall and Porcupine basins) (Roberts et al., 2018), southern Greenland, and Labrador (Peace et al., 2016). Geological research in the region (Figure 1) has been driven by both the promising hydrocarbon prospectivity of the marginal basins (Enachescu, 2006; Schofield et al., 2018), and because this region represents an ideal area to study some of the fundamental aspects of tectonics, including the "Wilson Cycle" (Wilson, 1966; Thomas, 2006, 2018).

Despite the research focus on the margins of the southern North Atlantic, the mechanisms driving extensional deformation in the continental domains leading to the creation of new oceanic crust, and thus passive margins, remains a topic of considerable current research interest (Nirrengarten et al., 2018; Gouiza and Paton, 2019). Current areas of research in this area include, but are not limited to: 1) timing of spatially and temporally overlapping and interacting rifting events (Gouiza et al., 2015), 2) sediment distribution, provenance and facies (Tyrrell et al., 2007), 3) timing of structural development and its relationship with hydrocarbon prospectivity (Enachescu et al., 2004), 4) the role of pre-existing structures in controlling rift evolution and margin architecture (Doré et al., 1999), and 5) the causes and consequences of rift- and breakup-related magmatism (Keen et al., 2014; Peace et al., 2018c).

Opening of the North Atlantic

Prior to breakup, the proto-North Atlantic was an amalgamation of Archean and Proterozoic terranes (Kerr et al., 1996; St-Onge et al., 2009), with the structures in these pre-existing terranes known to have exerted considerable influence on rift evolution (Doré et al., 1997; Ady and Whittaker, 2018; Peace et al., 2018a, 2018b; Schiffer et al., 2018a; Heron et al., 2019).

Between the Devonian collapse of the Caledonian Orogeny and breakup in the Mesozoic-Cenozoic, the proto-North Atlantic region experienced numerous discrete and overlapping extensional episodes, which are documented in the stratigraphic record (Umpleby, 1979; Sinclair, 1995; Stoker et al., 2017). Regional extension possibly started in the Permian, with events documented throughout the Jurassic, Triassic and Cretaceous (Stoker et al., 2017), as well as contemporaneous rift-related magmatism also suggesting regional extension (Larsen et al., 2009; Peace et al., 2018c, 2019a).

Following these regional rifting events, propagation of the Central Atlantic into the proto-North Atlantic began in Early Aptian time, producing the oldest oceanic crust in the present study area (Lundin, 2002; Eddy et al., 2017). This is recorded as the M0 anomaly offshore Iberia and Newfoundland (Funck, 2003). Seafloor spreading is believed to have reached the Galicia Bank (Figure 1) by the late Aptian (Boillot and Malod, 1988), followed by the formation of the Bay of Biscay triple junction in the Late Aptian or Early Albian (Lundin, 2002). In the Bay of Biscay (Figure 1), following the accretion of oceanic crust, partial subduction beneath Iberia occurred from the latest Cretaceous to the Eocene due to the NW movement of Iberia, and in the process formed the Pyrenees (Boillot and Malod, 1988). From the Bay of Biscay triple junction, seafloor spreading propagated to the NW reaching the Goban Spur (Figure 1) in middle to late Albian time (Tate, 1993). Breakup reached the Charlie Gibbs Fracture Zone (CGFZ) by the Santonian, and significant extension had also occurred in the Rockall Basin (Figure 1) by this time (Shannon et al., 1994; Hitchen, 2004). However, interpretation of the early syn-rift evolution of the Rockall Basin is hindered by overlying igneous rocks making seismic imaging difficult (Magee et al., 2014; Schofield et al., 2018).

The NW Atlantic (i.e. the Labrador Sea (Figure 1) and the adjacent Baffin Bay to the north) was the next region to partially break up (Abdelmalak et al., 2018). The NW Atlantic formed via multiphase, divergent motion between Greenland and North America, resulting in oceanic crust in the Labrador Sea and Baffin Bay but not the Davis Strait (Chalmers and Pulvertaft, 2001; Hosseinpour et al., 2013; Peace et al., 2018b; Jauer et al., 2019). Estimates of breakup timing in the Labrador Sea (Figure 1) are variable depending on the interpretation of the earliest magnetic anomaly, ranging from approximately 62 to 80 Ma (Roest and Srivastava, 1989; Chalmers and Laursen, 1995; Srivastava and Roest, 1999; Keen et al., 2017).

During the Early Eocene, seafloor spreading began in the NE Atlantic (i.e. between SE Greenland and Rockall-Hatton Bank) (Figure 1) (Martinez et al., 2019) resulting in a major tectonic reorganisation across the whole North Atlantic region (Gaina et al., 2009). This resulted in a change in spreading direction in the Labrador Sea and Baffin Bay system, to a new orientation oblique to the earlier ridge system (Hosseinpour et al., 2013). The breakup of the NE Atlantic also produced a triple junction between the Labrador Sea, the NE Atlantic, and the southern North Atlantic, which was active until spreading ceased in the Labrador Sea in the earliest Oligocene (Srivastava and Roest, 1999). As a result, Greenland (Figure 1) became part of the North American plate, causing the Labrador Sea spreading centre to be abandoned (Osler and Louden, 1992), whilst spreading has continued to present on the Mid-Atlantic Ridge (Martinez et al., 2019).

WHY ARE CONJUGATE MARGIN STUDIES USEFUL?

According to Romm (1994) the earliest dated recognition of the similarity, and suggestion of separation, between the coastlines of the Americas and Europe and Africa may have been in the Thesaurus Geographicus by Ortelius (1596). In effect, this early observation represents one of the first conjugate margin studies, and demonstrates the appeal of such observations. It is also clear through the early development of plate tectonics that observations on the now separate margins of the Atlantic Ocean (i.e. conjugate margin studies) provided crucial key lines of evidence (Bullard et al., 1965; Wilson, 1966).

Conjugate margin studies are useful for a number of reasons. The motivation behind using this concept to study passive margins is that in order to fully appreciate the “complete” rift, or plate separation, both sides must be included (Wilson et al., 2001). Through such studies globally, the large-scale structure of a rift system has been studied by numerous previous workers (Chian et al., 1995; Pichot et al., 2014; Kvarven et al., 2015; Peace et al., 2016). Such studies are useful because they reveal broad characteristics of rifting (Becker et al., 2014), such as rift asymmetry (Lister et al., 1986). These studies have shown that asymmetric rifts are common, with implications for exploration since structure, heat flow and thus hydrocarbon prospectivity vary between conjugate margins (Peace et al., 2016).

Another principle appeal of conjugate margin studies is that through reconstructing the margins into their pre-rift configuration we can extrapolate findings from one margin to its now separated partner (Sinclair, 1995; Sandoval et al., 2019). Moreover, understanding how currently separated rift-related basins may have once been linked or interacted is important for hydrocarbon exploration and production as it may allow explorers to find previously overlooked plays (Luheshi et al., 2012).

POSSIBLE COMPLICATING FEATURES IN CONJUGATE MARGIN STUDIES

Formation and evolution of the southern North Atlantic rift and spreading system was a complicated, multi-stage process (Hansen et al., 2009). Rifting and breakup were likely driven by numerous factors, with a strong influence of pre-existing structures, resulting in a structurally diverse region (Reston et al., 2004; O’Reilly et al., 2006; Sibuet et al., 2007a; Welford et al., 2012; Gouiza et al., 2015, 2016; Chen et al., 2018; Foulger et al., 2019). For example, in addition to the primary breakup axes, complex styles of deformation occurred on the continental margins of this region prior to, during, and after breakup, as well as other processes such as oceanic transform development, magmatism, and localised subduction that all may have contributed to making conjugate margin studies more difficult. Specifically, these aspects include:

1) The preservation of relatively undeformed continental fragments (e.g., the Flemish Cap (Figure 1) - Sibuet et al., 2007a; Peron-Pinvidic et al., 2010)
2) Formation of transform systems and also oblique rifts (e.g., the Charlie-Gibbs Fracture Zone (Figure 1) - Olivet et al., 1974)
3) Triple junctions (with both rift and spreading-axes) (e.g., the Bay of Biscay (Figure 1) - Sibuet and Collette, 1991)
4) Multiple failed rift axes (e.g., the Rockall Basin (Figure 1) - Roberts et al., 2018)
5) Post-breakup processes such as magmatism (Keen et al., 2014; Peace et al., 2017)
6) Localised subduction (Duarte et al., 2013) and
7) Ambiguity in the interpretation of geoscience data on conjugate margins. For example, different interpretations of the earliest oceanic crust age (Hosseinpour et al., 2013).

Schematic examples of how these factors may influence conjugate margin studies are shown in Figure 3, and suggestions for mitigating these potential issues are provided at the end of this article.

Many of these potential complicating factors are linked to one another, which might make identification of specific factors problematic. A related issue is that basins may display similar stratigraphy without actually being conjugate (Sandoval et al., 2019). As such, extra care must be taken when making stratigraphic correlations between candidate connected, or conjugate, basins. In the following sections, geological aspects of the southern North Atlantic passive margins are evaluated in detail for their potential to introduce complications into conjugate margin studies in the area.

Continental fragments

Numerous types of continental fragments have been recognised on passive margins and also stranded within the oceanic domain (Peron-Pinvidic and Manatschal, 2010). These include: microcontinents (e.g., Jan Mayen), continental ribbons (e.g., Flemish Cap and Porcupine Bank), outer highs (ODP-210-1277, Newfoundland Margin), and extensional allochthons (ODP 1069, Iberian Margin) (Peron-Pinvidic and Manatschal, 2010). Here, we use the term “continental fragment” to refer to any identifiable block of crust in a rift setting that has undergone less deformation relative to its present surroundings, but is larger than an individual fault block. This question of scale essentially refers to a block that is surrounded by rifts (or spreading centres) rather than a single graben. Although the aforementioned different types of continental fragments have distinct origins and structures, the preservation, and sometimes isolation of such entities is considered to be often highly controlled by structural inheritance (Schiffer et al., 2018b). Moreover, continental fragments have the potential to introduce complexities into conjugate margin studies for reasons that become apparent when considering the structural evolution of the present study area. The potential influence of independently rotating continental fragments is shown schematically in Fig. 3A1-A3, loosely based on the rotation of the Flemish Cap. Here, different starting positions for the rotating block are shown (Fig. 3A2 and A3) which could be hard to interpret given the post-breakup scenario (Fig. 3A1).

Varying degrees of internal deformation may occur within these fragments, again making conjugate margin studies problematic. On the margins of the southern North Atlantic for example, deformation may range from regions essentially devoid of any rift related deformation, to blocks that are only slightly less deformed than their surroundings. The Flemish

Cap, Porcupine Bank and Orphan Knoll (Figure 1) for example would all be reasonably classified as continental ribbons under the classification of Peron-Pinvidic et al. (2010). However, these blocks have undergone highly variable amounts of internal deformation (quantified by beta factors - Welford et al., 2012). This makes incorporating such features into models challenging, but necessary, for constructing more accurate and useful reconstructions of conjugate margins. The amount of extension across a rift system must be accounted for to make a valid full-fit reconstruction (Hosseinpour et al., 2013), which is difficult when deformation is highly variable, both spatially and temporally. A highly variable distribution of deformation is shown on the seismic reflection lines from across the Orphan Basin (Figure 2). Figure 2A shows the localisation of deformation into the East and West Orphan sub-basins, whilst Figure 2B shows the relatively undeformed Orphan Knoll compared to the surrounding rift.

The independent movement, and in particular rotation, of relatively coherent continental fragments within rift systems is a well-documented phenomenon (Sibuet et al., 2007a). As such, more recent plate tectonic models have sought to include separate poles of rotation for defined blocks of continental crust (Nirrengarten et al., 2018). However, developing such reconstructions is problematic, as constraints on the trajectories of continental fragments can be hard to obtain. The reason for this is because unlike in the oceanic domain where oceanic isochrons can be used for reconstructions (Hosseinpour et al., 2013; Matthews et al., 2016), constraints for the deformed continental domains have to be derived from proxies such as the age of syn-rift sediments and basin structure (Nirrengarten et al., 2018). This can often be complicated if the early syn-rift sediments are lacustrine or continental facies making age determinations difficult (Leleu et al., 2016). As such, a high level of ambiguity exists in reconstructing the past positions of continental fragments within rifts and passive margins. In addition, deriving poles of rotation for a coherent block (as in Nirrengarten et al., 2018) requires a hard boundary to be inferred around material that may have a diffuse structural relationship with its surroundings. While in some cases continental fragments may be defined by a discrete fault structure, this represents an uncommon or even unrealistic assumption. Overall, ambiguity in the nature, timing and amount of rotation of continental fragments can have significant implications for plate tectonic reconstructions of conjugate margins.

In the present study area, the amount of rotation that the Flemish Cap and Porcupine Bank (Figure 1) have undergone results in different aspects of these features being conjugate. In particular, the connected, or conjugate relationship between the East and West Orphan sub-basins on the Canadian margin and the Porcupine and Rockall basins on the Irish Margin (Figure 1) has been debated in previous work (Welford et al., 2012). Some interpretations suggest that the West Orphan Basin is more linked to the Rockall Basin, and East Orphan Basin to the Porcupine Basin (Figure 1). However, recent work suggests that East Orphan Basin may be more linked to the Rockall Basin, and that Porcupine Basin is in fact more comparable to the Galicia Bank (Nirrengarten et al., 2018; Sandoval et al., 2019) (Figure 1). This uncertainty partially arises from unclear past movements of the Flemish Cap, Orphan Knoll, Porcupine and Rockall/Hatton Bank (Figure 1) continental fragments. This relationship is explored later in this work through comparison of plate reconstructions.

Transforms, oblique rifting and spreading

Transforms are a common and integral part of many rift systems, often linking discrete structures (Basile, 2015; Farangitakis et al., 2019). The lateral movement of material in both rift and spreading systems can however complicate conjugate margin reconstructions, as often it is unclear just how much movement may have occurred on a transform-dominated, or oblique system. In addition, transform faults and systems can become particularly complex when the relative motion of the plates either side changes (Farangitakis et al., 2019), or a component of compression or extension is present, resulting in the development of transpressional and transtensional systems (Peace et al., 2018b). In addition to true transform faults and systems, it has been shown that the majority of rifts preceding conjugate margin formation can be considered to be oblique, lying on a spectrum between truly orthogonal rifts and transform-type margins (Brune et al., 2018). Spreading on mid-ocean ridges can also be oblique, and vary through the lifespan of a ridge, such as on the Reykjanes Ridge (Martinez et al., 2019), again complicating plate tectonic reconstructions, and conjugate margin studies. The potential influence of an oblique separation is shown schematically in Fig. 3B1-B3. Here, different starting positions for the candidate conjugate margins are shown (Fig. 3B2 and B3) which could be hard to interpret given the post-breakup scenario (Fig. 3B1). It may however be possible to use geophysical interpretation of oceanic fracture patterns to constrain oblique divergent plate movement, as shown by Phethean et al. (2016) for Madagascar's separation from Africa.

The present study area of the Canadian Margin and its conjugates is affected by a number of such features in both the continental and oceanic domains. For example, to the north of the primary study area, the Davis Strait between the Labrador Sea and Baffin Bay is a complex region of predominantly continental crust between the aforementioned small oceanic basins (Abdelmalak et al., 2018; Peace et al., 2018b; Heron et al., 2019; Jauer et al., 2019). Here, interaction of rift processes with pre-existing structures has resulted in a complex region containing widespread transpressional and transtensional structures (Wilson et al., 2006; Abdelmalak et al., 2012; Peace et al., 2018b), that present difficulties in reconstructions (Hosseinpour et al., 2013).

In the oceanic realm, the southern North Atlantic is also bisected by numerous structures presenting complications in reconstructing past plate motions, and thus conducting kinematic analyses. For example, the Charlie-Gibbs Fracture Zone (CGFZ, Figure 1) (Olivet et al., 1974) is a large-offset oceanic transform occurring near the intersection of the extinct Labrador Sea spreading axis and the main MAR (Fig. 1) that makes conjugate margin studies in the region more problematic. The CGFZ is interpreted to be related to the Iapetus suture (Buiter and Torsvik, 2014), again attesting to the role of structural inheritance in producing features that introduce complexities into conjugate margin studies.

Triple junctions

Triple junctions are a common feature of rifts and spreading systems (Sibuet and Collette, 1991; McClusky et al., 2010; Koptev et al., 2018). Although commonly thought of as the junction where three oceanic spreading ridges meet, we expand this definition to include junctions in rift systems, even if breakup was not achieved on any, or all limbs. Examples from the present study region include the North Sea, where the Moray Firth, South Viking and Central Grabens meet, forming a complex interaction between these rift systems (Davies et al., 1999), or where the Rockall Basin intersects oceanic crust produced at the main North Atlantic spreading centre (Shannon et al., 1999), and at the junction between the now extinct Labrador Sea spreading axis and the Mid-Atlantic Ridge (Srivastava, 1978). In the latter, this triple junction is further complicated by the presence of the CGFZ (Figure 1), as described above.

The potential influence of triple junctions is shown schematically in Fig. 3C1-C3. Here, different starting positions for the rotating block are shown (Fig. 3C2 and C3) which could be hard to interpret given the post-breakup scenario (Fig. 3C1). The reason that a triple junction has the potential to introduce complications into conjugate margin studies is that, at these locations, there is in essence more than one conjugate for a given margin segment (Figure 3). This can then be further complicated by oblique rifting and even transforms, leading to greater uncertainty.

Failed rifts and far-field deformation of proximal domains

A failed (or aborted/abandoned) rift is an area that underwent rifting but did not achieve breakup, and the production of new oceanic crust (Rattey and Hayward, 1993). Such features are common on passive margins where multiple rift axes often occur, before breakup is finally achieved, such as the Rockall Basin (Figure 1). Although originally interpreted as underlain by oceanic crust, most studies now conclude that the Rockall Basin is underlain by largely continental crust, albeit highly modified by the addition of igneous material (Magee et al., 2014). Another area where significant rifting occurred, but breakup did not, is the North Sea (Rattey and Hayward, 1993). In addition, regions of rifted continental crust lying between ocean basins can also present problems. To the north of the primary study area, an example of the latter is the Davis Strait, where previous work attempting a “full-fit reconstruction of the Labrador Sea and Baffin Bay” includes COBs despite such a boundary being unlikely in this region (Hosseinpour et al., 2013). The potential influence of intraplate deformation and failed rifts is shown schematically in Fig. 3D1-D3, loosely based on the opening of the Porcupine Basin. Here, the influence of including additional deformation (Fig. 3D2-D3) can be seen affecting the conjugate margins, which could be hard to interpret given the post-breakup scenario (Fig. 3A1).

Intraplate deformation is known to accompany rifting, with well documented deformation in the continental domains far from the loci of rifting during the opening of the Atlantic. This includes subtle intraplate deformation in Europe (Nielsen et al., 2007) and large-scale orogenesis such as the Eurekan Orogeny to the north of the present study area (Stephenson et al., 2013; Gion et al., 2017; Schiffer and Stephenson, 2017). The relevance of intraplate deformation to conjugate margin studies is that this deformation is not typically included in reconstructions that focus only on the oceanic domain (Peace et al., 2019b). Although inclusion of highly deformed domains remains a problem for traditional rigid plate tectonic models, it is being increasingly addressed by deformable plate models (Ady and Whittaker, 2018; Welford et al., 2018; Müller et al., 2019; Peace et al., 2019b).

Post-breakup processes

Post-separation, conjugate margins typically experience separate histories from one another. Thus, an appreciation of the margins as separate entities post-breakup is required when conducting conjugate margin studies. Comparison between conjugate margins may provide a means to decipher post-breakup processes; however, this requires careful interpretation and good temporal constraints. Some of the differences that margins experience post-breakup are ultimately controlled by the structures produced during the preceding rift phase, or earlier. For example, on the Labrador Sea conjugate margins, thicker post-rift deposits are documented on the Labrador Margin, compared to the Greenland Margin (Figure 1), which likely results from a combination of increased sediment supply on the Labrador side, as well as structural asymmetry inherited from an asymmetric rift (Peace et al., 2016). Post-breakup magmatism is a significant process that may influence one margin but not the other. This is significant because magmatism, such as overlying flood basalts, may prevent accurate interpretations of COTZs, hampering reconstructions, and thus hindering conjugate margin studies.

Subduction of oceanic crust

The conversion of passive to active margins is a key tenet of plate tectonic theory (i.e. the formation of subduction zones) (Hoffman, 2012; Heron, 2018). However, the mechanisms involved, and the nature of this transition, are relatively poorly understood. The Atlantic Ocean is nearly entirely surrounded by passive continental margins and is only locally affected by subduction zones (Duarte et al., 2013). This provides a near uninterrupted record from continental rifting to current oceanic accretion (Nirrengarten et al., 2018). Subduction of oceanic crust removes this record, making plate tectonic reconstructions of this material challenging, if not impossible. Recent work however has derived a methodology to interpret subducted slabs for plate reconstructions using seismic tomography (Wu and Suppe, 2018; Suppe and Wu, 2019).

However, in the southern North Atlantic, where spatial and temporal constraints are plentiful, of all the issues outlined herein, subduction has the least impact on conjugate margin studies. Elsewhere, where subduction is much more prevalent, it may drastically influence conjugate margin studies, and thus reconstructions.

Ambiguity in oceanic isochrons and continent-ocean transition zones

The concept of a simple, convenient linear boundary between continental and oceanic crust at passive continental margins, known as a COB (continent-ocean boundary), is recognised to be an oversimplification of a highly variable geological setting (Eagles et al., 2015). A COTZ (continent-ocean transition zone) may be a more appropriate concept in many locations as this transition is complicated by factors such as exhumation of mantle material and magmatic addition (such as overlying flood basalts which may prevent accurate interpretations of COTZs) (Franke, 2013).

A review of global COBs by Eagles et al. (2015) showed that the location of the COB is rarely consistently estimated between separate studies within the ~10–100 km uncertainty that might be expected from the geophysical data used. This demonstrates a significant potential source of uncertainty in the reconstruction of candidate conjugate margins. Despite this, COBs are often mapped because of their value in palinspastic and plate kinematic reconstructions mainly because they remain one of the best approaches to reconstructing past plate motions (Eagles et al., 2015; Matthews et al., 2016; Ady and Whittaker, 2018).

Beyond breakup anomalies, the interpretation of magnetic anomalies in the oceanic crust remains the principle method for reconstructing the past trajectories of plates for the Cenozoic and most of the Mesozoic (Seton et al., 2012; Matthews et al., 2016; Phethean et al., 2016). Prior to the Mesozoic however, due to the absence of large areas of preserved oceanic crust, geoscientists must primarily rely on palaeomagnetism to make such reconstructions (Buchan et al., 2000), which usually introduces greater ambiguity. The models described in this paper are primarily based on the interpretation of oceanic isochrons since minimal subduction has occurred in the southern North Atlantic (Duarte et al., 2013). However, for reconstructing older conjugate margins, poorer constraints on past plate kinematics could have a significant influence on resultant models.

Periods of magnetic quiescence (i.e. expanses of geological time when minimal reversals of the geomagnetic poles occurred) (Roots and Srivastava, 1984) may make interpretation of oceanic magnetic isochrons problematic, if not impossible. In addition, rifting and breakup magmatism can cause magnetic anomalies that may appear similar to those related to polarity reversals under steady-state seafloor spreading, as can serpentinization of exhumed mantle (Sibuet et al., 2007b). Ambiguity in the location of the first (oldest) oceanic crust also has the potential to hinder conjugate margin studies. For this reason, some work defines an "edge of continental crust"– ECC and a "last landward oceanic crust" – LaLOC (Nirrengarten et al., 2018).

COMPARISON OF PLATE TECTONIC RECONSTRUCTIONS

The role of the possible complicating factors outlined in the previous section on conjugate margin studies can be evaluated and observed through comparison of different plate tectonic reconstructions. Here, we use the GPlates software (version 2.2), an open-source plate tectonic reconstruction and modelling environment (Boyden et al., 2011; Cannon et al., 2014; Gurnis et al., 2018; Müller et al., 2018), to compare two published plate tectonic models (Matthews et al., 2016; Nirrengarten et al., 2018). Although various reconstructions of the North

Atlantic region exist (Roest and Srivastava, 1989; Gaina et al., 2009; Hosseinpour et al., 2013; Barnett-Moore et al., 2018), the fundamental difference between the two models compared here is that the Nirrengarten et al. (2018) models include independent plates for the Flemish Cap, Orphan Knoll, Porcupine Bank and Rockall-Hatton Bank (Figure 1), whereas the Matthews et al. (2016) model does not. This is not to imply either of these models is inferior, only that they fundamentally address different requirements. The Matthews et al. (2016) model is a global compilation, mostly using the Barnett-Moore et al. (2018) poles for the North Atlantic region, to produce a self-consistent global model. This is in contrast with the Nirrengarten et al. (2018) model, which is confined to the southern North Atlantic and includes continental fragments as separate plates. This difference allows us to investigate the implications for conjugate margin studies of including continental fragments in plate tectonic models. Through these reconstructions, we consider the reconstructed pre-rift locations of the undeformed domains, and in particular their inferred conjugate relationships.

No changes were made to the published versions of these models. Both of these models were designed with GPlates in mind, so each is provided with static polygons which were used to “cookie cut” the global crustal thickness model CRUST 1.0, which is a global compilation with a resolution of 1x1 degrees (Laske et al., 2013) (Figure 4). Although relatively coarse, this provides an appropriate background for the reconstruction, and location of the margin segments of interest.

Figure 5 shows selected time intervals in the southern North Atlantic reconstructions of Nirrengarten et al. (2018) and Matthews et al. (2016), allowing the potential conjugate relationships between the Orphan, Rockall and Porcupine Basins to be investigated. At 200 Ma in the Nirrengarten et al. (2018) reconstruction (Figure 5A1), the East Orphan Basin is conjugate to the Rockall Basin, whereas in the Matthews et al. (2016) (Fig. 5B1) model, East Orphan is closer to conjugate with the Porcupine Bank and Basin. This is also apparent at 135 Ma where in the Nirrengarten et al. (2018) reconstruction (Figure 5A2), the East Orphan Basin has now opened and is truly conjugate to Rockall, whereas in the Matthews et al. (2016) model (Figure 5B2) the Orphan Basin area is still conjugate to the Porcupine Bank and Basin area. By 83 Ma, the approximate breakup age between the Grand Banks and Iberia, a different scenario is apparent. In particular, in both the Nirrengarten et al. (2018) (Figure 5A3) and Matthews et al. (2016) (Figure 5B3) models, the West Orphan Basin is now conjugate to the Rockall Basin.

These reconstructions demonstrate how through the evolution of a complex rift system, such as the southern North Atlantic, different basins can be connected or conjugate at different times. The significant differences between these two models during earlier intervals, followed by more similarities later on in time, is principally caused by the inclusion or absence of rotating continental fragments and their spatio-temporal trajectories. The trajectories of these fragments result from many of the complicating factors previously outlined. Overall, the implications for conjugate margin studies of different reconstructions have consequences for determining which basins might be more related, which is important from a hydrocarbon exploration standpoint.

The reconstructions (Figure 5) also show how the influence of the different complicating factors, as outlined previously, is highly variable across the study area, as are the implications. Determining the conjugate of the Orphan Basin is a key problem. The relative timing of the opening of the East and West Orphan sub-basins used in the model drastically changes what will be conjugate, and when. By contrast, the Labrador Sea is relatively easy to reconstruct due to the limited amount of oceanic crust production, lack of major transforms, or oblique rifting and separation.

CONCLUDING REMARKS AND SUGGESTIONS FOR CONJUGATE MARGIN STUDIES

Conjugate margin studies have contributed greatly to the understanding of passive continental margins, particularly on the margins of the Atlantic Ocean, but also globally. However, determining exactly which margin segments are conjugate, and when they are conjugate, can be problematic and the influence of post-breakup processes can be significant. In this study, we have identified complicating factors to consider when conducting conjugate margin studies. These include: 1) the preservation of relatively undeformed continental fragments, 2) formation of transform systems and oblique rifts, 3) triple junctions (with both rift and spreading-axes), 4) multiple failed rift axes, 5) post-breakup processes such as magmatism, 6) localised subduction and, 7) ambiguity in identification of oceanic isochrons.

In some regions where complicating factors are absent, or are less influential over rift and margin architecture, conjugate margin studies may be easier to conduct, such as the Labrador Sea. Findings of this work are not limited to the passive margins of the southern North Atlantic as conjugate margins elsewhere are also influenced by the same, or similar, complicating factors. Given that, by many accounts, the margins of the southern North Atlantic represent the archetypical conjugate margins, additional complicating factors on passive margins are likely to be the norm rather than the exception. Hence, we make suggestions to assist reconstruction of candidate conjugate passive margins.

When appraising a complex area, such as the southern North Atlantic, considering multiple candidates as possible conjugates, and modelling multiple scenarios would be beneficial. In addition, the use of the term “connected basins”, rather than “conjugate basins” may be more appropriate in certain circumstances. For example, the currently debated relationship between the East and West Orphan sub-basins and the Rockall and Porcupine basins might be better described in these terms. However, the degree of connectivity in terms of sediment supply and source is a separate issue. We also suggest that the use of COTZs, or multiple different boundaries, rather than simple discrete linear COBs is more useful in reconstructions.

Many of the potential issues highlighted that may be encountered during the reconstruction of conjugate passive margins can be alleviated through the use of deformable plate tectonic models as opposed to the rigid-type shown herein. Deformable plate models allow us to incorporate the kinematics of “failed rifts” and pre-breakup deformation into reconstructions. In conclusion, a more 3-D approach to the study of rifts, including conjugate margins, generally is required, and could alleviate some of the issues outlined.

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Figure Caption

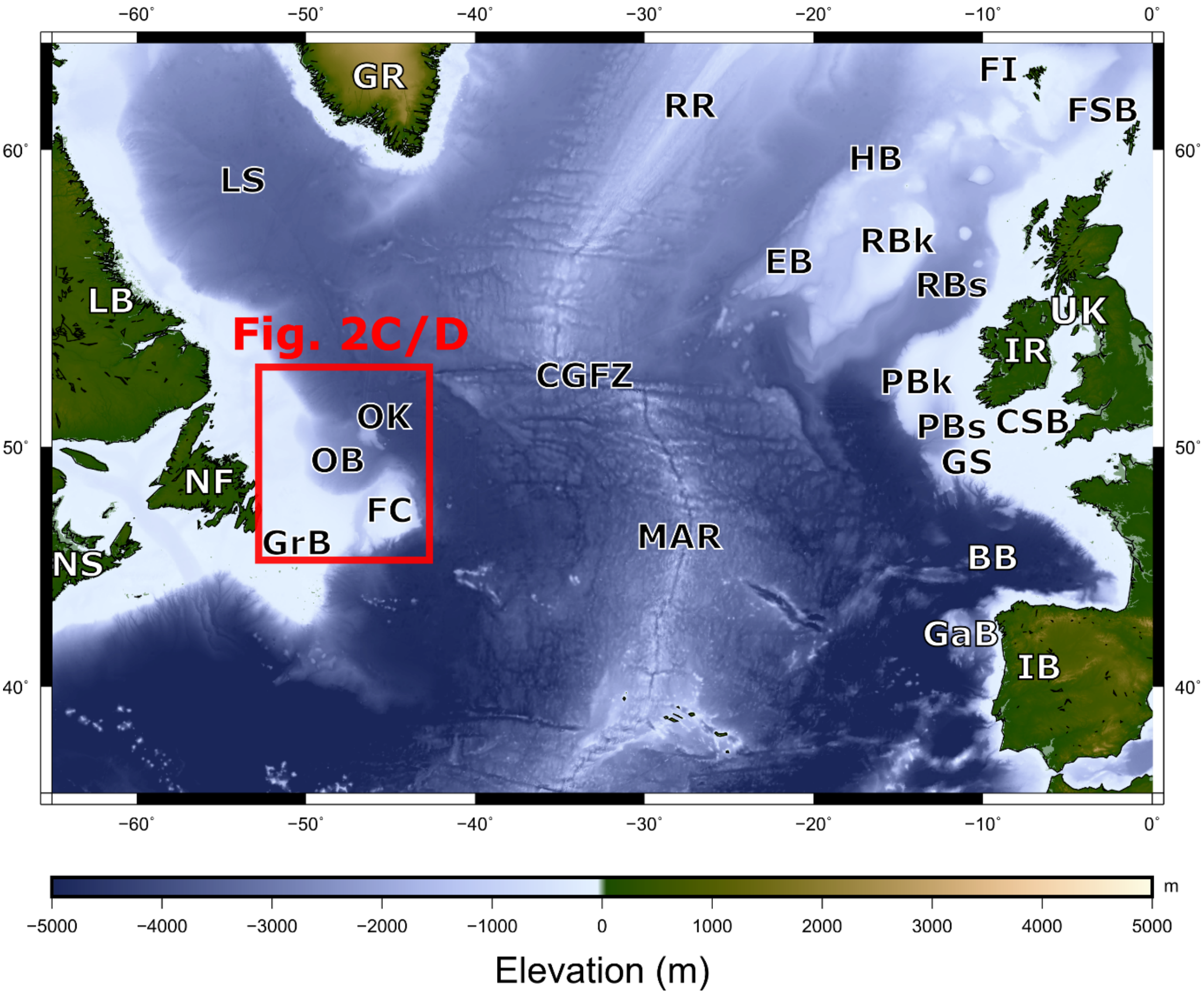

Figure 1 – Overview of the southern North Atlantic study area using the elevation data from Smith and Sandwell V18.1 (Smith and Sandwell, 1997). BB = Bay of Biscay, CGFZ = Charlie-Gibbs Fracture Zone, CSB = Celtic Sea Basin, EB = Edoras Bank, FC = Flemish Cap, FI = Faroe Islands, FSB = Faroe-Shetland Basin, GaB = Galicia Bank, GrB = Grand Banks, GR = Greenland, GS = Goban Spur, HB = Hatton Bank, IB = Iberia, IR = Ireland, LB = Labrador, LS = Labrador Sea, MAR = Mid-Atlantic Ridge, NF = Newfoundland, NS = Nova Scotia, OB = Orphan Basin, OK = Orphan Knoll, PBk = Porcupine Bank, PBs = Porcupine Basin, QB = Quebec, RBk = Rockall Bank, RBs = Rockall Basin, RR = Reykjanes Ridge, UK = United Kingdom

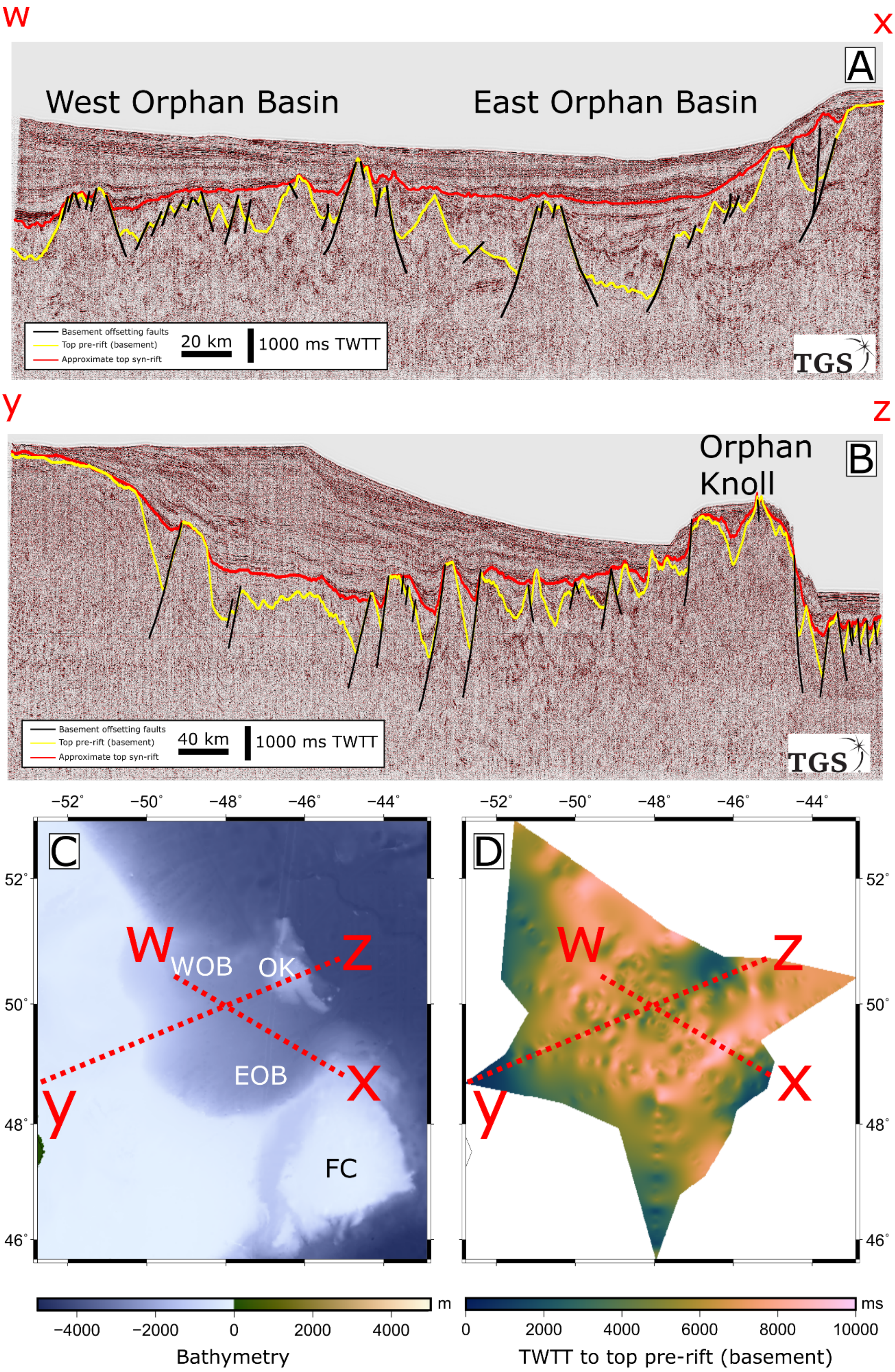
W
X
A
West Orphan Basin
East Orphan Basin
Basement offsetting faults
Top pre-rift (basement)
Approximate top syn-rift
20 km
1000 ms TWTT
TGS
Y
Z
B
Orphan Knoll
Basement offsetting faults
Top pre-rift (basement)
Approximate top syn-rift
40 km
1000 ms TWTT
TGS
C
−52˚
−50˚
−48˚
−46˚
−44˚
52˚
50˚
48˚
46˚
W
WOB
OK
Z
EOB
X
Y
FC
D
W
Z
X
Y
−4000
−2000
0
2000
4000
m
Bathymetry
0
2000
4000
6000
8000
10000
ms
TWTT to top pre-rift (basement)

Figure 2 – A) An approximately NE-SW seismic reflection profile through both the East and West Orphan sub-basins. B) An approximately NW-SE seismic reflection profile showing the large-scale structure of the Orphan Knoll. The seismic lines in both A) and B) are from the 2001 TGS survey, and the top pre-rift basement horizon is shown in yellow and the approximate top syn-rift horizon is shown in red. C) Bathymetry of the Orphan Basin (Smith and Sandwell V18.1) (Sandwell et al., 2014). D) Depth to basement (TWTT) interpreted from the TGS 2001 seismic survey in the Orphan Basin. We would like to acknowledge TGS for the provision of this data shown in this figure. EOB = East Orphan Basin, FC = Flemish Cap, OK = Orphan Knoll and, WOB = West Orphan Basin.

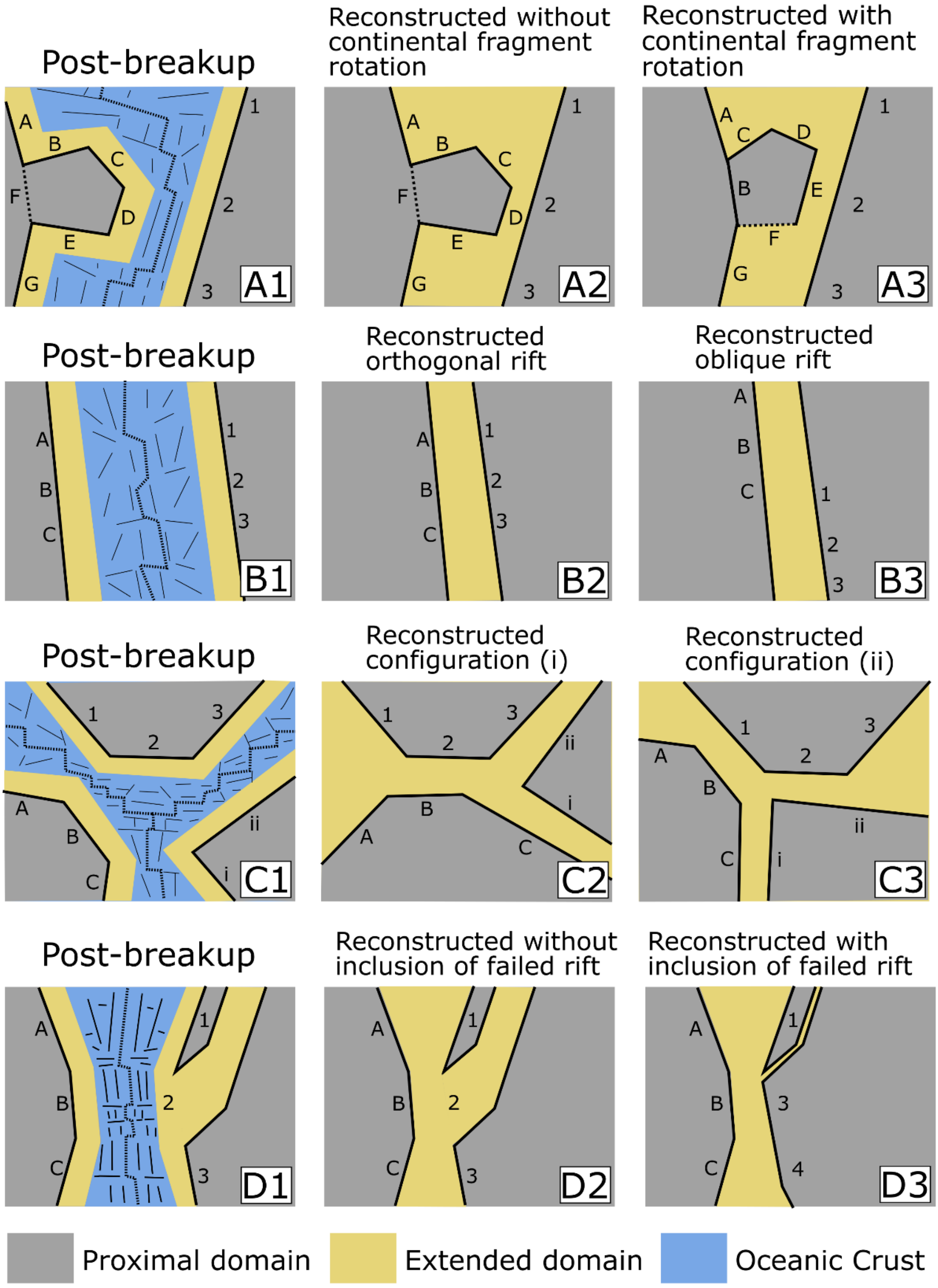

Figure 3 – Schematic diagrams of complications to conjugate margin studies that may occur generally but specifically in the North Atlantic.

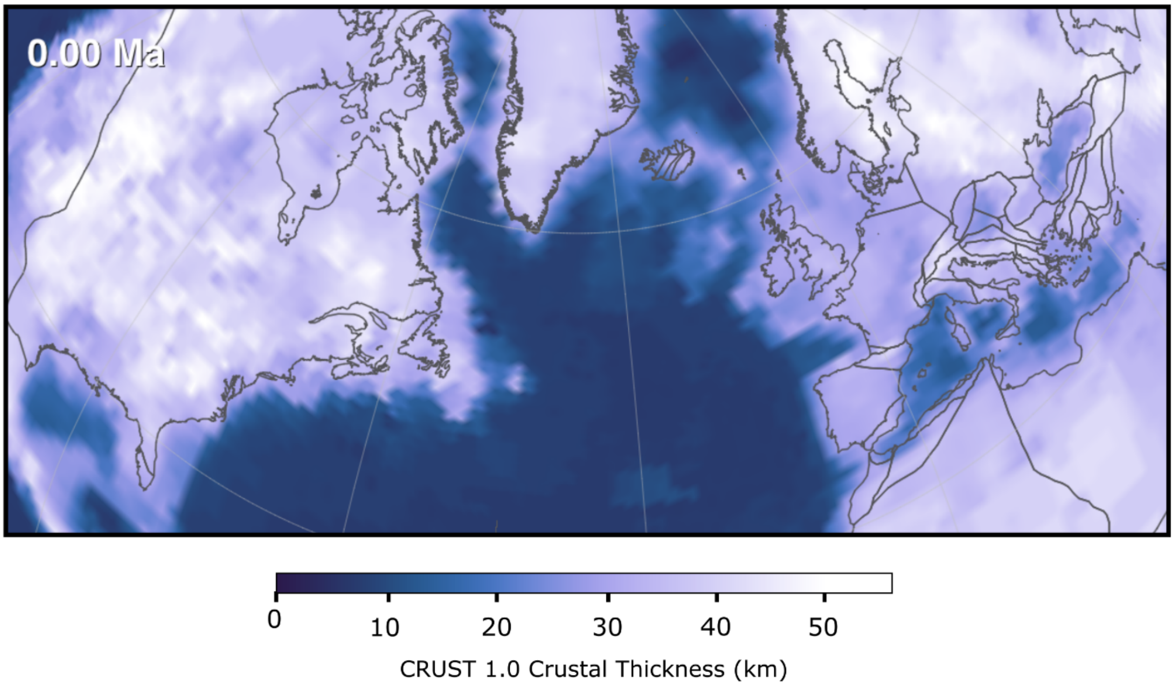

Figure 4 – Crustal thickness of the North Atlantic region from the CRUST 1.0 model (Laske et al., 2013) at present day (0 Ma), as used in the reconstructions shown in Figure 5.

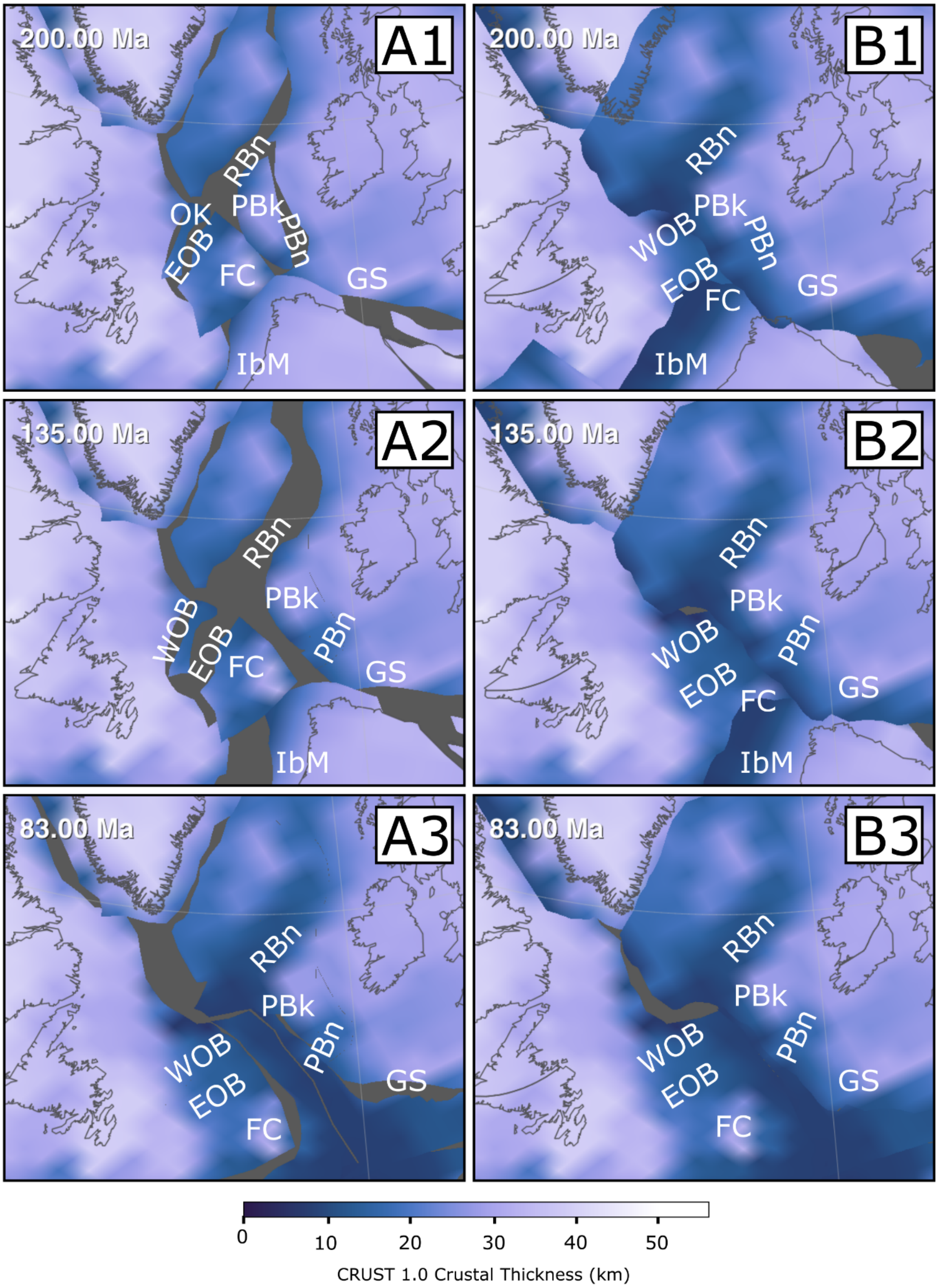

Figure 5 – Reconstructions of the southern North Atlantic using the models of Nirrengarten et al. (2018) (A1-3) and Matthews et al. (2016) (B1-3). For all reconstructions, Greenland is fixed and crustal thickness is the CRUST 1.0 model (Laske et al., 2013). EOB = East Orphan Basin,

FC = Flemish Cap, GS = Goban Spur, IbM = Iberian Margin, OK = Orphan Knoll, PBn = Porcupine Basin, PBk = Porcupine Bank, RBn = Rockall Basin, WOB = West Orphan Basin.