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# Seismic evaluation of the Flemish Cap and Goban Spur pre-rift relationship prior to the opening of the North Atlantic, with support from plate reconstruction

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**Abstract.** Recent geophysical investigations of the NE Newfoundland-Irish Atlantic rifted margin pair (North Atlantic) have called into question the previously assumed conjugate relationship and rift-perpendicular extension between the Flemish Cap and Goban Spur. In this study, we present multichannel seismic reflection profiles across the margins of the Flemish Cap, Porcupine Bank, and Goban Spur, and define their structural domains (proximal, necking, hyperextended, and/or exhumed mantle domains), which display varying degrees of asymmetry along strike. Observed intra-crustal reflectivity patterns are interpreted to be related to Paleozoic orogeny and/or orogenic collapse prior to the major Mesozoic rifting, consistent with this rift system having been strongly influenced by inherited Appalachian-Caledonian and Variscan structures. Reflective features within each structural domain are strikingly different across both margins, however similarities are most pronounced for the necking domains of the Porcupine Bank and Flemish Cap, which is consistent with a connection between the Porcupine Bank and Flemish Cap during Early Jurassic rifting. This inference is compatible with recently published deformable plate reconstruction models, which are used herein to relocate and reconstruct the representative seismic sections back through time to the onset of rifting. The changes of paleo-positions and geometric shapes of the seismic sections in deformable plate reconstruction models over time further show complicated 3D plate kinematics for the NE Newfoundland-Porcupine Atlantic margins, highlighting interplay of inherited structures, oblique extension, and poly-phase margin evolution between the Porcupine Bank, Goban Spur, and Flemish Cap and their intervening rift basins during the southern North Atlantic opening.

## 1 Introduction

The Goban Spur-Porcupine Bank region, offshore Ireland, represents an important segment of the North Atlantic rift system, as it involved interactions with both the Iberian and Newfoundland margins (Chenin et al., 2015; Nirrengarten et al., 2018; Sandoval et al., 2019) (Fig. 1). The Flemish Cap-Orphan Basin region along the Newfoundland margin and the Goban Spur-Porcupine Bank region along the Irish Atlantic margin are delimited by the Appalachian Orogenic Front to the north and the Variscan Front to the south (Fig. 1). Continental fragments are common along each margin (e.g., Flemish Cap, Porcupine Bank) and their intervening rift basins (e.g., Porcupine Basin and Orphan Basin) developed within the crustal terranes that formed from the collisional events associated with the Appalachian-Caledonian and Variscan orogenies (van Staal et al., 2009; van Staal and Barr, 2012; Willner

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et al., 2018; Schiffer et al., 2020; White and Waldron, 2022). These orogenic terranes were subsequently affected by three rifting stages: 1) Tethys rifting during the Late Triassic to Early Jurassic; 2) North Atlantic rifting during the Late Jurassic to Early Cretaceous; and 3) Labrador Sea rifting during the earliest Cretaceous (Berriasian?) to Albian (Enachescu, 2006; Štolfová and Shannon, 2009; Skogseid, 2010; Shannon, 2018).

The Goban Spur margin is generally thought to be the conjugate margin to the NE Flemish Cap (Fig. 1) (Masson and Miles, 1986; Srivastava and Verhoef, 1992; Seton et al., 2012; Matthew et al., 2016). Based on this assumption, Keen et al. (1989) favored pure shear rifting and an asymmetric lithospheric rupture, accompanied by a narrow necking zone across the NE Flemish Cap-Goban Spur conjugate margins. This interpretation relied on seismic line L85-3 on the Flemish Cap and the Western Approaches Margin (WAM) profile on the Goban Spur from Peddy et al. (1989), despite poor imaging of basement structures along the two vintage seismic profiles (Fig. 1). Gerlings et al. (2012) argued for asymmetric deformation occurring during each stage of the rift evolution of the conjugate margins based on combining seismic refraction velocity models (Gerlings et al. (2011); Bullock and Minshull (2005)) with the same 2D vintage seismic reflection data as used by Keen et al. (1989). The 2D asymmetric evolution was necessary to explain the pronounced differences in the modelled velocity structures and the imaged reflectivity patterns, if the widely accepted “conjugate” relationship between the two margins was left unchallenged.

It has been demonstrated from plate reconstructions that most segments of the North Atlantic hyperextended rift system involved moderate to high obliquity extension during the Mesozoic (Brune et al., 2018). For the Flemish Cap-Porcupine Atlantic margins, such oblique extension, coupled with inherited pre-rift heterogeneity (Chenin et al., 2015; Schiffer et al., 2020), would have resulted in complex 3D stress fields, rendering previously simplified 2D numerical models and 2D seismic profile comparisons less tenable. The rotation and displacement of the Flemish Cap with respect to the Orphan Basin during the Mesozoic, as demonstrated using potential field data (Sibuet et al., 2007; Welford et al., 2012), seismic reflection data (Welford et al., 2010a), and 3D geodynamic modelling (Neuharth et al., 2021), would have amplified this effect. Correspondingly, both rigid and deformable plate reconstruction models of the region that incorporate the rotation of the Flemish Cap (Nirrengarten et al., 2018; Peace et al., 2019; Yang et al., 2021; Yang and Welford, 2022; King and Welford, 2022a; 2022b), argue against the linkage between the Goban Spur and Flemish Cap, supporting instead the connectivity between the Flemish Cap and the Porcupine Bank prior to rifting. These plate models, however, mainly stem from potential field data analysis, lacking regionally-consistent seismic evidence that captures rift evolution across both margins.

In this study, we describe and interpret newly acquired deep penetrating seismic reflection profiles on the Flemish Cap margin (provided by TGS and PGS), as well as seismic profiles on the Porcupine Atlantic region (provided by the Department of Communications, Climate Action & Environment of Ireland) (Figs. 1b and 1c). Our interpretations allow for construction of a detailed crustal architecture map that captures the proximal, necking, hyperextended, exhumed, and oceanic domains from the continent to the ocean on both margins. The mapped domain distributions emphasize the structural complexity between the NE Flemish Cap and Goban Spur margins from a regionally-constrained seismic viewpoint. Using published plate reconstruction models of the Newfoundland-Irish Atlantic margin pair, the 2D seismic transects are reconstructed back to their pre-drift locations, enhancing our

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understanding of the 3D tectonic evolution between the Flemish Cap and Goban Spur margins, as well as revealing the challenges for plate restoration of this margin pair.

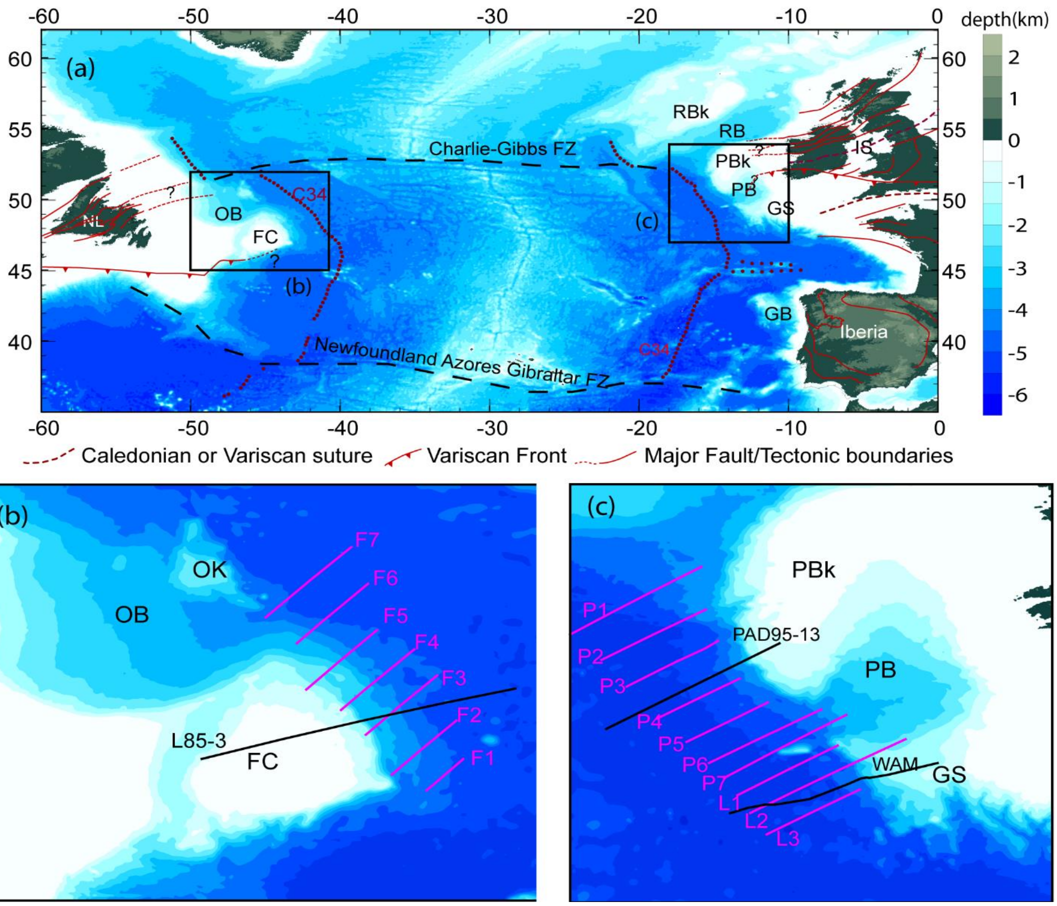


**Figure 1: (a) The bathymetry of the southern North Atlantic region. The Caledonian and Variscan major fault zones and crustal sutures are compiled from van Staal et al. (2009), van Staal and Barr (2012), Willner et al. (2018), and White and Waldron (2022). The round-dotted lines (red) show magnetic anomaly 34 (C34) (Müller et al., 2016). (b) The pink lines indicate seismic reflection lines (F1-F7) on the Flemish Cap margin, acquired in 2013, provided by TGS and PGS. The black line indicates vintage seismic profile L85-3 (Keen et al., 1989), the oceanward part of which is coincident with the seismic refraction FLAME line (Gerlings et al., 2011). (c) The pink lines indicate seismic reflection lines (P1-P7 and L1-L3) on the Porcupine Atlantic margin, acquired in 2013 and 2014, and provided by the Department of Communications, Climate Action & Environment of Ireland. The black lines show seismic line PAD95-13 on the Porcupine Bank and the Western Approaches Margin (WAM) line (Peddy et al., 1989), part of which is coincident with the seismic refraction line (Bullock and Minshull, 2005). Abbreviations: FC, Flemish Cap; FZ, Fracture Zone; GB, Galicia Bank; GS, Goban Spur; IS, Iapetus Suture; NL, Newfoundland and Labrador; PBk, Porcupine Bank; PB, Porcupine Basin; OB, Orphan Basin; RB, Rockall Basin; RBk, Rockall Bank.**

## 2 Crustal architecture across the Flemish Cap-Goban Spur-Porcupine Bank

The structural domains (including proximal, necking, hyperextended, exhumed and oceanic domains) along regional 2D multi-channel seismic reflection profiles across the Flemish Cap and Goban Spur-Porcupine Bank region were

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interpreted in either the time or depth domain by Welford et al. (2010a; 2010b), Yang et al. (2020), and Yang and Welford (2021; 2023), generating crustal architectural maps on both the Newfoundland and Irish sides, independently. Structural domain interpretation along each seismic line is based on the classification system of rift domains by Peron-Pinvidic et al. (2013), with detailed interpretations of select segments of the margins appearing in previous work (Yang et al. (2020); Yang and Welford (2021; 2023)). Briefly, there is minor extension and limited changes in Moho depth in the proximal domain with normal faults rooting at mid-crustal levels. The necking domain is characterized by dramatic crustal thinning and wedged-shaped basins bounded by extensional faults (Peron-Pinvidic and Manatschal, 2009). The top basement in the hyperextended domain is often offset by normal faults in a relatively regular way, whereas the top basement generally is characterized by a rough relief in the exhumed domain, probably associated with the presence of serpentinized peridotite ridges (Gillard et al., 2019). The top basement and Moho horizons are generally horizontal in the oceanic domain.

In this study, the interpreted crustal architecture distributions on the Irish Atlantic margin (Yang and Welford, 2021) and the Flemish Cap-Orphan Basin region (Yang and Welford, 2023), based predominantly on seismic reflection constraints, are reconstructed back to the Late Cretaceous (~ 83 Ma) and rejoined, as shown in Figure 2. In order to ensure the consistency of the seismic interpretations over both margins, four representative seismic lines that extend from the continental slope, through the extended continental crust, and into the oceanic domain are compared in the time domain (Fig. 3), including lines F3 and F5 on the Flemish Cap, PAD95-13 on the Porcupine Bank and L2 on the Goban Spur (Fig. 1). It should be noted that although the pink seismic lines are newly acquired, generating higher quality subsurface images than previously available (Yang and Welford, 2021), the acquisition designs themselves unfortunately failed to extend further landward into stretched continental crust. Due to the spatial coverage limitations of the new data on the Irish margin, the vintage seismic line PAD 95-13 on the Porcupine Bank is chosen to compare with the other three seismic lines as it is the only line that extends sufficiently landward (Fig. 3).

Similar to the Iberia-Newfoundland magma-poor passive margins (Tugend et al., 2014; Druet et al., 2018), the Newfoundland-Porcupine Atlantic margins also exhibit a gradual proximal-to-oceanic transitional region consisting of highly thinned continental crust and a zone of exhumed serpentinized mantle (Fig. 2). The geometries of each crustal domain from continent to ocean vary significantly on both sides. First, the necking domains for the Flemish Cap and Porcupine Bank are much narrower than that of the Goban Spur region based on the interpreted seismic data. This finding is consistent with crustal thickness variations from gravity inversion (Welford et al., 2012), which show the crust thinning from 18 km to 2 km over a distance of ~ 35 - 40 km on the Newfoundland margin and Porcupine Bank, while there is a more gradual crustal thickness gradient for the Goban Spur. The interpreted hyperextended domain is wider outboard of the Flemish Cap margin than for the Goban Spur-Porcupine Bank region. This hyperextended zone extends from, and is continuous with, the massive Orphan Basin to the northwest, which is interpreted to be underlain by hyperextended crust (Welford et al., 2020). The only departures from this pattern in the Orphan Basin correspond to the Orphan High and the Orphan Knoll, which have moderately thicker crust based on gravity inversion (Welford et al., 2012). The exhumed mantle domain across these margins remains undrilled and is interpreted based on basement seismic character and limited seismic refraction modelling (Bullock

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& Minshull, 2005; Gerlings et al., 2011). Nonetheless, the exhumed mantle zone appears wider on the Irish Atlantic side than on the Newfoundland side, with both zones ultimately pinching out to the north, with only localized evidence for mantle exhumation in the Orphan Basin (Welford et al., 2012) and the Porcupine Basin (Prada et al., 2017; Whiting et al., 2021).

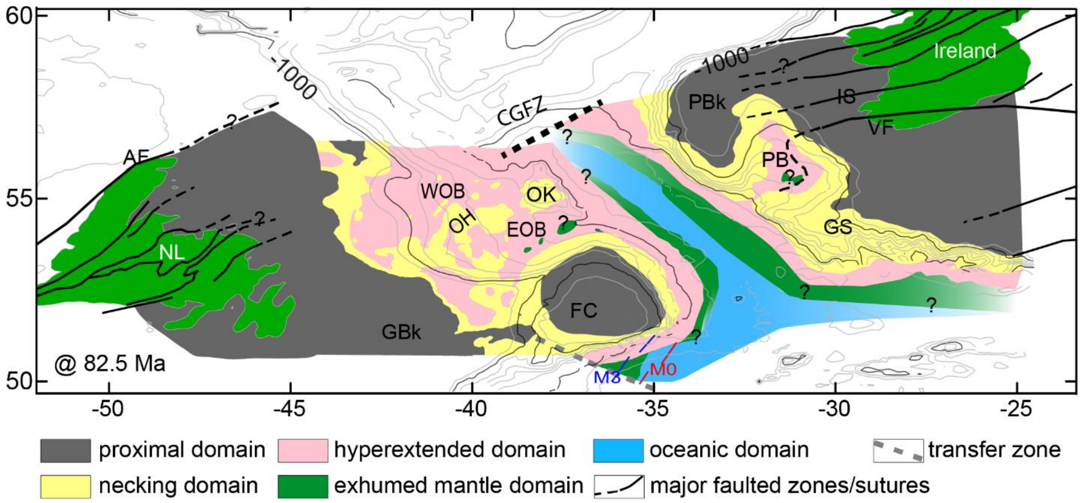


**Figure 2: Crustal architecture of the Porcupine Atlantic and Flemish Cap-Orphan Basin regions, reconstructed back to the Early Campanian based on a plate reconstruction model proposed by Nirrengarten et al. (2018), which is underlain by the present-day bathymetric contours replotted at ~ 82.5 Ma (shown by the thin grey lines). The crustal architectures on the Irish Atlantic and Newfoundland margins are, respectively, delineated based on seismic reflection datasets shown in Figure 1 (Yang and Welford, 2021; 2023). The Caledonian and Variscan major fault zones and crustal sutures are compiled from the following work: van Staal et al. (2009), van Staal and Barr (2012), Willner et al. (2018), White and Waldron (2022). Abbreviations: AF, Appalachian Front; CGFZ, Charlie-Gibbs Fracture Zone; EOB, East Orphan Basin; FC, Flemish Cap; GBk, Grand Banks; GS, Goban Spur; IS, Iapetus Suture; NL, Newfoundland; OH, Orphan High; OK, Orphan Knoll; PB, Porcupine Basin; PBk, Porcupine Bank; VF, Variscan Front; WOB, West Orphan Basin.**

From the four seismic lines (Fig. 3), it is clear that the top acoustic basement displays highly variable seismic facies along the NE Newfoundland-Porcupine Atlantic margins. In some places, the top of the basement is difficult to identify, while in other places it can be characterized by well-defined high-amplitude reflectors, marking a sharp impedance contrast between the overlying sediments and underlying crustal rocks. Within the sedimentary sequences, the syn-rift mega-sequences (pink polygons in Fig. 3) are predominantly controlled by normal faults that mainly developed during the Triassic/Jurassic and Early Cretaceous extension (Yang et al., 2021; Yang and Welford, 2023). These packages exhibit significant thickness variations both along strike and across both margins.

The proximal domain is not well imaged by these seismic transects but the displayed seismic lines do capture the seaward portions of the necking domains, indicated by the deepening of the top basement and shallowing of the interpreted Moho (see the dashed pink line along F3 and F5 in Figure 3). In contrast, the necking zone along L2 on the Goban Spur is highly faulted and spans a longer distance (Fig. 3), with more gradual crustal thinning based on gravity inversion (Welford et al., 2012). Curiously, for the Flemish Cap necking domain, continent-ward dipping

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normal faults bounding tilted blocks are observed to detach in the mid-crust along line F5, in contrast with the dominant seaward dipping normal faults along all of the other seismic profiles (Fig. 3). The reflectors below the top basement are chaotic in the transition from the necking zone to the hyperextension zone along F3 and F5 (see Figure 3). In comparison, there are not many visible reflectors on the seismic sections along PAD 95-13 and L2 over the Porcupine Atlantic region (see the enlargements of dashed blue rectangles along both lines in Figure 3). In the hyperextended domain, reflectivity patterns of the top basement are variable from one line to another on both sides, spanning variable distances. The interpreted exhumed mantle domains span a relatively longer distance along L2 and F3 than along F5 and PAD95-13. Finally, in the oceanic domain, the volcanic basement outboard of each margin displays highly variable relief as well. Of note, although seismic character of the top basement along these sections is variable, there are still some similarities regarding the sub-basins within necking zones along lines F3 and PAD 95-13 (see the geometry delimited by the dashed green lines in the enlargements in Figure 3).

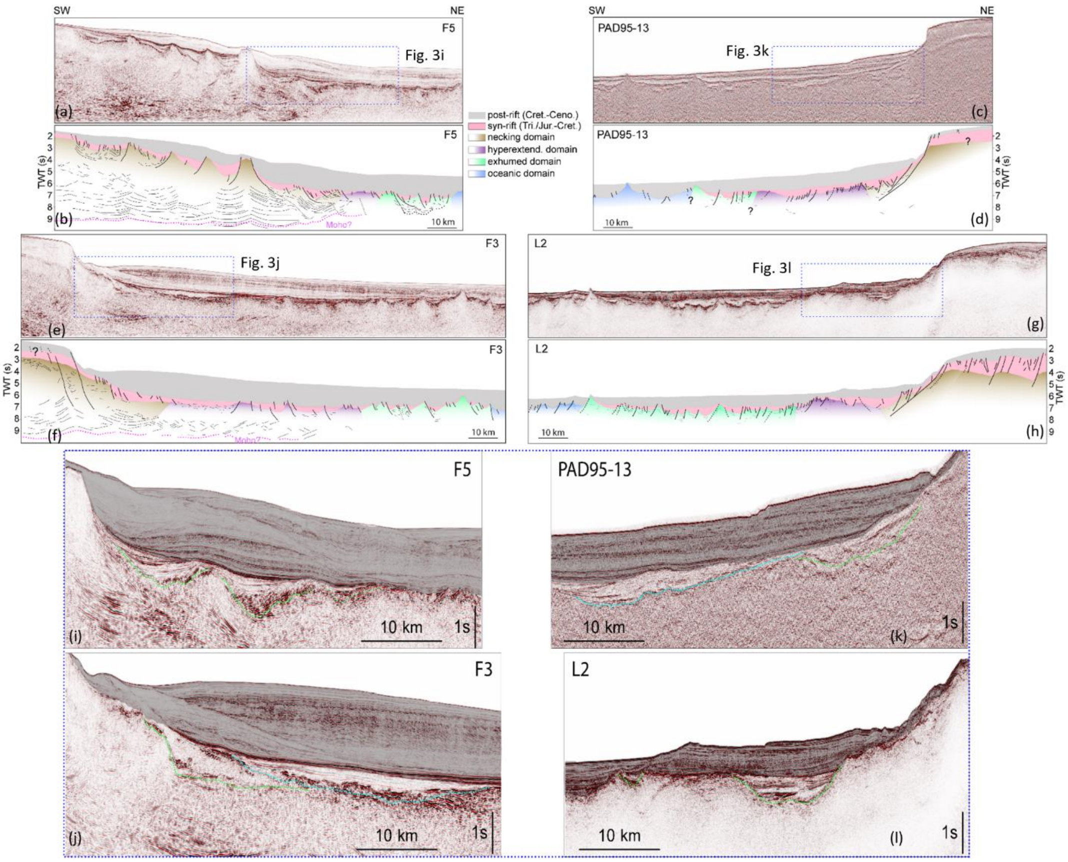


**Figure 3: Comparison of uninterpreted and interpreted seismic sections in the time domain over the Flemish Cap (Lines F3 and F5) and the Irish Atlantic margin (PAD95-13 modified from Yang et al. (2021), Line L2 from Yang et al. (2020)). Enlargements of sections F5, F3, L2, and PAD95-13 are also shown in the lower panel, outlined by the dashed blue rectangles, and the uninterpreted sections are shown in the supplementary file.**

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## 3 Margin transects reconstructed back in time based on plate reconstruction models

The striking differences in basement relief, geometry and thickness of sedimentary layers within each crustal domain, and in the overall crustal architecture from seismic profiles along both the Newfoundland and Irish Atlantic margins, challenge the previous conjugate relationship between the Flemish Cap and the Goban Spur (Figs. 2 and 3). Several global and regional plate reconstruction models have detailed how the Porcupine Bank, Goban Spur, and Flemish Cap interacted, evolved, and finally achieved crustal breakup (Matthews et al., 2016; Müller et al., 2018; Nirrengarten et al., 2018; Barnett-Moore et al., 2018; Peace et al., 2019; Yang et al., 2021; King and Welford, 2022a; 2022b). However, the kinematics of these continental fragments over time still varies for different plate reconstruction models due to their respective assumptions and simplifications. Recently, published regional plate modelling studies have concluded that the Flemish Cap and Goban Spur were not conjugate margins prior to the opening of the modern North Atlantic Ocean (Peace et al., 2019; Yang et al., 2021; King and Welford, 2022a; 2022b). Based on this understanding, in this study, seismic transects are reconstructed and relocated back through geologic time using two deformable plate reconstruction models, to see which seismic line pairs likely captured conjugate structures at different geologic times during the rift evolution (Fig. 4). In addition to relocating the seismic transects, the deformable plate reconstruction models for the southern North Atlantic region allow for crustal thicknesses to be reconstructed as well. Since lines F3 and F5 over the Flemish Cap and lines PAD95-13 and L2 over the Irish Atlantic margin (Figs. 1b and 3) extend further towards the proximal and necking domains than the totality of lines used to define the crustal architectures (Yang et al., 2020; Yang and Welford, 2021; 2023), these four lines are selected to be reconstructed within the plate models (Fig. 4).

Although there have been numerous global and regional plate models established for the southern North Atlantic realm (Matthews et al., 2016; Müller et al., 2018; Nirrengarten et al., 2018; Barnett-Moore et al., 2018; Peace et al., 2019), herein, the deformable plate model from Yang and Welford (2022) based on the work of Peace et al. (2019) is chosen to simulate the changes in crustal thickness and locations of seismic transects throughout geologic time. This model not only incorporates the rotation of both the Flemish Cap and Porcupine Bank margins, but also considers segmentation of the Porcupine Bank based on Caledonian inherited sutures and fault zones, as well as crustal-scale faults within the continental crust of the Goban Spur (Yang and Welford (2022)). The reconstruction begins at 200 Ma with a constant crustal thickness and the model is established based on the assumption that the continental blocks themselves (e.g., the Flemish Cap and Porcupine Bank) are rigid and the crustal thicknesses within their defined polygons remain constant during the entire model simulation (see the left column of Figure 4). Correspondingly, the seismic transects are assumed to be rigid lines and remain unchanged throughout the model simulation as well.

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Recently, King and Welford (2022a) proposed a more advanced deformable plate model for the southern North Atlantic, in which the deformable nature of continental blocks is considered by using time-dependent points to represent the geometries of continental blocks in plate reconstructions, enabling the restoration of present-day crustal thicknesses back through geologic time. Accordingly, the seismic transects are assumed to be points in this alternate model, with the directions and distances between points varying over time (see the right column in Figure 4). Present-day crustal thicknesses in this reconstruction model are derived from gravity inversion (Welford et al., 2012).

Deformable plate modelling results using both rigid polygons (left column of Fig. 4) and continental blocks discretized into points (right column of Fig. 4) are compared. During the Late Cretaceous (~ 110 Ma), lines F3 on the Flemish Cap and L2 on the Goban Spur appear to be parallel, while line F5 is far away from PAD95-13 due to the significant lateral offset between the Flemish Cap and the Porcupine Bank. Meanwhile, crustal thicknesses at this time over both the Flemish Cap-Orphan Basin and the Goban Spur-Porcupine Bank margins look similar regardless of whether the continental blocks are assumed to be rigid (left column) or deformable (right column) throughout the model simulations. In the Early Jurassic - Early Cretaceous (~ 140 Ma), lines F3 and F5 on the Flemish Cap appear to be parallel to L2 on the Goban Spur and PAD95-13 on the Porcupine Bank, respectively, with increasing crustal thicknesses for both the Flemish Cap and Porcupine Bank in the deformable polygons (right column in Fig. 4). Meanwhile, line F3 becomes curved and shorter, and line L2 becomes slightly curved. Further back in the Early Jurassic (~ 180 Ma), line F3 becomes even more curved and line L2 becomes straight and shorter; line F5 and PAD95-13 are slightly bent as well (Fig. 4b). During this stage, lines F5 and F3 appear to be in alignment with PAD95-13 and L2, respectively. Their alignment orientation (see the blue arrows in Figure 4) is oblique to the separation direction of the two margins (see the green arrows in Figure 4). By comparison, for the rigid continental block case (left column in Figure 4), the four seismic lines remain unchanged in length over time, with lines F3 and PAD95-13 intersecting and overlapping back in the Jurassic (Fig. 4a). This line overlap does not occur for the model with deformable polygons (Fig. 4b).

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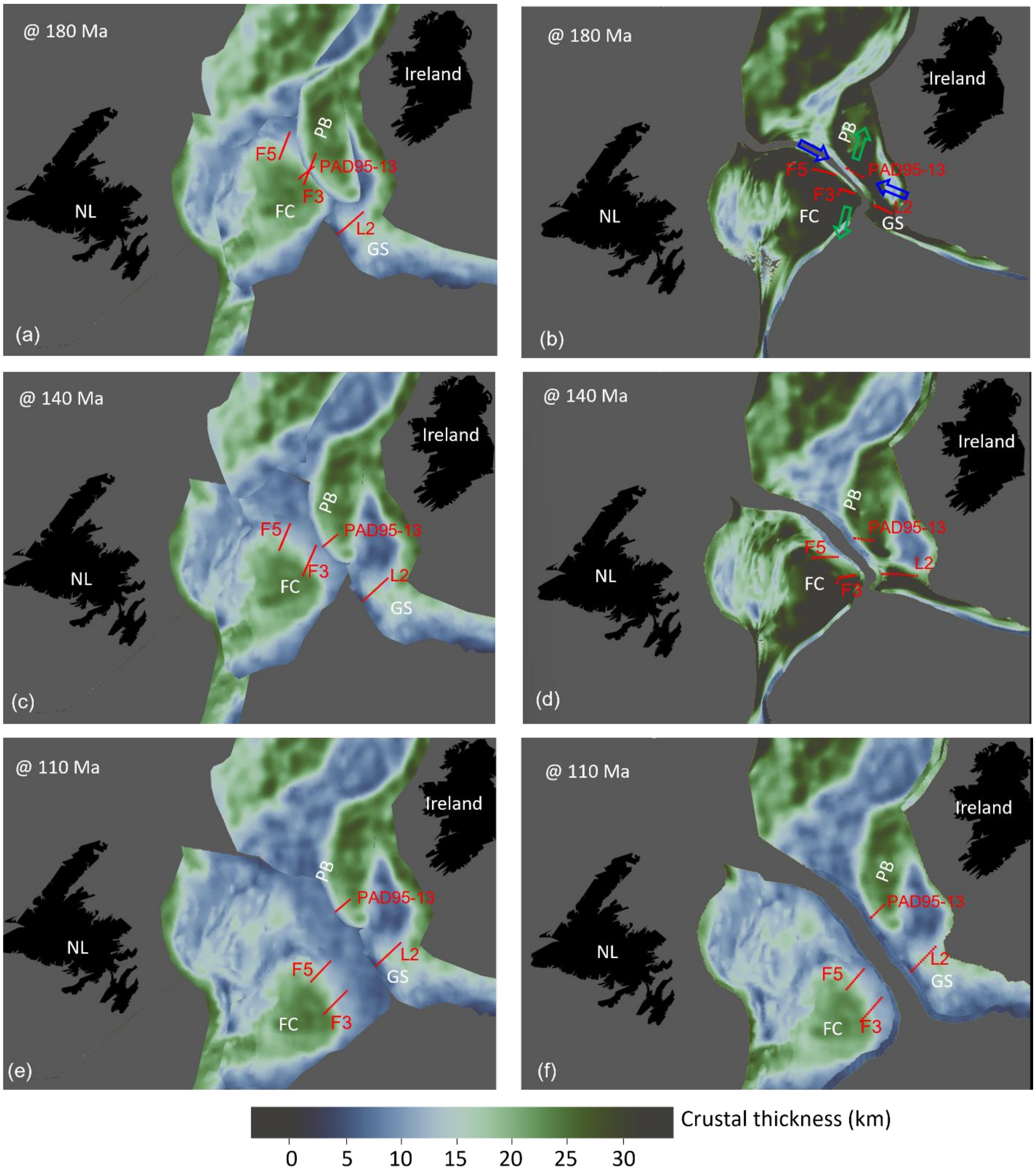


**Figure 4: Locations of seismic profiles and crustal thickness are reconstructed over Jurassic-Cretaceous time based on plate reconstruction models (Yang et al., 2021; King and Welford, 2022a; 2022b). Compared with the plate models in the left panel, the plate modeling with deformable polygons in the right panel includes crustal thickness variations as a function of time within those polygons. Red lines show the seismic profiles F3 and F5 on the Flemish Cap and PAD95-13 and L2 on the Porcupine Atlantic margins. The blue arrows in panel b indicate the aligned orientation of the seismic sections on both sides. The green arrows in panel b indicate the extension direction between FC and PB. Abbreviations: FC, Flemish Cap; GS, Goban Spur; NL, Newfoundland and Labrador; PBk, Porcupine Bank.**

## 4 Discussion

Pre-rift, orogenic structural inheritance significantly impacted the tectonic evolution of the magma-poor rifted margins of the North Atlantic (Manatschal et al. 2015; Chenin et al. 2015; Schiffer et al., 2020; King and Welford, 2022a; 2022b). Geographically, the locations of the present-day seismic sections on the Flemish Cap and Porcupine Atlantic regions appear distant from, and/or irrelevant to, the pre-existing inherited Appalachian-Caledonian and Variscan fault zones and crustal sutures mapped onshore Newfoundland and Ireland (Figs. 1 and 3). However, the possible offshore extrapolation of these orogenic sutures and fault zones has been argued to have impacted the evolution of the Newfoundland-Irish Atlantic rifted margins and associated rift basins based on newly-presented seismic profiles and plate reconstruction models (King and Welford, 2022a; 2022b; Yang and Welford, 2023). Furthermore, fault reactivation during distinct phases of extension and/or transtension in the Jurassic, Early Cretaceous, and Late Cretaceous in the intervening Orphan and Porcupine basins (Gouiza et al., 2017; Saqab et al., 2021; Peace et al., 2022) also emphasizes the controlling effects of structural inheritance on the evolution of this margin pair. Nonetheless, how those inherited structures affected the formation of the Newfoundland-Porcupine Atlantic margins remains enigmatic due to the limited coverage of seismic transects. In this study, the pre-existing inheritance is interpreted to be manifest in the intra-crustal reflectors observed below the top basement of the Flemish Cap on the newly presented seismic profiles F3 and F5 (Fig. 3). These are interpreted to be associated with Appalachian orogenic fabrics based on onshore-offshore correlations from pre-rift plate reconstructions, and/or to be related to a transitional stage between Paleozoic orogenic collapse and pre-Jurassic rifting (Yang and Welford, 2023). Although intra-crustal reflectors are rarely observed along L2 and PAD95-13 due to the lower quality of the vintage data and the seismic processing choices targeted at imaging the sediments, this paucity is not necessarily indicative of limited/no tectonic activity prior to Jurassic rifting over the Porcupine Atlantic region. For one thing, deep reflection patterns associated with Caledonian orogeny and orogenic collapse are well imaged within the northern and eastern Porcupine basins (Bulois et al., 2018; Whiting et al., 2021) and along the Mid-Norwegian margin (Peron-Pinvidic and Osmundsen, 2020). For another, the Porcupine Atlantic region is proposed to be compartmentalized through a series of fault structures observed on seismic profiles (Whiting et al., 2021; Yang and Welford, 2021), and these fault structures coincide with the offshore extrapolations of Caledonian and Variscan orogenic sutures and fault zones (Yang et al., 2021).

The newly presented multi-channel seismic reflection profiles also reveal a poly-phased and protracted period of lithospheric stretching, hyperextension, and/or serpentinized mantle exhumation between the Flemish Cap and the Irish Atlantic margin (Figs. 2 and 3), following the collapse of Variscan and Appalachian-Caledonian terranes. The highly variable basement features in the necking, hyperextended, and/or exhumed domains along these seismic profiles are suggestive of time-dependent asymmetric tectonic processes, rendering previous rift-perpendicular extension models (Keen et al., 1989) between the Goban Spur and Flemish Cap untenable. The pronounced variability in crustal architecture on both sides (Fig. 2) is also acknowledged to be common during the formation of many other magma-poor rifted margins, for instance, the Newfoundland-Iberia margins and the Australia-Antarctica margins (Reston, 2007; Peron-Pinvidic et al., 2013; Gillard et al., 2015), consistent with variable degrees of asymmetry during oblique rifting (Fig. 4). Meanwhile, what cannot be ignored is that, to a certain degree, similar

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geometries of sub-basins in the necking domains along lines F3 and PAD95-13 support the conjugate relationship between the Flemish Cap and Porcupine Bank from a seismic perspective (enlargements in Figure 3), consistent with the margin relationships interpreted from potential field datasets (Sibuet et al., 2007; Welford et al., 2012), plate reconstruction modelling (Peace et al., 2019), and 3D numerical modelling (Neuharth et al., 2021). The complex tectonic histories across both margins contribute to significant structural complexity (Figs. 2 and 3). Meanwhile, the changes in location, lengths and linearity of seismic sections within the model with deforming polygons (right column in Figure 4) are diagnostic of stress changes over time due to oblique extension between the two margins, which would also have involved changes in the composition, thermal and rheological characteristics of the crust and mantle (Manatschal et al., 2015).

Traditionally, seismic sections are often used to identify and predict geologic and geophysical features common to both margins since conjugate margin pairs often share common features (Gerlings et al., 2012; Peron-Pinvidic et al., 2013; Causer et al., 2019). Within the framework of deformable plate modelling, line F3 overlaps PAD93-15 when rigid continental blocks are modelled (Fig. 4a), while line PAD95-13 appears to be aligned with F5 in the model with deforming polygons (Fig. 4b). Similar seismic reflectivity is observed for both lines F3 and PAD95-13 (Fig. 3), consistent with their overlapping positions in the model with rigid polygons (Fig. 4a). However, overall, the deformable plate modelling with deforming polygons (right column in Figure 4) generates more geologically reasonable results in terms of crustal thicknesses, and the lengths and geometries of reconstructed seismic sections over time. This underlines the challenges involved in using seismic transects to determine the conjugate relationship between the Flemish Cap and Porcupine Bank, particularly when the margins experienced oblique extension. Furthermore, it should be noted that deformable plate models have their own uncertainties (e.g., geometry of deformable region, rotation parameters) (Gurnis et al., 2018; Müller et al., 2018), which can be minimized through the use of seismic constraints but never eliminated.

## 5 Conclusions

Newly presented multi-channel seismic reflection profiles support the conjugate relationship between the Flemish Cap and Porcupine Bank and reveal complex basement structures/reflectivities and crustal architectures for the Flemish Cap-Irish Atlantic margin pair. These complexities resulted from the interplay between inherited Variscan and Appalachian-Caledonian structures, extension obliquity, and poly-phase tectonic evolution between the Porcupine Bank, Goban Spur, and Flemish Cap and their intervening rift basins in the Mesozoic.

The reconstructed paleo-positions and geometries of seismic transects vary significantly over time in the presented deformable plate model simulations, due to the 3D plate kinematics experienced by the NE Newfoundland-Porcupine Atlantic margins. Choosing conjugate seismic profiles for investigation is challenged by the 3D nature of the rift evolution. More 3D numerical modelling and geophysical surveys are needed to comprehensively and quantitatively unravel the tectonic processes that were involved in the orogeny, orogenic collapse, and oblique rifting stages that affected the NE Newfoundland-Porcupine Atlantic conjugate margin pair.

**Data availability**

All plate reconstruction data can be provided by the corresponding authors upon request.

**Author contributions**

Pei Yang used software and wrote the manuscript draft; J.Kim Welford supervised, reviewed, and edited the manuscript.

**Competing interests**

The authors declare that they have no conflict of interest.

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