Reconstructing deformable continental blocks and crustal thicknesses back through time within the North Atlantic Ocean

Michael King*and J. Kim Welford

Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE
10.1029/2022GC010372

Advances in Deformable Plate Tectonic Models: 1. Reconstructing Deformable Continental Blocks and Crustal Thicknesses Back Through Time

Michael T. King[1] and J. Kim Welford[1]

[1]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, Canada

This article is a companion to King and Welford (2022), https://doi.org/10.1029/2022GC010373.

Key Points:

- A new deformable plate modeling approach is presented using GPlates and pyGPlates
- The pre-rift templates of offshore rifted margins throughout the North Atlantic are assessed
- Temporal variations in deformation within continental blocks throughout the North Atlantic are investigated

Correspondence to:
M. T. King,
mtk282@mun.ca

Citation:
King, M. T., & Welford, J. K. (2022). Advances in deformable plate tectonic models: 1. Reconstructing deformable continental blocks and crustal thicknesses back through time. *Geochemistry, Geophysics, Geosystems*, *23*, e2022GC010372. https://doi.org/10.1029/2022GC010372

Abstract Deformable plate tectonic models have been demonstrated to be a useful technique for quantifying temporal variations in strain rate and crustal thickness within recent plate kinematic studies. Using the GPlates software, deformable plate models offer an approach to visualize and assess the interplay of plate kinematics and deformation. However, several assumptions are imposed in previous studies that limit their ability to explain the crustal evolution of various tectonic regimes. Examples of these assumptions include, but are not limited to, the rigid nature of continental blocks and boundaries used to define deformable regions, and uniform crustal thickness assumptions at model start times. In this study, we address these assumptions with newly presented applications using the interplay of GPlates and its python programming library, pyGPlates. In particular, we demonstrate the ability to create deformable continental blocks, reconstruct present day crustal thickness estimates back through time, 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. To demonstrate their application and validity, these concepts are evaluated using a previously published deformable plate model of the southern North Atlantic that is tested using 4 modeling scenarios herein to assess the impact of variable model inputs. These models provide insight regarding the pre-Jurassic (200 Ma) crustal thickness template of the southern North Atlantic, the evolution of continental blocks during rift-related deformation, and the potential impact of ancient orogenic terranes during subsequent rifting within the North Atlantic.

Plain Language Summary The opening and closing of oceans and the development of Earth's

https://doi.org/10.1029/2022GC010372

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE
10.1029/2022GC010373

Advances in Deformable Plate Tectonic Models: 2. Reconstructing the Southern North Atlantic Back Through Time

Michael T. King[1] and J. Kim Welford[1]

[1]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, Canada

This article is a companion to King and Welford (2022), https://doi.org/10.1029/2022GC010372.

Key Points:

- Continental blocks had a large impact on pre-rift crustal thicknesses calculated within sedimentary basins throughout the North Atlantic
- The Flemish Cap, Porcupine Bank, and Rockall-Hatton Bank played a key role during rift related deformation throughout the North Atlantic
- Appalachian and Caledonian terrane boundaries were very influential on pre-rift templates calculated throughout the North Atlantic

Correspondence to:
M. T. King,
mtk282@mun.ca

Citation:
King, M. T., & Welford, J. K. (2022). Advances in deformable plate tectonic models: 2. Reconstructing the southern North Atlantic back through time. *Geochemistry, Geophysics, Geosystems*, *23*, e2022GC010373. https://doi.org/10.1029/2022GC010373

Abstract The offshore rifted margins of the North Atlantic have a spatially complex crustal structure comprised of variable crustal morphologies, continental blocks, and inherited structures. Recently, deformable plate tectonic models have permitted the interplay of plate kinematics and deformation to be assessed throughout the North Atlantic, and elsewhere. In particular, the ability to calculate temporal variations in crustal thickness has provided insight into the kinematic role of continental blocks and their interplay with large and micro-tectonic plates during the formation of the North Atlantic offshore rifted margins. In this study, the deformable plate modeling workflow introduced in the companion contribution of this study (Part 1) is used to investigate previously published and newly presented deformable plate models of the Newfoundland, Irish, and West Iberian margins. This approach permits the deformation and subsequent crustal thickness evolution within previously recognized continental blocks and sedimentary basins throughout the southern North Atlantic Ocean to be visualized and assessed from 200 Ma to present day. The segmentation of early rift crustal thicknesses calculated by deformable plate models demonstrate strong correlations with the offshore extension of Appalachian and Caledonian terrane boundaries. Thus, our observations suggest that inherited orogenic boundaries potentially play a key role in the early rift crustal structure of sedimentary basins and the partitioning of deformation around and within continental blocks.

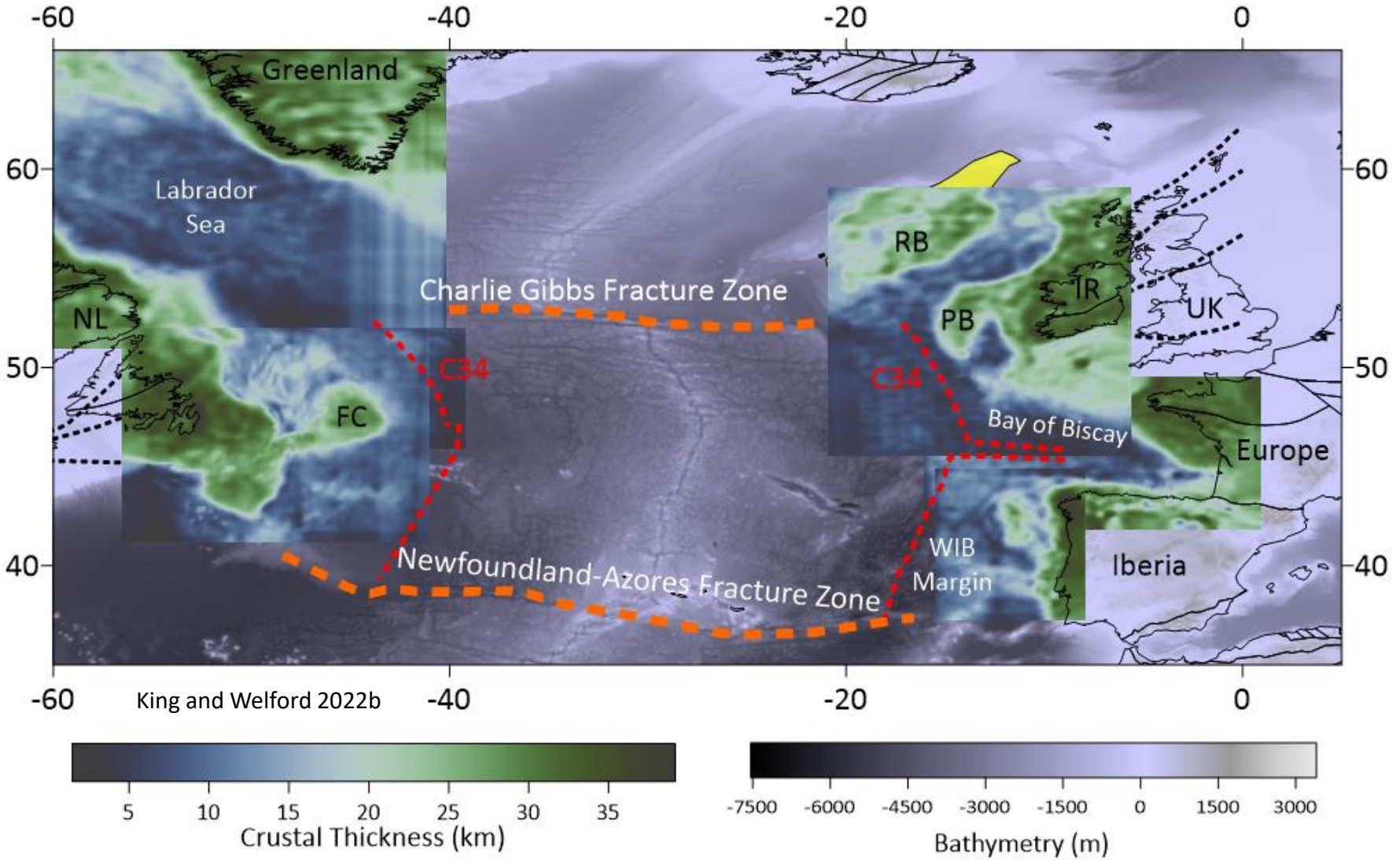
Plain Language Summary The Earth is made up of large and small tectonic plates that are actively moving and can have variable thicknesses and morphologies. Over the last 200 million years, the gradual separation between the North American and Eurasian plates has led to the formation of the southern North

https://doi.org/10.1029/2022GC010373

Freely available data, model files, and code:

https://data.mendeley.com/datasets/wjfw5fcj97/draft?a=a4418b3d-be52-47a4-b544-6a8c90d179b2

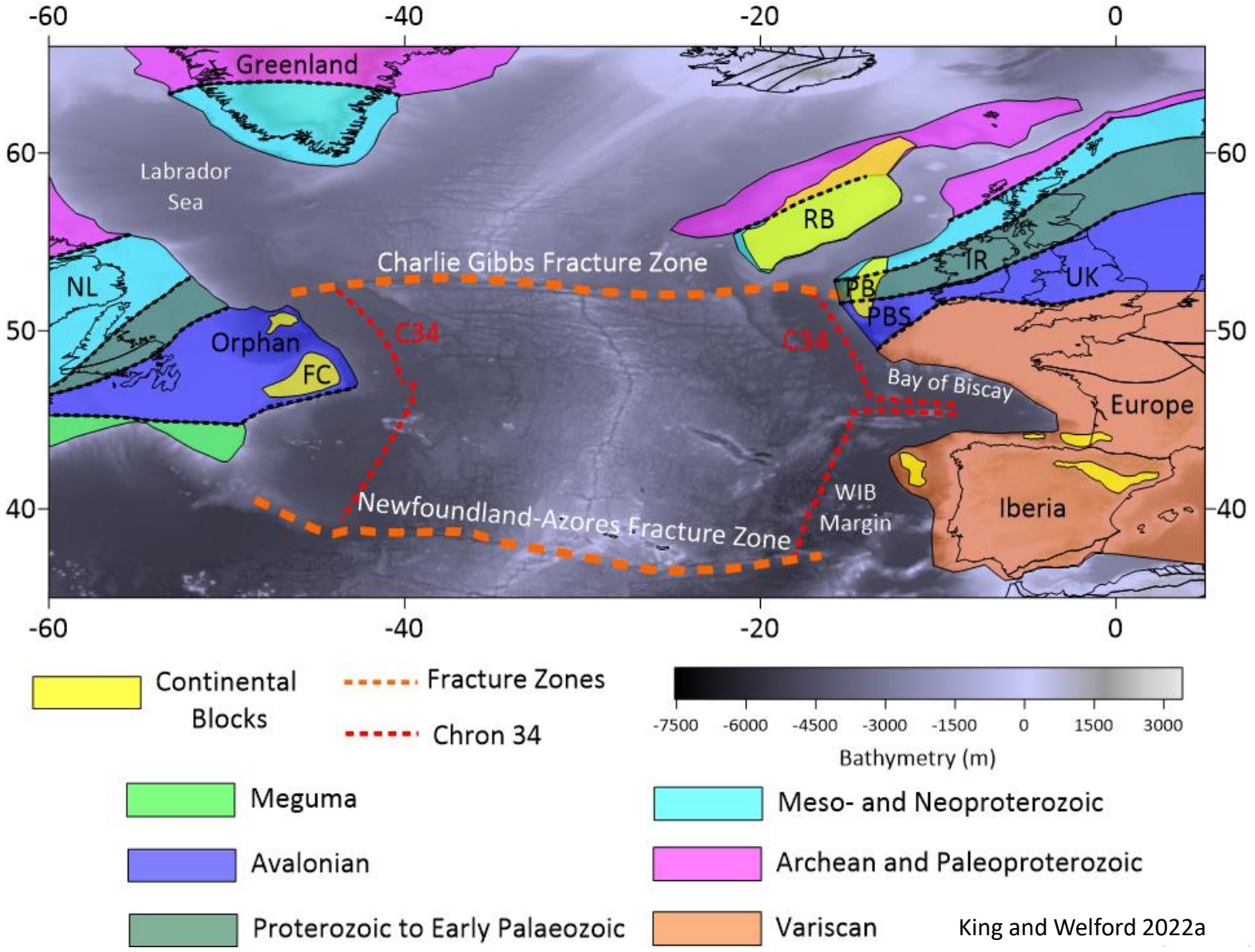
North Atlantic Crustal Structure



North Atlantic gravity inversion crustal thickness estimates

- **Continental blocks:**
  - ~ 20-30 km thick (via gravity inversion and seismic refraction).
  - Examples include the Flemish Cap **(FC)**, Porcupine Bank **(PB)**, and Galicia Bank.

Study Objectives

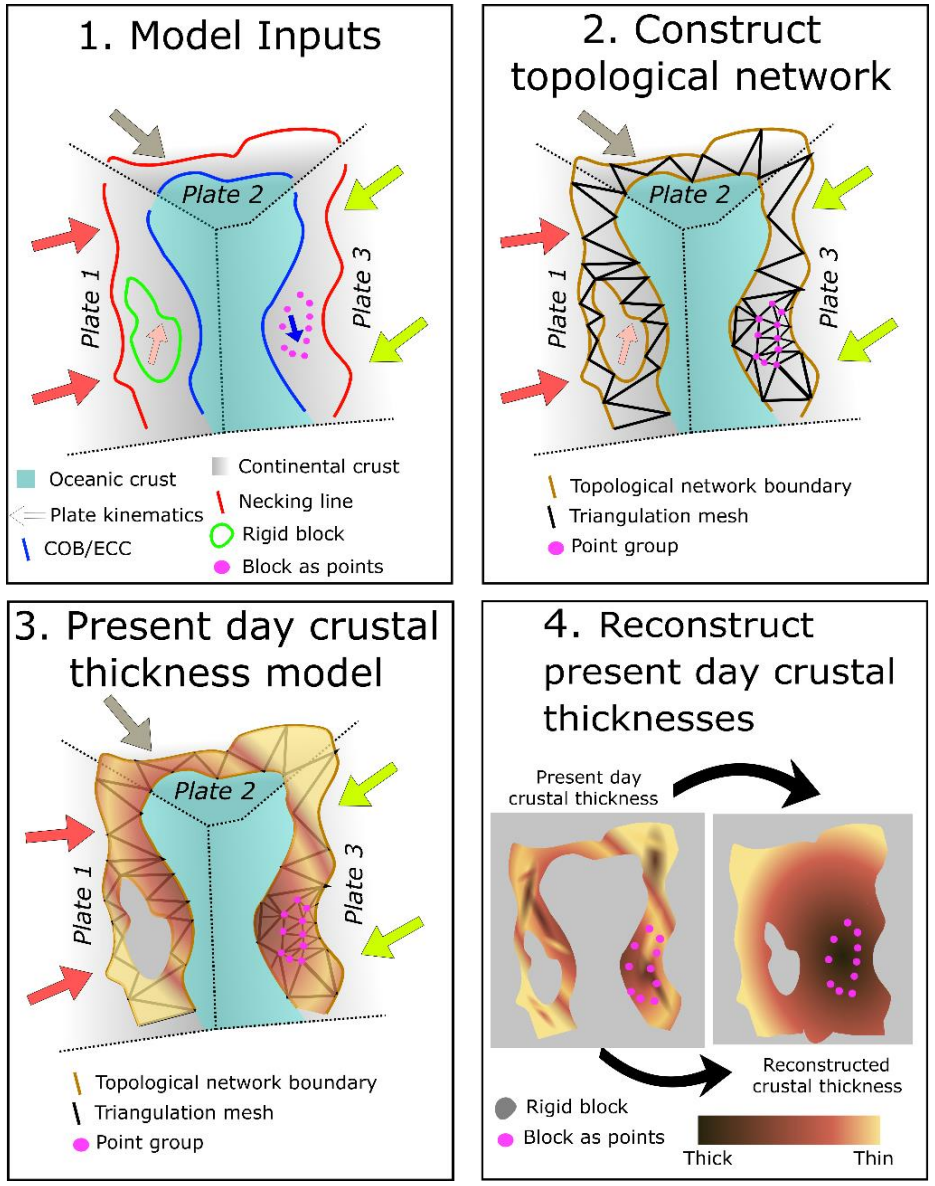


King and Welford 2022a

1. Investigate the kinematics and crustal evolution of continental blocks.
2. Assess the potential role of ancient orogenic terrane boundaries.

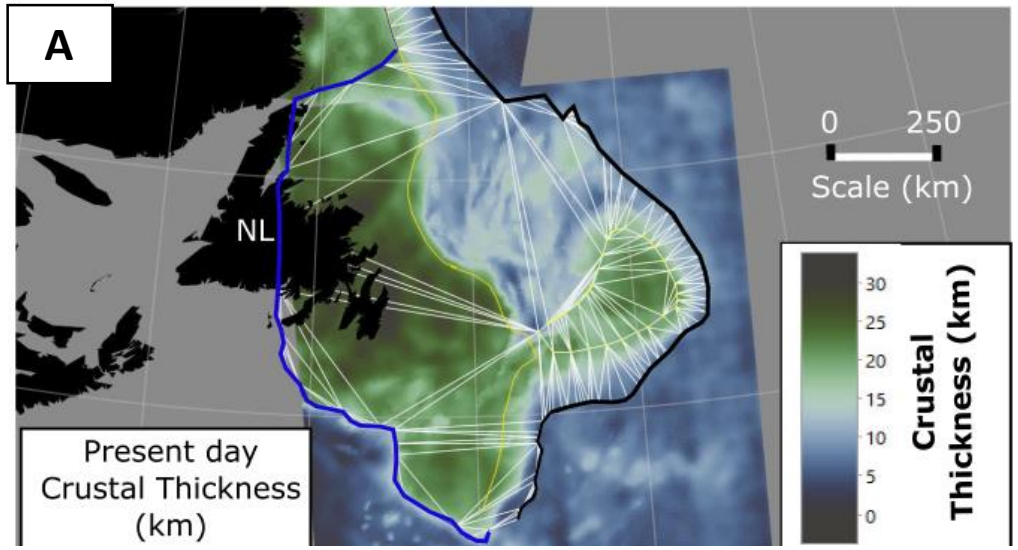
Deformable Plate Tectonic Reconstructions

- Deformable plate tectonic models built using pyGPlates and GPlates.
- Model inputs:
  - Rigid boundaries
  - Deformable continental blocks
- Workflow:
  - Reconstructing present day crustal thickness estimates back through time:
    - Reconstruct pre-rift templates
    - Assessing deformation within continental blocks and sedimentary basins through time.

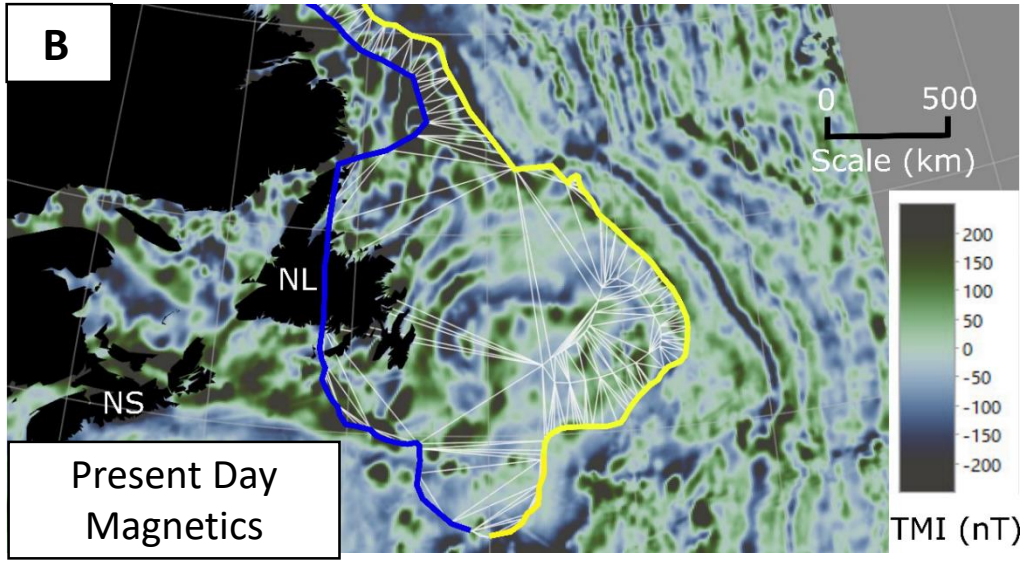


Deformable Plate Tectonic Reconstructions

Crustal thicknesses back through time



Magnetics data back through time



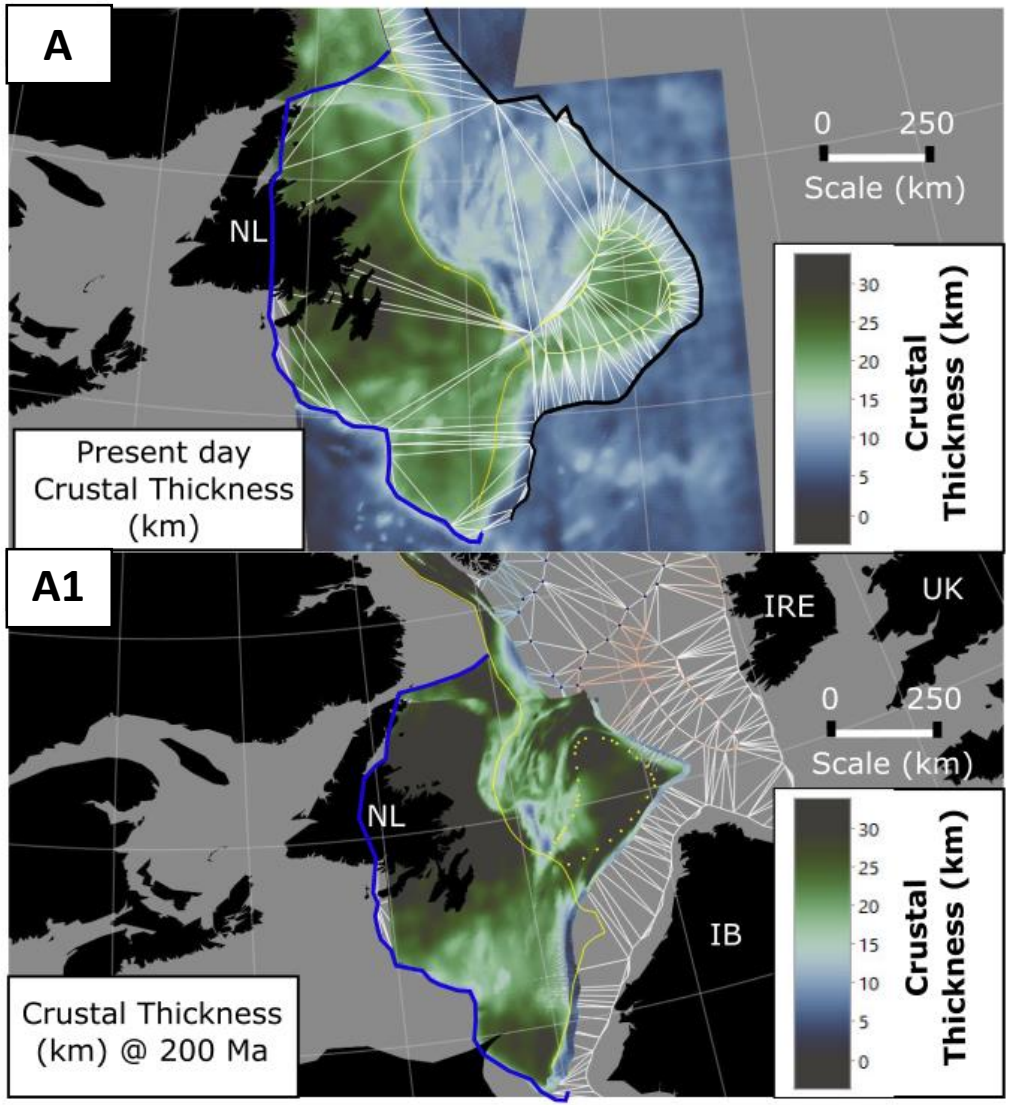
- Using **GPlates and pyGPlates** to reconstruct present day crustal thicknesses estimates back through time:
  - Reconstruct pre-rift templates
  - Assessing deformation within continental blocks and sedimentary basins through time.

GPlates

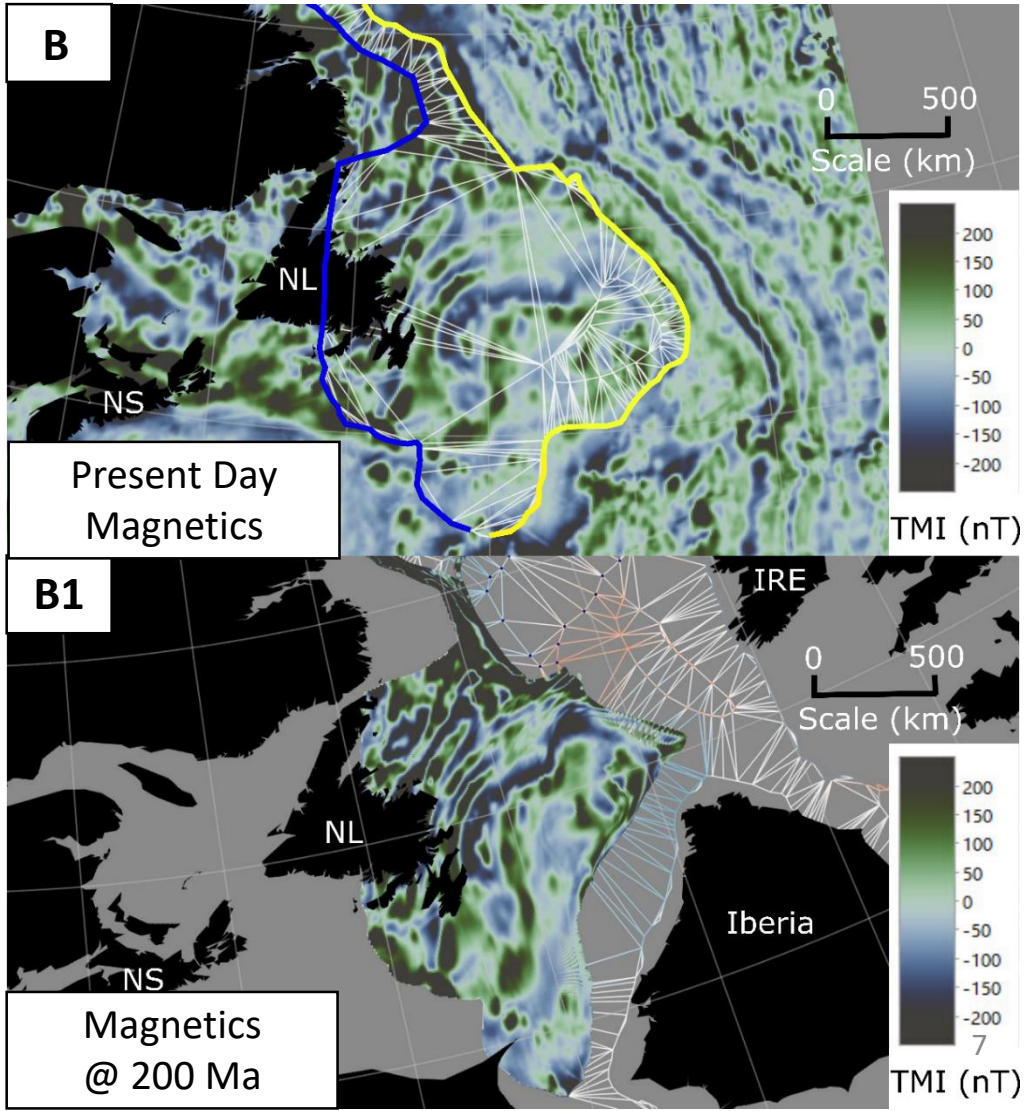
EarthBYTE
Building a Virtual Earth

Deformable Plate Tectonic Reconstructions

Crustal thicknesses back through time

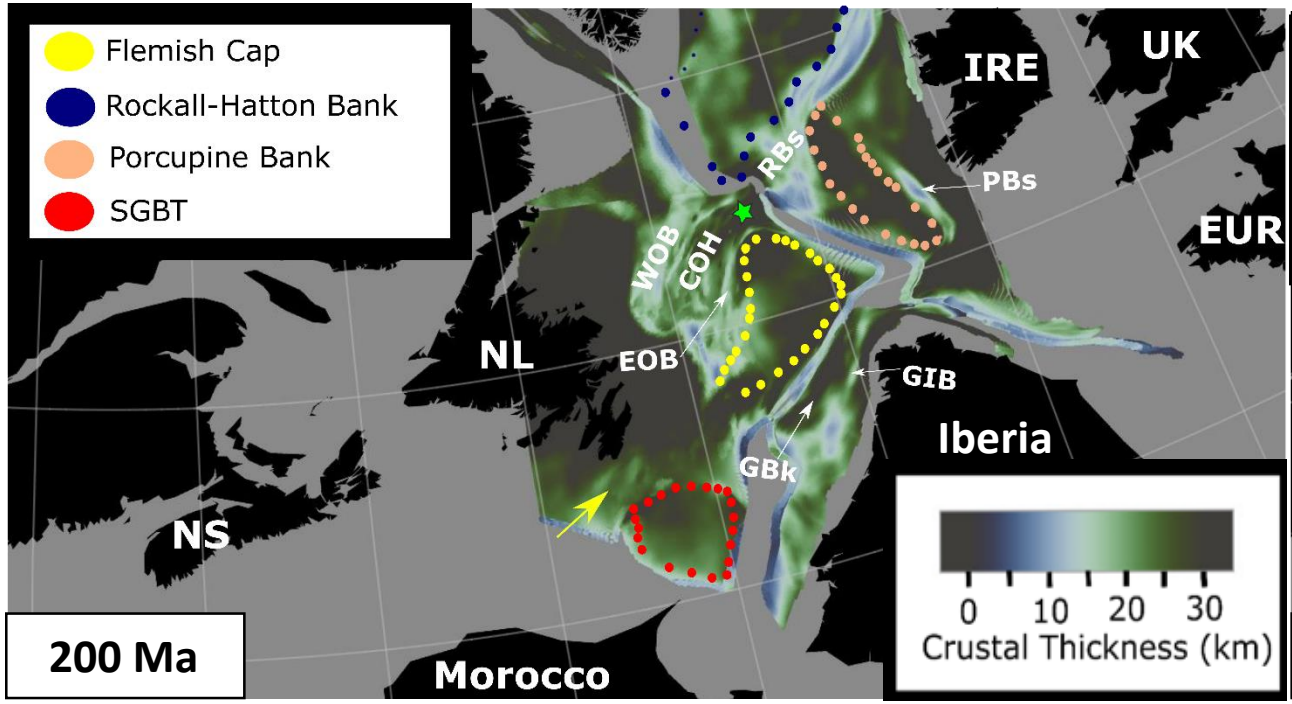


Magnetics data back through time



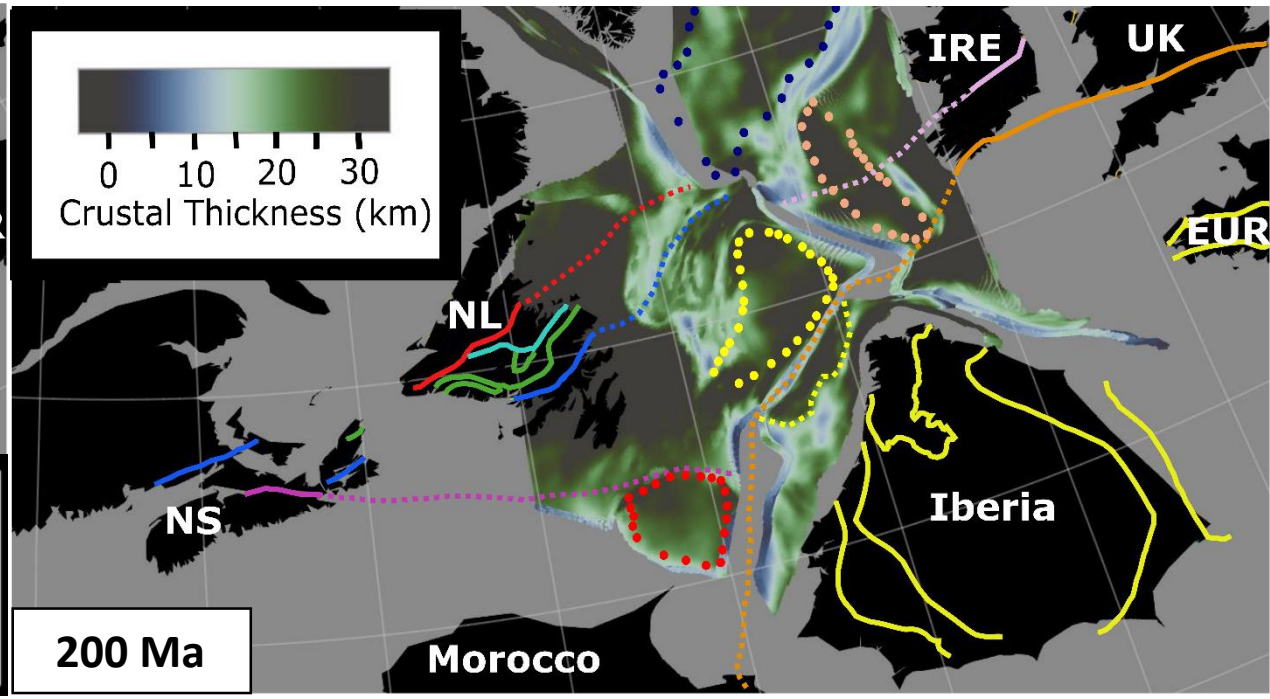
Pre-Jurassic template of the North Atlantic

Pre-Jurassic nature of continental blocks



King and Welford 2022b

Crustal segmentation by ancient orogenic boundaries

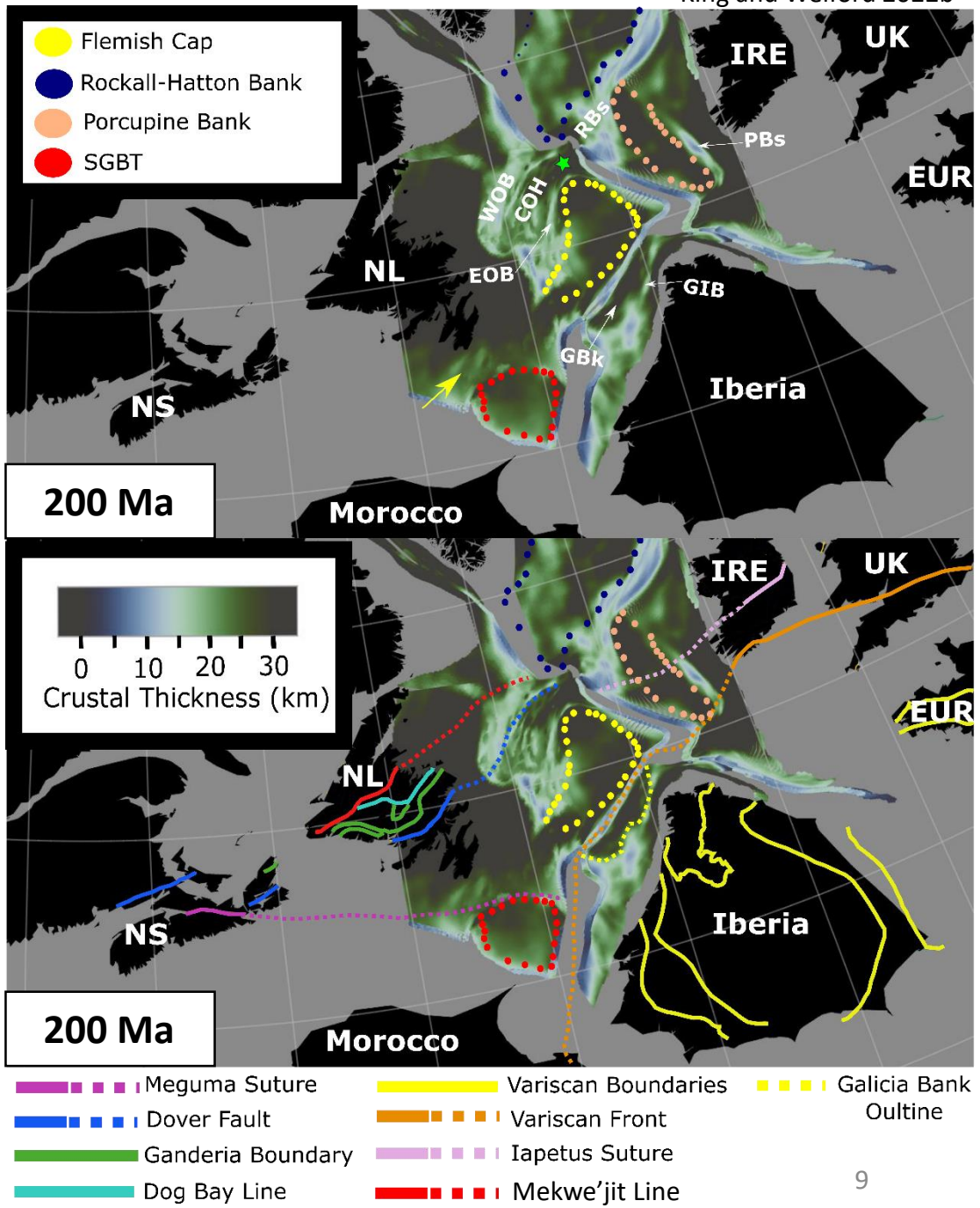


- **Primary blocks** – Flemish Cap, Porcupine Bank, and Rockall-Hatton Bank.
- **Secondary blocks** – Galicia Bank (GBk) and Orphan Knoll (★).

Conclusions

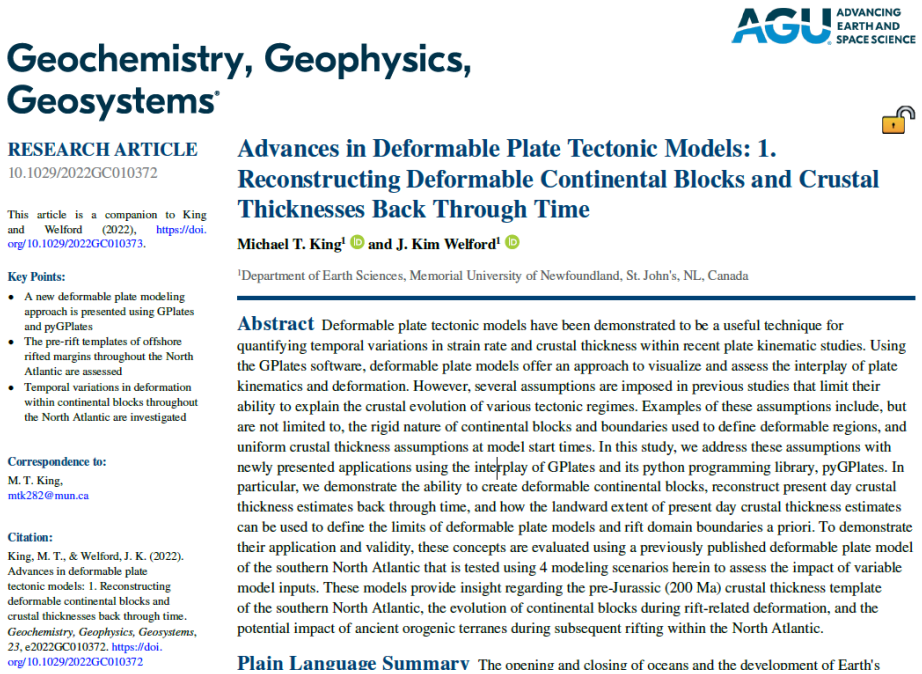
- **Kinematic role of continental blocks:**
  - **Primary blocks** – Flemish Cap, Porcupine Bank and Rockall Hatton Bank.
  - **Secondary blocks** – Galicia Bank and Orphan Knoll.
- **Impact of orogenic inheritance:**
  - Strong correlations between the offshore extension of orogenic terrane boundaries and crustal thickness segmentation.
  - Continental block and margin segmentation through time.

King and Welford 2022b



Acknowledgments

- Special thanks to:
  - Dr. Kim Welford (Ph.D. Supervisor)
  - NSERC
  - NL Oil and Gas Company
  - Cenovus/Husky Energy
  - MAGRiT research group
  - EGU



Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE
10.1029/2022GC010372

This article is a companion to King and Welford (2022), https://doi.org/10.1029/2022GC010373.

Key Points:
- A new deformable plate modeling approach is presented using GPlates and pyGPlates
- The pre-rift templates of offshore rifted margins throughout the North Atlantic are assessed
- Temporal variations in deformation within continental blocks throughout the North Atlantic are investigated

Correspondence to:
M. T. King,
mtk282@mun.ca

Citation:
King, M. T., & Welford, J. K. (2022). Advances in deformable plate tectonic models: 1. Reconstructing deformable continental blocks and crustal thicknesses back through time. *Geochemistry, Geophysics, Geosystems*, *23*, e2022GC010372. https://doi.org/10.1029/2022GC010372

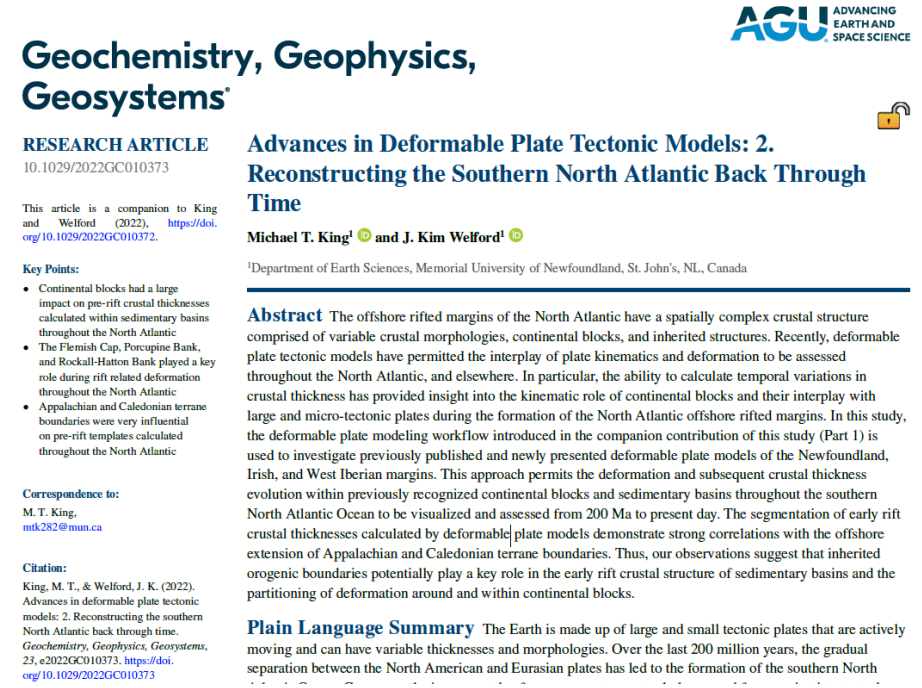
Advances in Deformable Plate Tectonic Models: 1. Reconstructing Deformable Continental Blocks and Crustal Thicknesses Back Through Time

Michael T. King[1] and J. Kim Welford[1]

[1]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, Canada

Abstract Deformable plate tectonic models have been demonstrated to be a useful technique for quantifying temporal variations in strain rate and crustal thickness within recent plate kinematic studies. Using the GPlates software, deformable plate models offer an approach to visualize and assess the interplay of plate kinematics and deformation. However, several assumptions are imposed in previous studies that limit their ability to explain the crustal evolution of various tectonic regimes. Examples of these assumptions include, but are not limited to, the rigid nature of continental blocks and boundaries used to define deformable regions, and uniform crustal thickness assumptions at model start times. In this study, we address these assumptions with newly presented applications using the interplay of GPlates and its python programming library, pyGPlates. In particular, we demonstrate the ability to create deformable continental blocks, reconstruct present day crustal thickness estimates back through time, 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. To demonstrate their application and validity, these concepts are evaluated using a previously published deformable plate model of the southern North Atlantic that is tested using 4 modeling scenarios herein to assess the impact of variable model inputs. These models provide insight regarding the pre-Jurassic (200 Ma) crustal thickness template of the southern North Atlantic, the evolution of continental blocks during rift-related deformation, and the potential impact of ancient orogenic terranes during subsequent rifting within the North Atlantic.

Plain Language Summary The opening and closing of oceans and the development of Earth's



Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE
10.1029/2022GC010373

This article is a companion to King and Welford (2022), https://doi.org/10.1029/2022GC010372.

Key Points:
- Continental blocks had a large impact on pre-rift crustal thicknesses calculated within sedimentary basins throughout the North Atlantic
- The Flemish Cap, Porcupine Bank, and Rockall-Hatton Bank played a key role during rift related deformation throughout the North Atlantic
- Appalachian and Caledonian terrane boundaries were very influential on pre-rift templates calculated throughout the North Atlantic

Correspondence to:
M. T. King,
mtk282@mun.ca

Citation:
King, M. T., & Welford, J. K. (2022). Advances in deformable plate tectonic models: 2. Reconstructing the southern North Atlantic back through time. *Geochemistry, Geophysics, Geosystems*, *23*, e2022GC010373. https://doi.org/10.1029/2022GC010373

Advances in Deformable Plate Tectonic Models: 2. Reconstructing the Southern North Atlantic Back Through Time

Michael T. King[1] and J. Kim Welford[1]

[1]Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, Canada

Abstract The offshore rifted margins of the North Atlantic have a spatially complex crustal structure comprised of variable crustal morphologies, continental blocks, and inherited structures. Recently, deformable plate tectonic models have permitted the interplay of plate kinematics and deformation to be assessed throughout the North Atlantic, and elsewhere. In particular, the ability to calculate temporal variations in crustal thickness has provided insight into the kinematic role of continental blocks and their interplay with large and micro-tectonic plates during the formation of the North Atlantic offshore rifted margins. In this study, the deformable plate modeling workflow introduced in the companion contribution of this study (Part 1) is used to investigate previously published and newly presented deformable plate models of the Newfoundland, Irish, and West Iberian margins. This approach permits the deformation and subsequent crustal thickness evolution within previously recognized continental blocks and sedimentary basins throughout the southern North Atlantic Ocean to be visualized and assessed from 200 Ma to present day. The segmentation of early rift crustal thicknesses calculated by deformable plate models demonstrate strong correlations with the offshore extension of Appalachian and Caledonian terrane boundaries. Thus, our observations suggest that inherited orogenic boundaries potentially play a key role in the early rift crustal structure of sedimentary basins and the partitioning of deformation around and within continental blocks.

Plain Language Summary The Earth is made up of large and small tectonic plates that are actively moving and can have variable thicknesses and morphologies. Over the last 200 million years, the gradual separation between the North American and Eurasian plates has led to the formation of the southern North