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Reconstructing the southern North Atlantic Ocean back through time

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Summary

The offshore rifted margins of the southern North Atlantic Ocean have been demonstrated to have a complex present day crustal structure comprised of sedimentary basins, inherited structures, variable basement affinities, and continental blocks. Consequently, this has led to challenges when studying the crustal evolution of the southern North Atlantic; in particular when investigating the kinematic history of continental blocks (e.g. Flemish Cap) and micro-plates (e.g. Iberia) and their subsequent impact on strain-partitioning during poly-phase rifting experienced along the Newfoundland, Irish, and West Iberian margins. Recently, deformable plate tectonic models, built using the GPlates software, have proven to be an advantageous method for investigating the interplay between plate kinematics and deformation experienced throughout the North Atlantic. Furthermore, their ability to calculate temporal variations in strain rate and crustal thickness provides a quantitative method of comparison with present day crustal thickness estimates derived from gravity inversion and interpretations made from offshore seismic and well data. However, previous deformable plate models of the North Atlantic have included assumptions that are geologically problematic. Examples of assumptions include, but are not limited to, the rigid nature of continental blocks and model boundaries, and the specification of uniform crustal thicknesses within pre-rift templates.

In this study, we present a new deformable plate modelling approach using GPlates and its python programming module, pyGPlates, which aims to address these limitations by reconstructing present day crustal thicknesses back through time. Using previously published and newly presented models, our results demonstrate the pre-rift crustal thickness template of the southern North Atlantic and the crustal thickness evolution of continental blocks and sedimentary basins within. In addition, this study highlights the potential impact of Appalachian and Caledonian terrane boundaries on the crustal segmentation observed within pre-rift templates and subsequent rift events.

Method and Workflow

Deformable plate tectonic models, built using the open-source software, GPlates (Gurnis et al., 2018; Müller et al., 2018), have proven to be a useful technique for investigating plate kinematics and deformation experienced on global (Flament et al., 2014; Müller et al., 2019) and regional scales (Welford et al., 2018; Peace et al., 2019; Cao et al., 2020; King et al., 2020, 2021; Yang et al., 2021). To construct deformable plate models via the design of topological networks in GPlates (Figure 1), model inputs are required in order to define exterior (e.g. continent-ocean boundaries) and interior boundaries (e.g. necking lines) between which deformation takes place. These boundaries can be used to define topological networks in the form of a continuously closed polygon (e.g. a sedimentary basin) (Gurnis et al., 2012; Cao et al., 2020) or models where the exterior boundaries of deformation are assigned a timing of appearance in order to simulate continental breakup (Welford et al., 2018; Peace et al., 2019; King et al., 2020, 2021; Yang et al., 2021). In addition, optional model inputs can be placed within the interior of deformable regions such as rigid continental blocks or other features (e.g. topological lines and points) with independent plate kinematic histories.

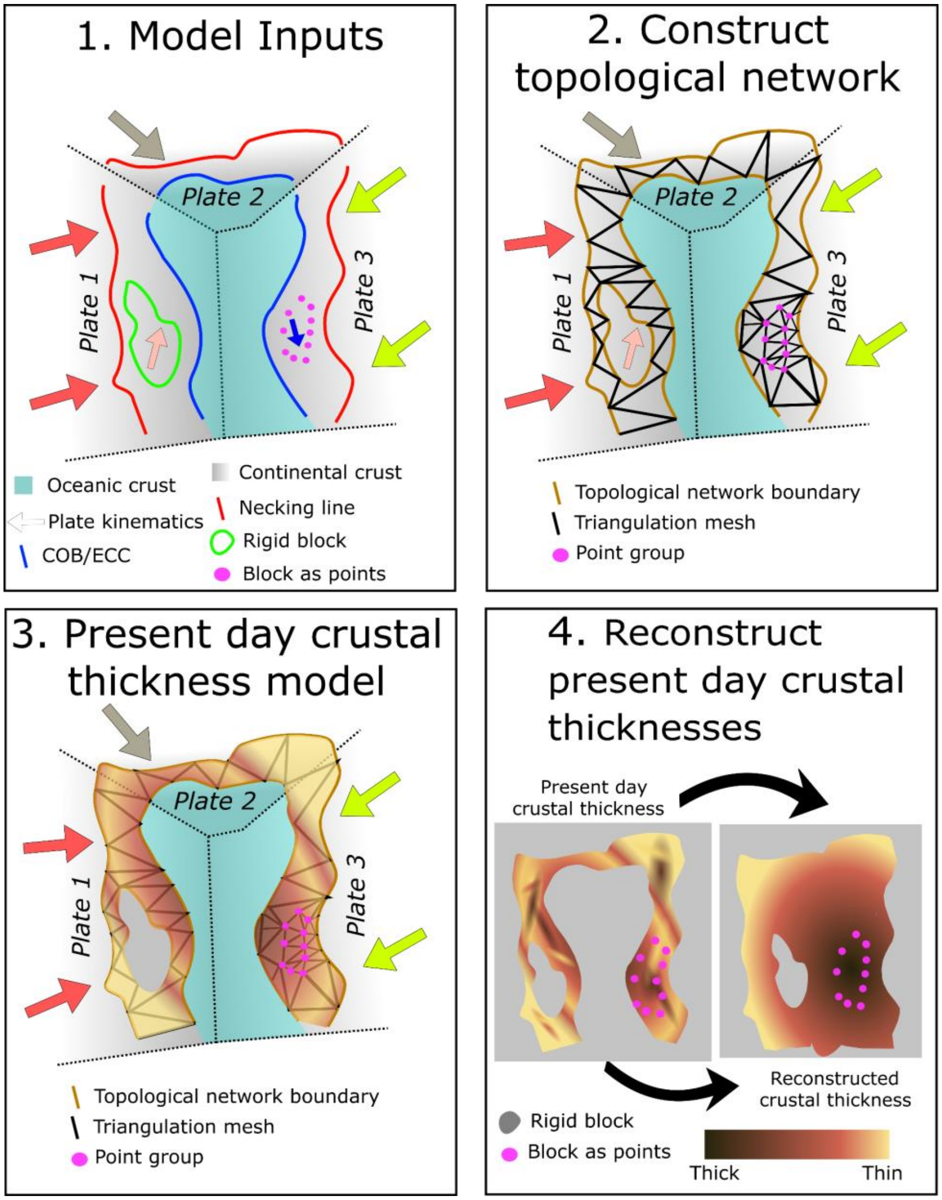

Figure 1 Deformable plate tectonic modelling workflow for this study modified after Peace et al., (2019) and King et al., (2020, 2021).

The use of rigid continental blocks, such as the Flemish Cap and Porcupine Bank, within deformable plate models has proven to be useful for studying the complex kinematics and crustal thickness evolution of offshore rifted margins throughout the southern North Atlantic Ocean (Peace et al., 2019; King et al., 2020, 2021; Yang et al., 2021). However, the majority of previously published deformable plate models have been carried out using several assumptions that are often geologically insufficient. Some notable examples include the lack of deformation experienced within continental blocks and a constant crustal thickness assumption specified at the start time of deformable plate models. In this study, these two assumptions are addressed using newly presented methodologies using the current capabilities of GPlates 2.3 and pyGPlates. In particular, we demonstrate the ability to create deformable continental blocks, reconstruct present day crustal thickness estimates calculated by gravity inversion back through time (Figure 2), and how the landward extent of present day crustal thickness estimates can be used to define the limits of deformable plate models and rift domain boundaries *a priori*. In order to demonstrate their application and validity, a modified version of a previously published deformable plate model of the southern North Atlantic (Peace et al., 2019) will be used to present the methodologies and their application.

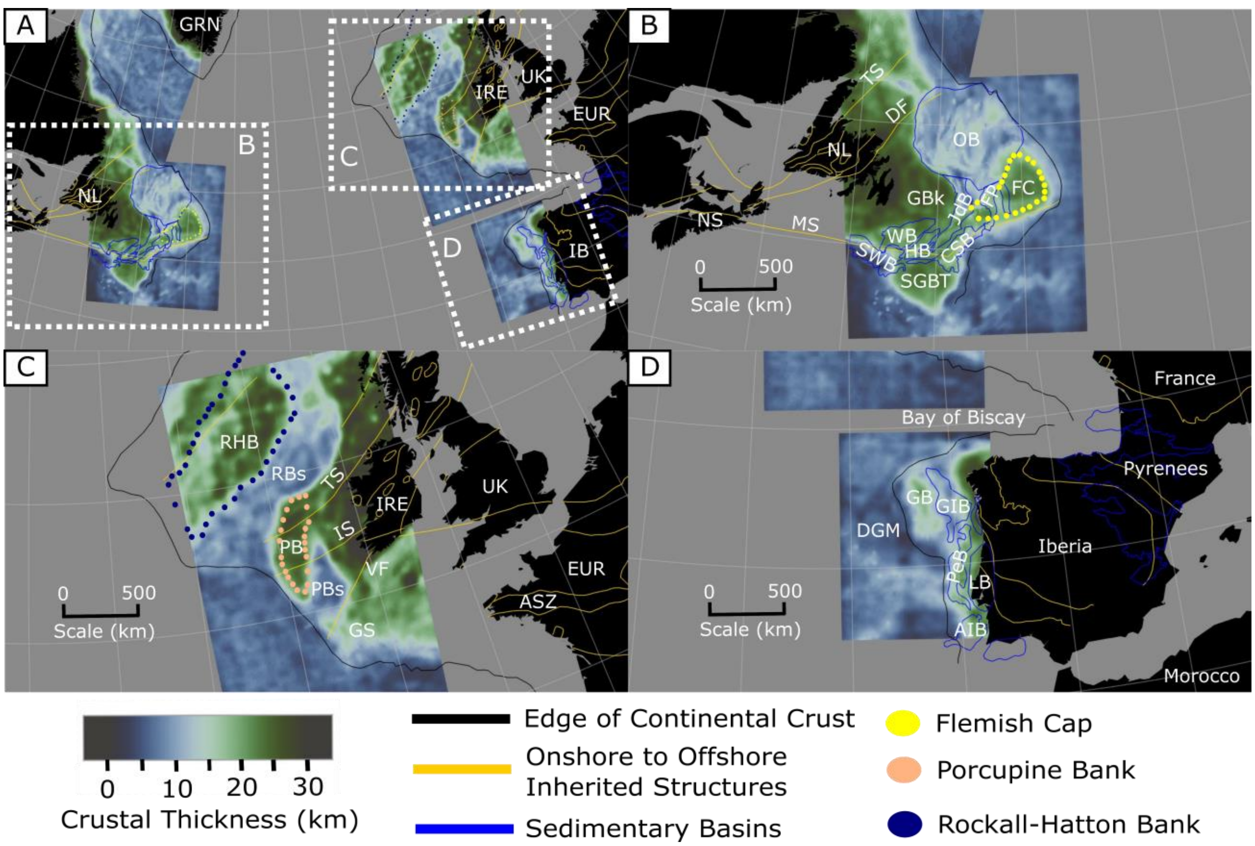

Figure 2 Southern North Atlantic crustal thickness estimates calculated by gravity inversion with onshore to offshore inherited basement terranes extracted from Welford et al. (2012) and Nirrengarten et al. (2018). The geometries of continental blocks were extracted from Peace et al. (2019). The dashed white boxes in panel (A) correspond to the enlarged panels (B), (C), and (D). AIB = Alentejo Basin, ASZ = Armorican Shear Zone, BP = Bonavista Platform, EUR = Europe, COH = Central Orphan High, CSB = Carson-Salar Basins, DF = Dover Fault, DGM = Deep Galicia Margin, EOB = East Orphan Basin, FC = Flemish Cap, FP = Flemish Pass, GB = Grand Banks, GBk = Galicia Bank, GIB = Galicia Interior Basin, GS = Goban Spur, HB = Horseshoe Basin, IRE

= Ireland, IS = Iapetus Suture, JdB = Jeanne d'Arc Basin, LB = Lusitanian Basin, MS = Meguma Suture, NL = Newfoundland and Labrador, NS = Nova Scotia, PB = Porcupine Bank, PBs = Porcupine Basin, PeB = Peniche Basin, RBs = Rockall Basin, RHB = Rockall-Hatton Bank, SGBT = Southern Grand Banks Tail, SWB = South Whale Basin, TS = Taconian Suture, UK = United Kingdom, VF = Variscan Front, WOB = West Orphan Basin.

Pre-rift crustal thickness template of the southern North Atlantic

The pre-rift (200 Ma) crustal thicknesses calculated by the preferred model in this study (Figure 3) demonstrate significant segmentation along the Newfoundland, Irish, and West Iberian margins. Along the Newfoundland margin, segmentation is observed throughout the Orphan Basin as the West Orphan Basin appears to be a wider NE-SW trending region with thinner crust (~ 20 km thick) relative to the Central Orphan High and East Orphan Basin. Considering pre-rift crustal thicknesses calculated within previously recognized continental blocks (Flemish Cap and Orphan Knoll), crustal thicknesses within these blocks vary from about 20-35 km thick. Within the Flemish Cap, crustal thicknesses mostly range from about 25-35 km thick, aside from the western edge of the Flemish Cap (Flemish Pass) where the crust is approximately 20 km thick. At 200 Ma, the Orphan Knoll (green star in Figure 3) comprises the northeastern portion of the Central Orphan High, a relatively thicker NE-SW trending crustal block (~ 20-30 km thick) whose structure is partitioned by localized depocenters to the southwest. Additionally, the Orphan Knoll appears to be conjugate to the Rockall-Hatton Bank, suggesting that the two blocks may have been connected prior to the onset of rift-related deformation within the Orphan Basin. Along the Grand Banks, pre-rift crustal thicknesses range from about 20-30 km thick, aside from localized regions of relatively thinner crust (~ 15-20 km thick) (yellow arrow in Figure 3) in the vicinity of the Horseshoe and Whale basins (Figure 2) to the west of the Southern Grand Banks Tail.

Throughout the Irish margin, pre-rift crustal thicknesses calculated by our model are highly variable. Within the Porcupine Bank, crustal thicknesses range from about 25-35 km thick, aside from a localized region of thinner crust (~ 20-25 km thick) near the center and western edge of the Porcupine Bank. This segmentation demonstrates interesting correlations with previous studies that suggest segmentation of the Porcupine Bank's pre-rift structure (Yang et al., 2021). In particular, the pre-rift position of the Porcupine Bank appears to intersect the offshore extension of the Iapetus Suture from the Irish interior, correlating with the region of crustal thickness segmentation calculated by the preferred model.

The pre-rift crustal thickness template calculated along the West Iberian margin demonstrates interesting variabilities from north to south. Within the northwest Iberian margin, the pre-rift geometry and crustal thickness of the Galicia Bank (~ 25-30 km thick) are revealed. In addition, the reconstructed position of the Galicia Bank appears to be connected to the Flemish Cap, suggesting their connection as one continental block at 200 Ma. Thus, similar to the Orphan Knoll (green star in Figure 3), the position and reconstructed thickness of the Galicia Bank is deemed to be highly dependent on the kinematics of the Flemish Cap. Furthermore, although it is still considered a continental block, the Galicia Bank appears to be an extensional relic of the Flemish Cap during the formation of the North Atlantic Ocean. As for the cause of their separation, a possible scenario relates to the position of the Variscan Front relative to the Flemish Cap and Galicia Bank at 200 Ma (Figure 3). Analysis of well data drilled into the Flemish Cap concluded that the Flemish Cap encompasses Avalonian terrane rocks (King et al., 1985). In contrast, the Galicia Bank is often assumed to be Variscan in nature, despite a lack of drilling into the Galicia

Bank itself. As a result, the Variscan Front is interpreted to extend between the Galicia Bank and Flemish Cap (Figure 3), suggesting that it acted as an inherited weakness that promoted the breaking apart of the two blocks following the onset of significant rift related deformation during the Early Cretaceous.

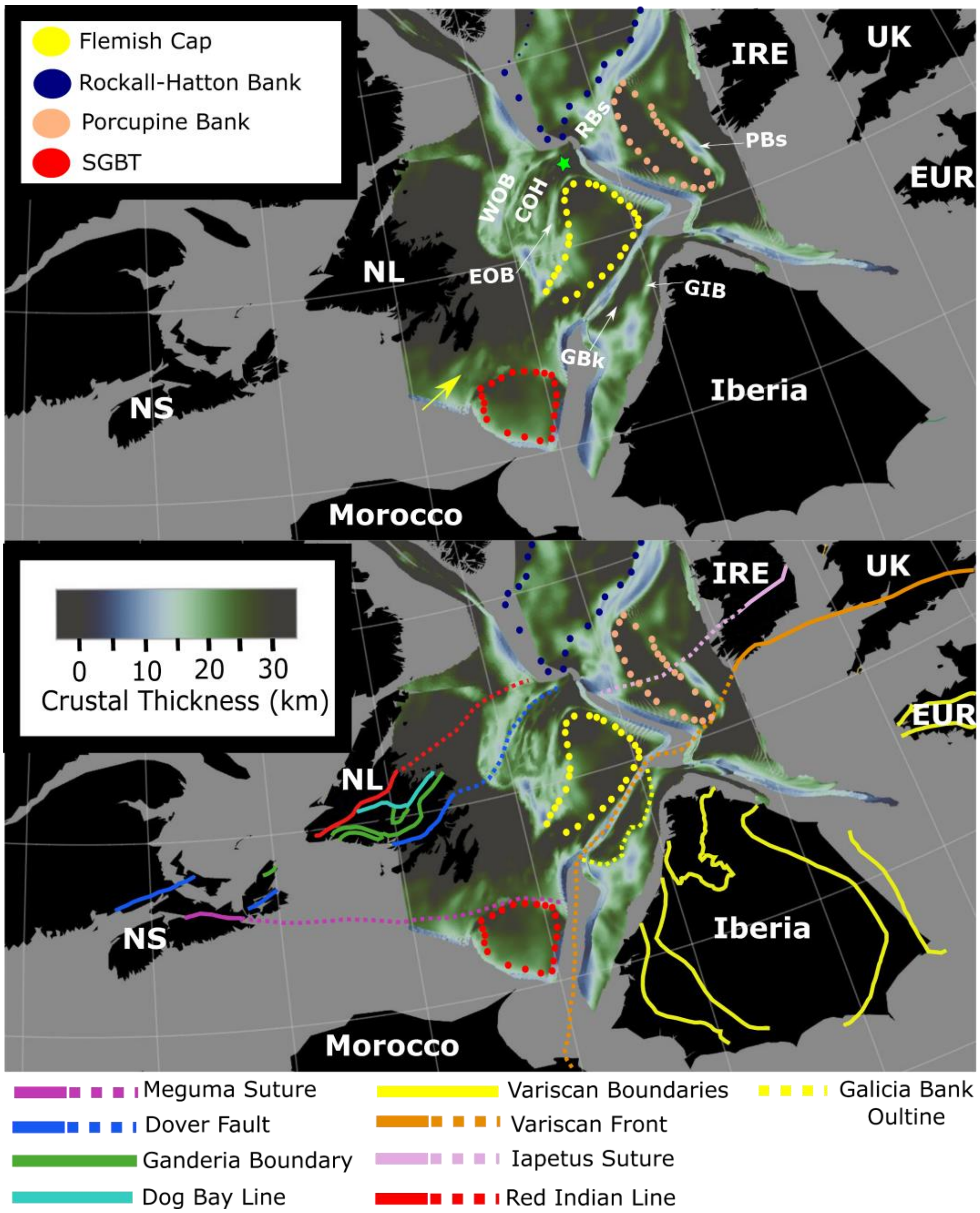

Figure 3 A) Crustal thicknesses calculated by the preferred model at 200 Ma. B) Same as (A) except with the orientation of offshore-onshore inherited boundaries modified after Waldron et al.

(2019) and Nirrengarten et al. (2018) overlain on crustal thicknesses calculated by the preferred model. COH = Central Orphan High, EOB = East Orphan Basin, EUR = Europe, GBk = Galicia Bank, GIB = Galicia Interior Basin, IRE = Ireland, NL = Newfoundland and Labrador, NS = Nova Scotia, PBs = Porcupine Basin, RBs = Rockall Basin, UK = United Kingdom, WOB = West Orphan Basin.

Conclusions

In conclusion, the deformable plate tectonic modeling approach presented in this work is used to study the pre-rift crustal architecture of the southern North Atlantic and its temporal evolution. The correlation between the segmentation of pre-rift crustal thicknesses with the offshore extension of Appalachian and Caledonian terrane boundaries suggests that ancient terrane boundaries were very influential on the pre-rift template and subsequent rift evolution of the North Atlantic. Furthermore, the independent kinematics of continental blocks (e.g. Flemish Cap and Porcupine Bank) had a large impact on the strain-partitioning within surrounding sedimentary basins and the deformation experienced within smaller blocks (e.g. Orphan Knoll and Galicia Bank).

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