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RESEARCH ARTICLE

# REVISED Orogenic bridge theory: towards a predictive tool for past and future plate tectonics

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## Abstract

Plate tectonics is a centerpiece of Earth's geodynamics and key to making our planet habitable, natural resources, geohazards and climate change, and the evolution of life. Understanding plate tectonics is increasingly important due to the ongoing energy transition. At the core of plate tectonics, the supercontinent cycle suggests that landmasses repeatedly accrete into supercontinents and then break up during rifting. Thus far, rifting was thought to gradually unzip continents from one another and to be mostly controlled by geodynamic processes (e.g. subduction, mantle plumes). Orogenic Bridge Theory (OrBiT) suggests another first-order factor controlling supercontinent breakup. It states that preexisting orogens perpendicular to active rifts hinder breakup, forcing rifts to adapt, e.g., by jumping, and localizing major transform faults. Orogens take longer to break due to their thickened crust and obliquity of related structures. Thus, while seafloor spreads on either side of rift-orthogonal orogens, extension continues to stretch the orogenic crust until breakup occurs there later. We call these regions of stretched continental crust flanked by oceanic crust "orogenic bridges". OrBiT implies that the extent of continental crust in the oceans may be underestimated and, thus, that our understanding of plate tectonics is incomplete. OrBiT may help refine future predictions of plate tectonics, e.g. localization of future rifts and transform faults, which are typical sites of natural resources and geohazards. OrBiT is based on a new global correlation of major transform faults with rift-orthogonal orogens and ongoing work at various potential orogenic bridges and continental margins, which are discussed herein. Further testing of this new theory is encouraged.

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**REVISED** **Amendments from Version 1**

The authors of the present manuscript have made significant changes to the manuscript, often rewriting entire paragraphs to better convey their message and ideas. Most of the figures were modified to include more details about the theory and/or better illustrate the structural relationships between old orogens and present-day transform faults. In addition, various paragraphs were added to existing sections and new sections and figures were added to further demonstrate the proposed theory.

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## Introduction

### New correlations

We report a remarkable correlation between the strike of major transform faults around the world and those of orogens and related contractional structures on adjacent continental margins. A striking characteristic of the orogens correlating with major transform faults is that they consistently strike highly oblique to orthogonal to the rift and mid-ocean ridge and parallel to the transform faults that offset the rift and mid-ocean ridge (Figure 1). Since the orogens are consistently older than the rifts and transforms with which they correlate (Figure 1), we propose that they played a central role in controlling the formation of the transform faults and in forcing the rift to step sideways and/or hindering (i.e., delaying or preventing) continental breakup, acting as potential barriers to rifting.

It has been possible to establish this correlation in great part due to major improvements in the quality of seismic reflection imaging and partly to our ability to now identify major shear zones (e.g., Bird *et al.*, 2016; Fazlikhani *et al.*, 2017; Hedin *et al.*, 2016; Lenhart *et al.*, 2019; Phillips *et al.*, 2016; Ye *et al.*, 2020), thrust systems and related contractional structures, whose seismic facies are now well established (e.g., Koehl, 2020; Koehl, 2021; Koehl, 2024a; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Koehl & Stokmo, 2024; Morley *et al.*, 2017). Although mylonitic detachments have been

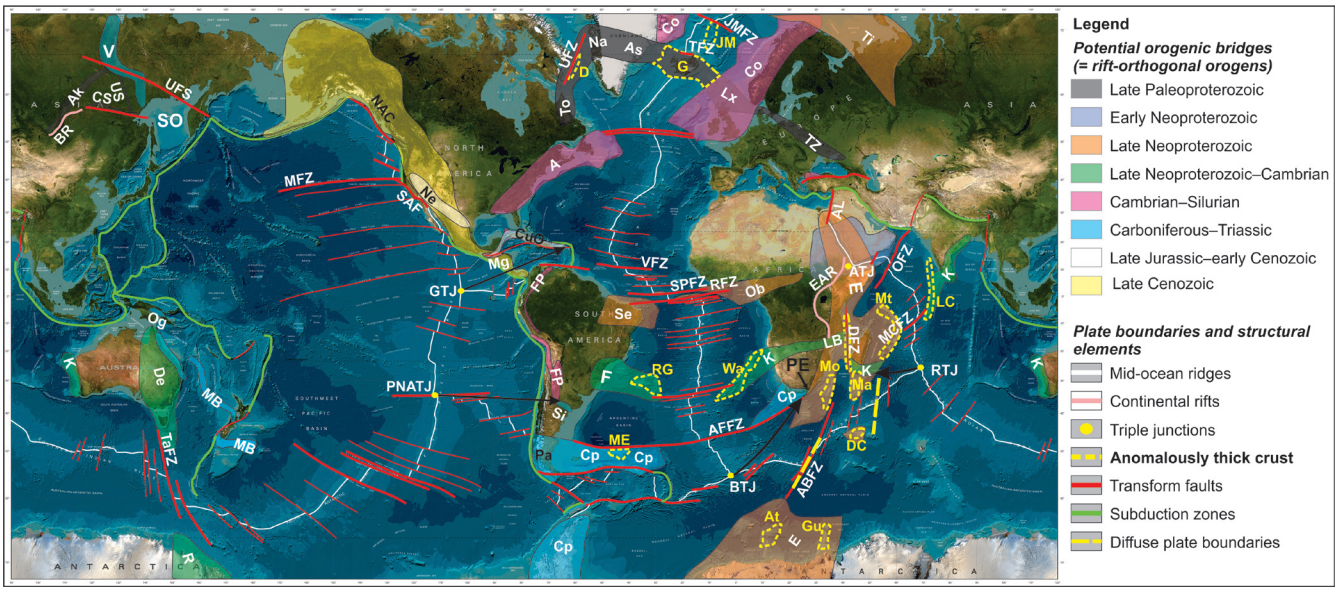


**Figure 1. World topographic and bathymetric map showing the location and extent of proposed orogenic bridges, related orogens (colored by age of last deformation events), and associated major transform faults (except the Timanian orogenic bridge in the Fram Strait).** The diffuse plate boundaries in the southwestern Indian Ocean are from Chu and Gordon (1999). The basemap is from Jakobsson *et al.* (2004). Abbreviations: A: Appalachian Orogen; AFFZ: Agulhas–Falkland fault zone; Ak: Akitkan Orogen; AL: Aqaba–Dead-Sea–Levant fault zone; As: Ammassalik Belt; At: Astrid Ridge; ATJ: Afar Triple Junction; BR: Baikal Rift; BTJ: Bouvet Triple Junction; Ca: Cape Fold Belt; Co: Caledonian Orogen; CS: Cis–Stanovoy Orogen; CuO: Cuban Orogen; DC: Del Cano Rise; DFZ: Davie fault zone; E: East African–Antarctica Orogen; EAR: East African Rift; F: Dom Feliciano Belt; FP: Famatinian–Pampean Orogen; G: Greenland–Iceland–Faroe Ridge; GTJ: Galapagos triple junction; Gu: Gunnerus Ridge; JMFZ: Jan Mayen fault zone; K: Kuunga Orogen; LB: Lurio Belt; LC: Laccadive–Chagos Ridge; Lx: Laxfordian Orogen; Ma: Madagascar Ridge; MB: Median Batholith; MCFZ: Marie Celeste fault zone; ME: Maurice Ewing Bank; MFZ: Mendocino fault zone; Mg: Motagua Suture Zone; Mo: Mozambique Ridge; Mt: Mauritia; Na: Nagssugtoqidian Orogen; NAC: North American Cordillera; O: Ne: Nevadan Orogen; Ob: Oubangides/Central African Orogen; OFZ: Owen fault zone; Og: Omung Group metamorphics; Pa: Patagonia; PE: Port Elizabeth; PNATJ: Pacific–Nazca–Antarctica Triple Junction; Pu: Puerto Rico; R: Ross Orogen; RFZ: Romanche fault zone; RG: Rio Grande Ridge; RTJ: Rodrigues Triple Junction; SAC: South African Cordillera in Colombia and Venezuela; SAF: San Andreas fault; Se: Sergipano Belt; Si: Sierra de la Ventana Fold-and-Thrust Belt; SO: Sea of Okhotsk; SPFZ: Saint Paul fault zone; Ta: Tasman–Delamerian–New England–Lachlan–Thompson–Mosman Orogen; TaFZ: Tasman fault zone; TFZ: Tjörnes fault zone; Ti: Timanian Orogen; To: Torngat Orogen; TZ: Tornquist Zone; UFS: Ulakhan fault system; UFZ: Ungava fault zone; US: Ulkan Orogen/Suture; V: Verkhoyansk Fold-and-Thrust Belt; VFZ: Vema fault zone; Wa: Walvis Ridge.

identified for some time on seismic data (e.g., Christensen, 1965; Fountain *et al.*, 1984; Hurich *et al.*, 1985), the spectrum of contractional structures correlated from onshore outcrops to subsurface seismic data was significantly broadened only very recently. It now includes stacks of thrust sheets separated by mylonitic shear zones, contractional duplexes, antiformal thrust stacks, and asymmetric (up to recumbent and isoclinal) folds within shear zones (Koehl, 2021; Koehl *et al.*, 2022; Koehl *et al.*, 2023a).

## Remaining challenges of plate tectonics

Plate tectonics, which evolved from Alfred Wegener's Continental Drift Theory (1929), governs our vision of the evolution of Earth's surface over time (e.g., Wilson, 1966). Surface movements are related to deep processes, which are thought to be a key component of present-day plate tectonics (e.g., Burke & Torsvik, 2004). However, deep processes do not explain all data, in particular offshore areas of anomalously thick crust (e.g., Iceland). Such crust typically displays continental affinities (e.g., Foulger *et al.*, 2020a).

Some major transform faults in the Atlantic and Indian oceans, e.g., the Romanche and Andrew Bain fault zones (Figure 1), do not conform with typical transform fault geometries. Instead, they comprise multiple segments (Ligi *et al.*, 2002) that bound slivers of lithosphere that switched movement direction as seafloor spreading progressed (the "oscillatory spreading" of Bonatti and Crane, 1982). These faults show the largest age offset of the mid-ocean ridges they truncate and most likely have a different thermal structure, i.e., they probably also involve cold lithosphere (Bonatti *et al.*, 2001; Ligi *et al.*, 2002). In addition, they do not lie on small circles about the Eulerian pole of rotation (Cande *et al.*, 1988; Chu & Gordon, 1999; Sclater *et al.*, 2005; Shaw & Cande, 1990), so their strikes do not fit well with the spreading direction. We explore the factors controlling the formation of major transform faults.

Large areas of (hyper-) extended continental crust have now been discovered offshore. New offshore continental blocks generally not included in full-plate-tectonic reconstructions (e.g., Cao *et al.*, 2021; Domeier & Torsvik, 2014; Merdith *et al.*, 2021; Young *et al.*, 2019) include the Lomonosov Ridge (Knudsen *et al.*, 2017; Rekant *et al.*, 2019), the Alpha–Mendeleev Ridge (Foulger *et al.*, 2024; Jackson & Chian, 2019), the De Long Islands block (Ershova *et al.*, 2016), the Laptev Sea (Shipilov *et al.*, 2021), portions of the Eurasian Basin (Jokat & Schmidt-Aursch, 2007), and the Chukchi Borderlands in the Arctic Ocean (Brumley *et al.*, 2015; O'Brien *et al.*, 2016). In the northeastern Atlantic Ocean, they include the Hovgård and East Greenland ridges (Dumais *et al.*, 2020), Icelandia (Foulger *et al.*, 2020a; Geoffroy *et al.*, 2022a), the Jan Mayen Microcontinent Complex (Bott, 1985; Johnson & Heezen, 1967; Schiffer *et al.*, 2018), the Rockall Plateau and Rockall Bank (Dickin, 1992; Roberts *et al.*, 1973), and the Davis Strait High in the northwestern Atlantic Ocean (Dafoe *et al.*, 2022). In the Central Atlantic Ocean, such blocks include the Newfoundland and Iberian margins (Lymer *et al.*, 2019; Shillington *et al.*, 2006). In the South Atlantic, blocks of continental affinity include the Walvis–Rio Grande Ridge (Fromm *et al.*, 2017a; Fromm *et al.*, 2017b; Santos *et al.*, 2019), a wide portion of the continental margin off Namibia (Geoffroy *et al.*, 2022b), and Maurice Ewing Bank and the Falkland Plateau (Chemale Jr. *et al.*, 2018; Stanca *et al.*, 2022). In the Indian Ocean, continental affinities are probable for the Mozambique and Madagascar ridges (Klimke *et al.*, 2018; Ryzhova *et al.*, 2022; Sato *et al.*, 2022), the Del Cano Rise (Sato *et al.*, 2022), Mauritia (Torsvik *et al.*, 2013), and Zealandia in the southwestern Pacific Ocean (Luyendyk, 1995; Mortimer *et al.*, 2006; Mortimer *et al.*, 2017).

The issues around transform faults and relatively recently discovered offshore continental blocks have major implications for past and present-day plate tectonics, the formation of oceanic crust at mid-ocean ridges, and the repeated opening and closing of oceans between the continents (e.g., opening and closing of Iapetus between Laurentia and Svalbard followed by the opening of the northeastern Atlantic Ocean). They imply that current models are overly simplistic and that revisions to the basic model should be considered. We propose a new approach and views that can address these issues. Notably, we propose that major transform faults form along rift-orthogonal orogens and that RRR triple junctions form at the intersection of two or more orogens. This new approach would also help predict future tectonic evolution of Earth's surface (e.g., propagation and steps in rift axis) and test the existence of paleo-transform faults. These ideas suggest less dynamism in paleo-plate tectonics. Whilst embracing modern plate tectonics, the new theory introduces a role for prolonged connection between continents locally and for limited time periods. This general concept was originally introduced in a simplistic form as Land Bridge Theory.

## Orogenic bridge theory (OrBiT)

Every major transform fault on Earth strikes parallel to an orogen and related structures on one or several adjacent rifted margins. By "major transform faults" we mean transform faults showing offset of active mid-ocean ridges greater than a few tens of kilometers. By "orogens", we mean belts deformed intensely during contractional strain for several tens of million years leading to the development of kilometer-wide, hundreds-of-kilometers long, kilometer-thick structures such as thrust faults, shear zones, folds, and other related fabrics. This process also forms crust thicker than regular, anorogenic 40 km-thick continental crust.

This relationship has been pointed out and investigated locally at a few margins by a few studies only (Buiter & Torsvik, 2014; Peace *et al.*, 2018). However, the global pattern defined by transform faults and rift-orthogonal orogens has received little attention despite the potential significant implications. This may be because of the challenge of doing the required interdisciplinary science, inhomogeneity of necessary data, and conflicting opinions and methods. Contributing issues may be outdated, faulty assumptions about the geology of specific areas, incomplete data particularly from remote areas (e.g., the Arctic, Fram Strait, and Davis Strait), or areas of poor exposure that are covered by young basins and sediments.

Geophysical data may also be limited in extent, especially in areas where it is more challenging to acquire, e.g., in mountainous onshore regions, whereas decades of exploration for natural resources in offshore areas like the North Sea have produced rich seismic reflection datasets.

In this paper, we review the relationship between major transform faults and preexisting orogens on adjacent margins across all oceans. Orogenic bridge theory (OrBiT) states that the style of continental rifting (e.g., orthogonal, oblique, transform) is controlled by preexisting orogens. Orogens parallel to a propagating rift will facilitate rifting and breakup, whereas orogens perpendicular to the opening rift form strong barriers and result in the development of orogenic bridges, which deflect the rift and/or delay breakup.

Preexisting orogenic belts striking parallel to a propagating rift will facilitate the opening and propagation of the rift and control the strike and geometry of structures formed during rifting. These include dominantly extensional structures such as brittle normal faults and ductile detachments bounding sedimentary basins and basement horsts and metamorphic core complexes (Figure 2a). This endmember ("rift-parallel endmember") has been discussed in several papers (e.g., Brune *et al.*, 2023; Chenin *et al.*, 2015; Corti *et al.*, 2022; Li *et al.*, 2023; Osagiede *et al.*, 2020; Péron-Pinvidic & Osmundsen, 2020; Péron-Pinvidic *et al.*, 2022; Salazar-Mora *et al.*, 2018).

Conversely, orogens striking highly oblique to perpendicular to a propagating rift ("rift-orthogonal endmember") will act as barriers and significantly hinder rift propagation, i.e., significantly

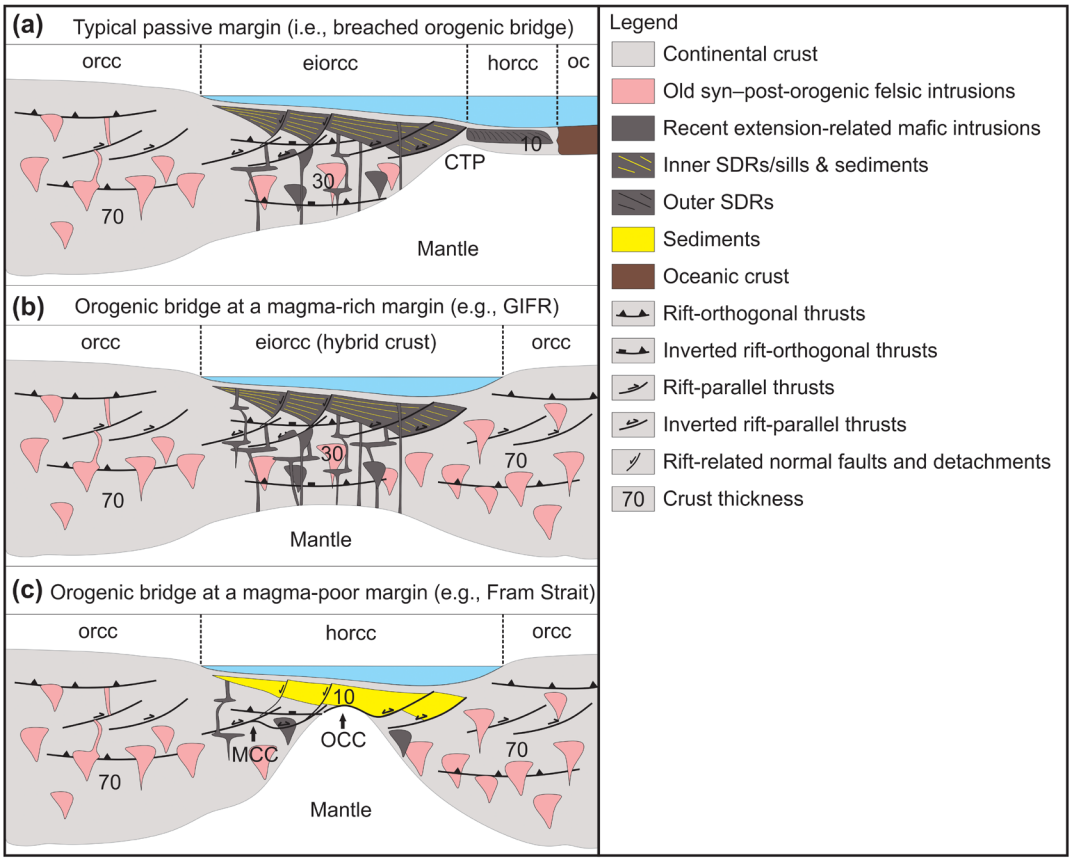


**Figure 2. Sketch illustrating different types of crusts.** (**a**) Typical rifted margin with thinned continental crust, SDRs, and oceanic crust (based on the new classification of SDRs and new margin architecture by Geoffroy *et al.*, 2022b). Note the occurrence of the continent–ocean boundary somewhat farther seaward than typically suggested. (**b**) Orogenic bridge at a magma-rich margin, e.g., the GIFR, where large amounts of mafic magma intruded thinned orogenic continental crust, thus producing hybrid continental crust (i.e., extensively intruded by mafic magma). (**c**) Orogenic bridge at a magma-poor margin, e.g., the Fram Strait, where metamorphic and oceanic core complexes formed both orthogonal (parallel to the section) and parallel (annotated on the sketch) to the active rift. In both (**b**) and (**c**), preexisting thrust systems parallel and perpendicular to the rift thinned the continental crust. This implies that the regions studied here were affected by at least two (non-coeval) orogenic events whose main stress were perpendicular to one another. Orogens (in the present case parallel to the propagating rift) generally show a dominant transport direction (i.e., the orogens are generally asymmetric rather than symmetric) and, therefore, the internal crustal asymmetry of continental margins in (**b**) and (**c**) is rather the rule than the exception. Abbreviations: CTP: Crustal Thin Point; eiorcc: extended and intruded orogenic continental crust; horcc: hyperextended orogenic continental crust; MCC: metamorphic core complex; oc: oceanic crust; OCC: oceanic core complex; orcc: orogenic continental crust; SDRs: seaward-dipping reflectors.

delaying breakup or preventing the rift from opening in a linear fashion or from propagating. This endmember has thus far been little studied (Molnar *et al.*, 2020). The term "orogenic bridge" refers to the orogenically thickened crust of a rift-orthogonal orogen, which was (hyper-) extended during rifting (Figure 2b and c) and is applied to areas of continental crust that extend further into the oceanic realm than normal passive margins. The term "bridge" is used in reference to the land bridges (also called Isthmian Links) inferred by the Land Bridge Theory to explain similar fauna and flora on separate continents, while rifting had already initiated (e.g., Gregory, 1929; Schuchert, 1932; von Ihering, 1931; Willis, 1932). All the previously proposed land bridge sites match the location of hereby proposed orogenic bridges, thus suggesting that parts of Land Bridge Theory may hold the key to unlocking a more advanced understanding of plate tectonics (Figure 1).

Despite the apparent correlation of the location of some of the proposed orogenic bridges with that of so-called land bridges, orogenic bridges are clearly different from land bridges. While land bridges imply continent fixity, orogenic bridges work in symbiosis with plate tectonics and extend and contract together with adjacent plate segments undergoing seafloor spreading. This is due to the fact that preexisting thrust systems at orogenic bridges strike dominantly oblique to orthogonal to the active rift (Figure 3a–b). As such, these structures are unsuitable to accommodate crustal thinning (Figure 3c). In addition, the low-angle character of thrust faults makes them unsuitable to accommodate transform movements. However, their rift-orthogonal orientation is suitable to control the formation of new subvertical transform faults. Thus, rift-orthogonal thrust systems hinder rifting, forcing the rift to jump or bypass certain areas (e.g., Greenland–Iceland–Faroe Ridge; Figure 3d). While oceanic crust forms on either side of orogenic bridges, the continental crust at orogenic bridges continues to stretch until break up occurs there too. Should there be any speed difference between seafloor spreading at mid-ocean ridges and stretching within the thinning orogenic bridge, these may be accommodated by transform faults at the continent–ocean boundary.

Clear evidence of the reworking of orogenic bridges during orogenesis and rifting are shown in Koehl *et al.*, (2024; 2025). Notably at the GIFR, WNW–ESE-striking late Paleoproterozoic thrust systems of the Laxfordian–Nagssugtoqidian Orogen interpreted within the GIFR and adjacent continental margins of the Faroe Islands and southeastern Greenland (Figure 3a) were reworked as 100–200 km wide open anticlines during the Caledonian Orogeny (i.e., shortened orogenic bridge; Figure 3b) and were later inverted during post-Caledonian extension, thus contributing to thinning the crust (extending orogenic bridge; Koehl *et al.*, 2024 their figure 2e; Koehl *et al.*, 2025; Figure 3c).

Should rifting continue long enough, rift-orthogonal orogens will force the rift to reorient locally (e.g., Molnar *et al.*, 2017) to accommodate a major sideway step (Figure 3d) before propagating further or merging two propagating rifts on either side of an orogenic bridge. An example is the parallel northeastern Atlantic (Mohns Ridge) and Arctic rifts (Gakkel Ridge) that are linked via the oblique Fram Strait rift (Knipovich Ridge, Molloy Deep, and Lena Trough), which opened tens of millions of years after seafloor spreading initiated at the Mohns and Gakkel ridges. As a result, rift-orthogonal orogens are thought to localize the formation of major (> a few tens of kilometers lateral offset) transform faults.

Through the concept of offshore orogenic bridge (Figure 3a–d), Orogenic Bridge Theory suggests that a fair portion of the submarine areas around the globe consists of (hyper-) extended and/or extensively intruded (i.e., hybrid) orogenic continental crust (Figure 2b and c). Rift-related (hyper-) extension of continental crust, the intrusion of continental crust by large volumes of mafic magma at magma-rich rift segments, and the occurrence of thickened orogenic crust with structures striking orthogonal to propagating rifts all together may, thus, explain present-day datasets. Land bridges were once proposed by knowledgeable geoscientists in the early 20th Century. It is therefore not surprising that they may hold some truth after all.

OrBiT highlights a new relationship between major transform faults and rift-orthogonal orogens by demonstrating the occurrence of ridges of orogenically-thickened, (hyper-) extended continental crust (orogenic bridges) striking perpendicular to propagating rifts offshore. It suggests that the amount of oceanic crust on Earth and, consequently, the amount of horizontal movement by the continental blocks over the history of the Earth are currently overestimated. OrBiT also potentially enables the prediction of the location of future rift steps, transform faults, rift propagation, and breakup.

## Previous work

Large-scale relationships in the Atlantic Ocean were discussed by Lundin & Doré (2005). They noted a coincidence of Neoproterozoic–Phanerozoic fold-and-thrust belts with the volcanic segments of the continental rifted margins. However, the Central African Orogen/Oubangides branch of the Pan African Orogeny, which strikes E–W and separates the Sahara meta-craton from the Congo craton (e.g., Kouémo *et al.*, 2014; Kröner & Stern, 2004; Toteu *et al.*, 2022) and extends into northeastern Brazil as the Sergipano Belt (D'el-Rey Silva, 1999; Finoto Bueno *et al.*, 2009; Oliveira *et al.*, 2006; Oliveira *et al.*, 2010; Oliveira *et al.*, 2015; Figure 1) was not included. With the addition of this orogen, the relationship of volcanic margins with preexisting orogens and of non-volcanic margins with the absence of preexisting orogens becomes tenuous. Another disagreement is the occurrence of the Timanian Orogen at the magma-poor segment of the northeastern Atlantic rift in the Fram Strait along the western Svalbard–Barents Sea margin and the northern Greenland margin (Estrada *et al.*, 2018a; Klitzke *et al.*, 2019; Koehl, 2020; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl, 2024b; Rosa *et al.*, 2016).

Lundin *et al.* (2022) further highlighted the relationship of preexisting orogens with the location of major transform faults, showing that the continental crust at transform margins

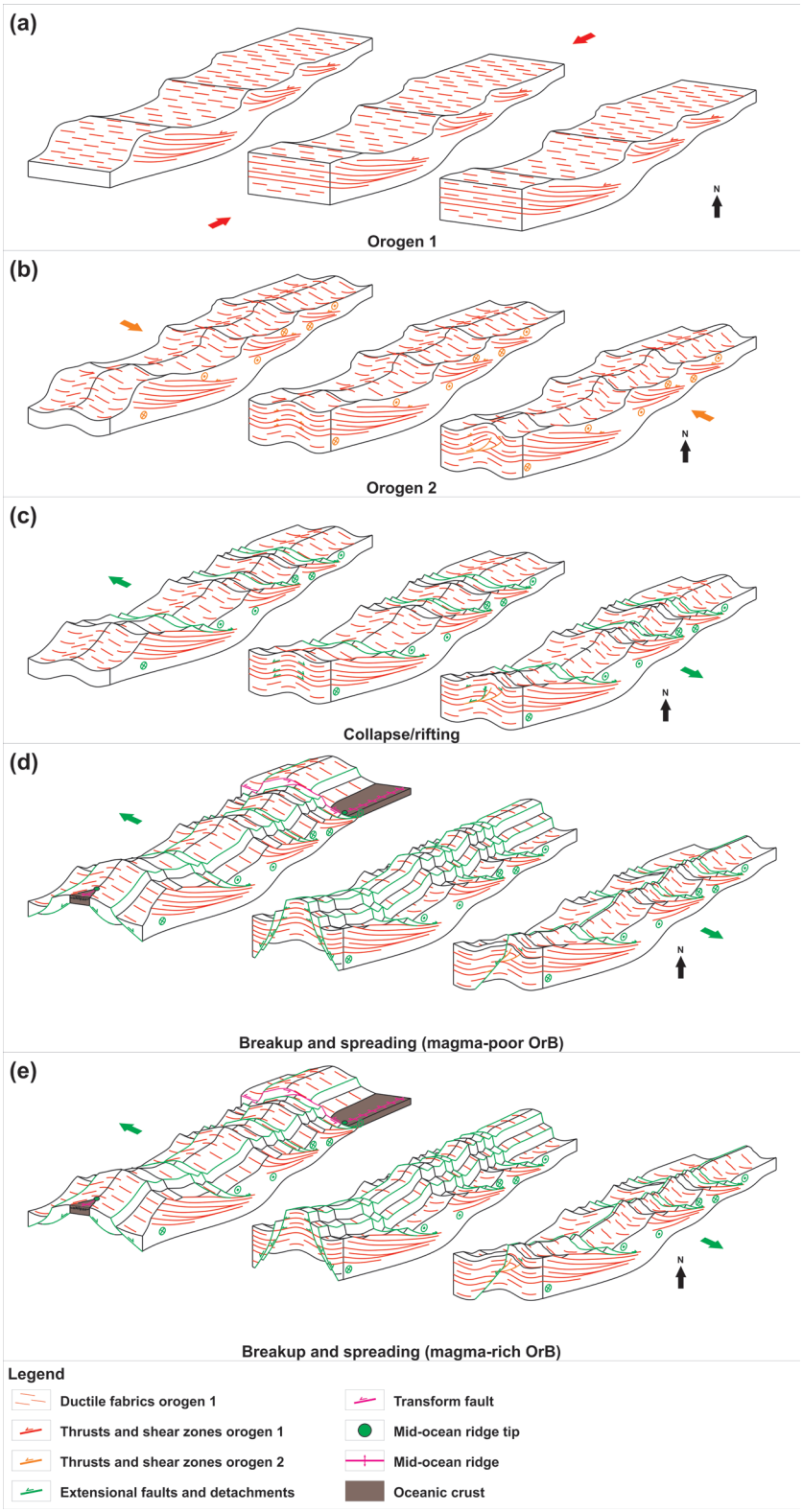


**Figure 3. Development of orogenic bridges.** (**a–b**) Orogenic bridges typically form through at least two orogeneses perpendicular to one another, which allows tightening and locking of the crust, e.g., in the case of the GIFR (**a**) WNW–ESE-striking Laxofordian–Nagssugtoqidian Orogen and (**b**) NE–SW-striking Caledonian Orogen. (**c**) Several episodes of post-orogenic extension (e.g., in the Devonian, Permian–Triassic, and Jurassic–Cretaceous at the GIFR) are accommodated along extensional faults and detachments formed along inherited orogenic structures. (**d**) Breakup occurs along inherited, reactivated and/or overprinted orogenic structures. In the case of the GIFR breakup occurred first in the Cenozoic at the Reykjanes Ridge south of the GIFR and at the Ægir Ridge northeast of the GIFR. Note that any number of additional orogeneses and/or extensional collapse/rifting may be added in between these events. Abbreviations: GIFR: Greenland–Iceland–Faroe Ridge; TFZ: Tjörnes fault zone. Modified after Koehl *et al.* (2024).

is on average thicker than the continental crust at rifted margins. This supports the orogenically-thickened character of the continental crust at major transform margins (e.g., Fram Strait). Other studies suggested that oblique and associated major transform fault systems may result in asymmetric hyperextended margins (e.g., Le Pourhiet *et al.*, 2017). However, these studies did not address the causes of major rift offsets or steps.

Another relevant study is the modeling of the influence of preexisting zones of weakness in the crust and mantle on rifting (Dunbar & Sawyer, 1989). While mantle weaknesses were suggested to explain the formation of "wet" rifts with intense magmatism and narrow passive configurations, crustal weaknesses were associated to the formation of "dry" rifts and broad passive margins. Like Lundin & Doré (2005), this study attempted to relate zones of intense magmatism with preexisting structural fabrics.

Other studies investigated the impact of oblique preexisting discontinuities on rift segmentation and obliquity (e.g., Brune *et al.*, 2017; Brune *et al.*, 2018; Molnar *et al.*, 2017; Zwaan *et al.*, 2021). However, they did not address the formation of transform faults and the specific influence of preexisting orogens, which the present study attempts to generalize for the first time.

## Discussion

### Extent of continental vs oceanic crust

#### *Potential Orogenic Bridges (OrBs)*

Potential orogenic bridges we discuss include the Fram Strait (Dumais *et al.*, 2020; Koehl, 2020; Koehl & Mottram, 2024; Koehl *et al.,* 2025 awaiting peer review; Koehl *et al.*, 2021), the Greenland–Iceland–Faroe Ridge (GIFR; Foulger *et al.*, 2003; Foulger *et al.*, 2020a; Foulger *et al.*, 2020b; Foulger, 2006; Geoffroy *et al.*, 2022a; Torsvik *et al.*, 2015), and the Davis Strait (Dafoe *et al.*, 2022; Dalhoff *et al.*, 2006) in the North Atlantic region. We also discuss Maurice Ewing Bank and the Falkland Plateau (Chemale Jr. *et al.*, 2018; Stanca *et al.*, 2022) in the South Atlantic, and the Mozambique, Madagascar, and Gunnerus ridges and the Del Cano Rise (Klimke *et al.*, 2018; Leitchenko *et al.*, 2008; Sato *et al.*, 2022) in the Indian Ocean.

#### Continuous Orogenic Bridges (OrBs)

The concept of continuous orogenic bridge implies that continental crust continues across a previously inferred oceanic domain. In such areas, true oceanic crust is proposed to be absent (i.e., not yet present and overestimated by 100%). Instead, these areas may include possible sections of hybrid crust (see Figure 2a and b) – continental crust capped by thick successions of volcanic rocks (e.g., lava flows) and extensively intruded by igneous rocks (e.g., seaward-dipping reflectors). Sections of hybrid crust are locally believed to extend the width of previously assumed oceanic domains. Three potentially continuous orogenic bridge are discussed here, the Timanian orogenic bridge in the Fram Strait, the Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and the Greenland–Iceland–Faroe orogenic bridge (Figure 4).

*Timanian orogenic bridge*

The recent discovery of continuous, late Neoproterozoic Timanian thrust systems extending from northwestern Russia to the Svalbard Archipelago through the Barents Sea has dramatically changed our perception of the pre-Caledonian tectonic history in this entire region (Koehl, 2020; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl, 2024b; Figure 4). Some of these structures can be traced across the magma-poor Fram Strait (e.g., in the Hovgård Ridge; Koehl, 2020 pp. 163–166; Koehl *et al.*, 2021) into blocks of continental crust that are now known to be fully attached to Laurentia and Greenland's continental crust (Dumais *et al.*, 2020; Figure 4). While the Svalbard margin thins rapidly and is relatively narrow (< 200 km), the Greenland margin is much broader (up to 600 km at the East Greenland Ridge; Figure 4), which is possibly related to the dominant top-east vergence of Caledonian thrusts (rift-parallel endmember of OrBiT; e.g., Koehl, 2024b; Ohta *et al.*, 1986; Ohta *et al.*, 1995).

New magnetic data at the Knipovich Ridge by Dumais *et al.* (2020) and seismic reflection data between the Molloy and Spitsbergen fault zones (Koehl, 2020 pp. 167–180, Koehl *et al.*, 2021 pp. 9–20; Figure 4) show that there is little to no oceanic crust *sensu stricto* along the Molloy Ridge. Seismic reflection data nevertheless show thin layers of volcanics and possibly mantle exhumed along extensional detachments, e.g., a possible core complex parallel to the Molloy fault zone (Koehl, 2020; Koehl *et al.*, 2021). This together with the dramatically thin character of the continental crust on the northeastern Greenland margin indicate that the crust is hyperextended and is generally thinner than 12 km except at the Hovgård Ridge and East Greenland Ridge where it is about 12 km (Døssing *et al.*, 2008; Dumais *et al.*, 2020; Ritzmann *et al.*, 2004). Furthermore, Timanian subduction-related magmatism was recently identified in northern Greenland (Estrada *et al.*, 2018a; Rosa *et al.*, 2016), Arctic Canada (Estrada *et al.*, 2018b), and the Lomonosov Ridge (Rekant *et al.*, 2019; Figure 4), further supporting the continuation of the Timanian Orogen across the northeastern Atlantic–Arctic rift.

Most studies of seismic reflection data west of Svalbard show that the margin lacks evidence of strike-slip movements (Austegard *et al.*, 1988; Eiken, 1994; Eiken & Austegard, 1987; Gabrielsen *et al.*, 1990; Lasabuda *et al.*, 2018; Riis & Vollset, 1988). This is surprising given the expectation of a major N–S-striking paleo-transform there, the so-called De Geer Zone (Figure 4), which has been inferred on the basis of the linear geometry of the Svalbard–Barents Sea margin and the conjugate margin in northern Greenland (du Toit, 1937; Harland, 1961; Harland, 1967; Harland, 1969; Horsfield & Maton, 1970; Wegmann, 1948). Recent studies show that several late Neoproterozoic Timanian thrust systems extend past the speculated location of the early Cenozoic De Geer Zone without any lateral offset (Koehl, 2024b). This suggests that Timanian thrusts may extend from northwestern Russia to northern Greenland thus forming a continuous orogenic bridge across the Fram Strait (Figure 4). The two active transform faults in the Fram Strait,




**Figure 4. International Bathymetric Map of the Arctic Ocean showing the continent–ocean boundary, continental blocks, major orogens and associated thrust faults, and major transform faults in Arctic regions.** Three orogenic bridges are proposed in the area: the Timanian orogenic bridge in the Fram Strait, the Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and the Greenland–Iceland–Faroe orogenic bridge between Greenland, Iceland, and the Faroe Islands (the Greenland–Iceland–Faroe Ridge – GIFR). Basemap is from Jakobsson *et al.* (2012). Abbreviations: AB: Ammassalik Belt; AR: Alpha–Mendeleev Ridge; BB: Bjørnøya Basin; BFZ: Bight fault zone; CGFZ: Charlie Gibbs fault zone; CO: Caledonian Orogen; DGZ: De Geer Zone; DSH: Davis Strait High; EGR: East Greenland Ridge; EJMFZ: East Jan Mayen fault zone; FB: Farsund Basin; HB: Hammerfest Basin; HR: Hovgård Ridge; JM: Jan Mayen Microcontinent Complex; KO: Ketilidian Orogen; KoR: Kolbeinsey Ridge; KnR: Knipovich Ridge; LO: Laxfordian Orogen; LaR: Labrador paleo-mid-ocean ridge; LoR: Lomonosov Ridge; LRATJ: Labrador–Reykjanes–Mid-Atlantic paleo triple junction; MAR: Mid-Atlantic Ridge; MF: Moray Firth; MFZ: Molloy Fault Zone; MJR: Morris Jesup Rise; MO: Makkovikian Orogen; MR: Mohns Ridge; NJT: North Sea failed triple junction; NO: Nagssugtoqidian Orogen; SFZ: Spitsbergen Fault Zone; STZ: Sorgenfrei–Tornquist Zone; TiO: Timanian Orogen; TO: Torngat Orogen; TTZ: Teisseyre–Tornquist Zone; UFZ: Ungava Fault Zone; WBTJ: Western Barents Sea failed triple junction; WF: Wegener Fault; WJMFZ: West Jan Mayen fault zone; YP: Yermak Plateau; ÆR: Ægir Ridge.

the Molloy and Spitsbergen fault zones, strike parallel to and probably developed along preexisting Timanian thrusts (Koehl *et al.*, 2021; Koehl & Mottram, 2024; Koehl *et al.*, 2025 awaiting peer review).

The proposed late Neoproterozoic (650–550 Ma) age of the rift-orthogonal orogen in the Fram Strait, which is supported by various geochronological studies throughout Svalbard (Koglin *et al.*, 2022; Koehl & Mottram, 2024; Manecki *et al.*, 1998;

Majka *et al.*, 2008; Majka *et al.*, 2012) is a conservative estimate. It is possible that the orogen in the Fram Strait and the Barents Sea may be part of the late Paleoproterozoic Svecofennian Orogen, which crops out in western Troms in northern Norway and displays the same structural trend (WNW–ESE) and dominant thrust vergence (top-SSW) as the Timanian Orogen (Bergh *et al.*, 2010; Bergh *et al.*, 2022). The Svecofennian Orogen is a time-equivalent to the Laxfordian and Nagssugtoqidian orogens, which if traces of late Paleoproterozoic orogenesis were to be found in Svalbard and the Barents Sea would suggest a first-order impact of this ca. 1.9–1.8 Ga orogenic event on Orogenic Bridge Theory and resulting plate tectonics.

*Nagssugtoqidian–Torngat orogenic bridge*

The Davis Strait connects the Labrador Sea, which is undoubtedly partly underlain by oceanic crust (e.g., Oakey & Chalmers, 2012; Peace *et al.*, 2016), and Baffin Bay, where the existence of oceanic crust is more speculative (e.g., Funck *et al.*, 2012; Welford *et al.*, 2018). Along the strait, a major transform fault, the Ungava Fault Zone (Chalmers & Pulvertaft, 2001; Dafoe *et al.*, 2022; MacLean *et al.*, 1982; Oakey & Chalmers, 2012) along which the mid-ocean ridge is believed to have stepped, flanks a basement high, the Davis Strait High, which is thought to be of continental nature based on dredge samples (Dalhoff *et al.*, 2006) and seismic reflection data (Dafoe *et al.*, 2022).

On either side of the strait, numerous onshore studies have revealed well-developed Paleoproterozoic orogenic structures of the ENE–WSW-striking Nagssugtoqidian Orogen in western Greenland (Mengel *et al.*, 1998; van Gool *et al.*, 2002a) and of the N–S-striking Torngat Orogen in northeastern Canada (van Gool *et al.*, 2002b; van Gool *et al.*, 2005; Figure 1 and Figure 4). Despite being highly oblique, the two orogens are believed to merge with one another in the Davis Strait and to be part of the same (folded? Indented?) orogen. In northeastern Canada, the Torngat Orogen appears to curve into an ENE–WSW strike in northern Labrador–southeastern Baffin Island, thus potentially forming an arch hundreds of kilometers wide with the Nagssugtoqidian Orogen in map view (Figure 4).

This arch is interpreted as a potentially continuous orogenic bridge (Figure 4) given the continental nature of the Davis Strait High (Dafoe *et al.*, 2022; Dalhoff *et al.*, 2006). This is supported by consistent kinematics in both orogens, i.e., sinistral shear zones and top-SSE (i.e., hanging wall moving to the south-southeast) thrusts in the Nagssugtoqidian Orogen and sinistral shearing and top-east thrusting in the Torngat Orogen (Mengel *et al.*, 1998; van Gool *et al.*, 2002a; van Gool *et al.*, 2002b; van Gool *et al.*, 2005). The continuity character of the Nagssugtoqidian–Torngat orogenic bridge is consistent with the absence of apparent lateral offset of the orogen across the Ungava Fault Zone. The latter was recently proposed to have formed along preexisting late Paleoproterozoic structures of the Torngat Orogen based on seismic reflection interpretation and modeling (Heron *et al.*, 2019; Peace *et al.*, 2018). This calls for further reexamination of movements along this major fault.

*The Greenland–Iceland–Faroe Ridge orogenic bridge*

The 25–40 km thick crust below the GIFR (Darbyshire *et al.*, 1998) has long been interpreted as thick oceanic crust formed through the activity of a deep mantle plume, with magmatism initiating at ca. 62 Ma or 54 Ma or even 252 Ma depending on the model (e.g., Torsvik *et al.*, 2015; White & McKenzie, 1995). The anomalously thick crust nevertheless suggests that a continental/hybrid crustal model, i.e., continental crust extensive intruded by mafic magma (Figure 2a and b) should be considered (Foulger *et al.*, 2003; Foulger *et al.*, 2020a; Foulger, 2006; Geoffroy *et al.*, 2022a). Foulger *et al.* (2020a) suggested that the GIFR might represent a section of previously orogenically-thickened but now stretched continental crust, which presented high resistance to rifting and continental breakup. They suggested that this anomalous crust could be the northern continuation of the western frontal thrust of the Caledonian Orogen in Scotland and might link with the Caledonides of southeastern Greenland.

This model is plausible considering the similarly abrupt (c. 90°) bend of the Scandinavian Caledonides in the southern Barents Sea (Gernigon & Brönner, 2012; Gernigon *et al.*, 2014) from an overall NE–SW strike in Norway and Sweden (e.g., Corfu *et al.*, 2014; Roberts, 2003) to a N–S trend in Svalbard (e.g., Harland *et al.*, 1992; Manby, 1986; Witt-Nilsson *et al.*, 1998). Other orogens worldwide show similar 90° bends (e.g., Verkhoyansk Orogen in northeastern Russia; Figure 1). However, the model neglects the Scandinavian Caledonides, which were proposed to represent the continuation of the southern Scottish Caledonides (e.g., Coward, 1990; Fossen, 2010; McClay *et al.*, 1986; Norton *et al.*, 1987).

If the Scottish Caledonides represent the continuation of the southeastern Greenland Caledonides, it is unclear how and where the Scandinavian Caledonides continue to the southwest. In addition, this model requires not one but two abrupt c. 90° bends of the Caledonian Orogen, and the required two bends of the Caledonian Orogen would have to be generated by overall NW–SE-oriented Cenozoic extension during rifting. This is unlikely because NW–SE extension is more likely to have inverted and overprinted NE–SW-striking Caledonian structures instead of deflecting them by 90°. Major post-Caledonian shear zones onshore southern and western Norway are now known to extend in a northeast–southwest strike offshore (Fazlikhani *et al.*, 2017; Fossen & Hurich, 2005; Lenhart *et al.*, 2019; Osagiede *et al.*, 2020; Phillips *et al.*, 2016; Serck *et al.*, 2022) and to merge with their analogously striking counterparts in the northern UK (Bird *et al.*, 2016; Coward *et al.*, 1989; Platt & Cartwright, 1998).

An alternative source for orogenically thickened crust below the GIFR may be the Paleoproterozoic, WNW–ESE-striking Ammassalik Belt, the probable continuation of the Nagssugtoqidian Orogen in southeastern Greenland (Figure 1 and Figure 4; Bridgewater & Myers, 1979; Chadwick & Vasudev, 1989; Chadwick *et al.*, 1989; van Gool *et al.*, 2002b; van Gool *et al.*, 2005). Major structures in the belt show top-SSW kinematics consistent with structures in the Nagssugtoqidian Orogen in western Greenland (Kalsbeek *et al.*, 1993;

van Gool *et al.*, 2002b; van Gool *et al.*, 2005). Another alternative is the Ketilidian Orogen in southern Greenland (Chadwick *et al.*, 2000; Garde *et al.*, 1997; Garde *et al.*, 2002a), but it occurs further to the southwest. The coeval Ammassalik Belt is a possible candidate (Figure 4).

In northern Europe, the correlate of the Ammassalik Belt is the late Paleoproterozoic Laxfordian Orogen on the Rockall Plateau and northern Scotland. This orogen was thought to consists of WNW–ESE-striking, subvertical shear zones showing strike-slip kinematics (Attfield, 1987; Coward & Park, 1987; Dickin, 1992). However, recent mapping on reprocessed seismic reflection data has revealed that the Laxfordian shear zones onshore northern Scotland are part of much larger structures, namely tens of km thick, WNW–ESE-striking, dominantly NNE-dipping thrust systems around the Faroe Islands (Koehl *et al.*, 2024). These were reworked into hundreds of km wide, NE–SW-striking open folds during the Caledonian Orogeny and extend beyond the seaward-dipping reflectors and previously assumed continent–ocean boundary off the Faroe Islands (Koehl *et al.*, 2024). Ongoing seismic mapping at the GIFR indicates that these late Paleoproterozoic structures extend to below southeastern Iceland and thus that the Iceland–Faroe segment of the GIFR is largely continental (Koehl *et al.*, 2025).

The hundreds of km wide, NE–SW-striking open folds mapped along the entire length of the GIFR by Hjartarson *et al.* (2017) coincide with the Caledonian folds reworking late Paleoproterozoic structures off the Faroe Islands and at the Iceland–Faroe Ridge (Koehl *et al.*, 2024; Koehl *et al.*, 2025). This may explain the thickness variations of the GIFR along its length (i.e., in a WNW–ESE direction; Hjartarson *et al.*, 2017 their figure 3c). This also suggests that the ca. 1.8 Ga U–Pb age obtained for zircons from basalts in southeastern Iceland (Schaltegger *et al.*, 2002), where Laxfordian thrust systems occur at shallow crustal level (c. a few km; Koehl *et al.*, 2025), may be genuine. Further efforts should therefore concentrate on dating zircons from lavas in southeastern Iceland.

In eastern Europe, the WNW–ESE-striking Tornquist Zone, i.e., the Teisseyre–Tornquist Zone (Krzywiec *et al.*, 2022; Mazur *et al.*, 2015) and its probable continuation the Sorgenfrei–Tornquist Zone (Ponikowska *et al.*, 2024), extends from the Black Sea (Mikolajczak *et al.*, 2019; Narkiewicz *et al.*, 2015) to the southern North Sea (Kalani *et al.*, 2020; Phillips *et al.*, 2018) and is a natural potential continuation for some of the Laxfordian structures at the GIFR and off the Faroe Islands (Koehl *et al.*, 2024; Koehl *et al.*, 2025; Figure 4). Available seismic reflection data in the central and northern North Sea and west of the Faroe Islands suggest that the Sorgenfrei–Tornquist Zone may continue as far north as the Shetland Plateau (e.g., Bird *et al.*, 2016; Fossen & Hurich, 2005; Gabrielsen *et al.*, 2015; Koehl, 2025; Serck *et al.*, 2022). The Tornquist Zone accommodated significant contractional deformation and related crustal thickening as early as the Neoproterozoic during the closure of the Tornquist Ocean (Torsvik & Rehnström, 2003). The Tornquist Zone possibly consists of top-northeast (Abramovitz *et al.*, 1999; Krzywiec *et al.*, 2017; Lyngsie & Thybo, 2007; Mazur *et al.*, 2015; Mazur *et al.*, 2018) and top-SSW thrusts (Phillips *et al.*, 2018 their figures 2 and 11; Koehl, 2025).

Both the Tornquist Zone in Europe and structures of the Ammassalik Belt in southeastern Greenland parallel the GIFR and the Tjörnes fault zone, a major right-lateral complex shear zone in northern Iceland that connects the Icelandic Northern Volcanic Zone and the Kolbeinsey Ridge, i.e., a c. 100 km offset of the rift axis (Einarsson, 1976; Einarsson, 1991; Khodayar, 2018; Khodayar & Björnsson, 2018; Rögnvaldsson *et al.*, 1998; Young *et al.*, 1985; Figure 4). We therefore propose that the GIFR represents a continuous orogenic bridge, which is currently preventing through-going propagation (or unzipping) of the Mid-Atlantic Ridge.

The c. 100 km offset of the rift axis along the Tjörnes fault zone is relatively modest. However, many major transform faults may have initiated with small offsets, e.g., the Andrew Bain, Charlie Gibbs, and San Andreas fault zones (e.g., Mueller & Jokat, 2019 their figure 15; Seton *et al.*, 2012 their figures 4 and 10; Vormann & Jokat, 2021 their figure 3). The offset at the Tjörnes fault zone may grow over time should seafloor spreading continue and rifting possibly rupture the GIFR orogenic bridge. The Kolbeinsey Ridge only recently took over spreading (at ca. 22 Ma) from the now-extinct Ægir Ridge, which is offset from the Reykjanes Ridge by ≥ 350 km (e.g., Blischke *et al.*, 2016; Gernigon *et al.*, 2020). Thus, the small present offset at the Tjörnes fault zone may reflect its embryonic development stage.

Further analysis of geophysical data at the GIFR is ongoing. Further attention should be given to the expression of Paleoproterozoic structures of the Ammassalik Belt and Laxfordian Orogen on offshore seismic reflection data at the GIFR because of the well-constrained top-SSW kinematics and NNE-dipping geometry onshore (e.g., Kalsbeek *et al.*, 1993) and offshore continuation into the GIFR (Koehl *et al.*, 2024; Koehl *et al.*, 2025), and our present ability to identify deep-seated orogenic structures and thrust systems on seismic reflection data (e.g., Fazlikhani *et al.*, 2022; Freeman *et al.*, 1988; Hedin *et al.*, 2016; Juhlin *et al.*, 2016; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Platt & Cartwright, 1998).

Previous studies have suggested that continental crust beneath Iceland is connected to the Jan Mayen Microcontinent Complex (Torsvik *et al.*, 2015). Northeast of Jan Mayen, the West and East Jan Mayen fault zones are parallel to late Paleoproterozoic orogenic structures in northern and southern Scandinavia (Svecofennian–Svecokarelian Orogen; Bergh *et al.*, 2010; Johansson *et al.*, 2015; Saintot *et al.*, 2011) and at the GIFR and northern Scotland (Coward & Park, 1987; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Figure 4). These transform faults, as depicted in Blischke *et al.* (2022 their figure 5a), dip gently at depth and display a geometry more typical of thrust faults. This and the occurrence of wiggly

seismic reflections along the entire length of the Jan Mayen Microcontinent Complex, which probably represent contractional asymmetric folds (e.g., Koehl, 2021; Koehl *et al.*, 2022), strongly suggest that deep rift-orthogonal orogenic structures controlled the formation of the Jan Mayen fault zones. Like in northern Scotland, northern Norway, and elsewhere, these late Paleoproterozoic orogenic structures were mildly reworked during the Caledonian Orogeny (e.g., Koehl *et al.*, 2024; Koehl *et al.*, 2025).

Knowing that the Baltica craton already existed in the late Paleoproterozoic, it is logical that late Paleoproterozoic structures analogous to those found at the surface in northwestern Norway (the West Troms Basement Complex; Bergh *et al.*, 2010; Bergh *et al.*, 2015) and southern Sweden (Johansson *et al.*, 2015; Saintot *et al.*, 2011) continue at depth below Caledonian nappes to the northwest where they were reworked by Caledonian contraction. Their original geochronological signal was most likely overprinted in many places. Thus, late Paleoproterozoic rift-orthogonal orogenic structures should be expected at depth along the entire length of the Norwegian continental shelf in the northwest, including adjacent to the Jan Mayen Microcontinent Complex and Jan Mayen fault zones. The presence of such structures could be tested using the dense coverage of 2D–3D seismic reflection data in Norway. As such, the Jan Mayen Microcontinent Complex represents a ruptured segment of the discussed late Paleoproterozoic orogenic bridge between Greenland and Europe and was rifted in the Cenozoic from Europe by seafloor spreading at the extinct Ægir Ridge and from Greenland by ongoing oceanic crust formation at the Kolbeinsey Ridge (Figure 4).

**Ruptured orogenic bridges**

Numerous orogenic bridges were previously continuous and have now been ruptured by rifting. Here we discuss two notable examples – the late Paleozoic Cape Fold Belt in South Africa and its continuation into the Falkland Plateau and Maurice Ewing Bank off the southeastern coast of South America (Figure 5a–b) and the late Neoproterozoic East African–Antarctica Orogen, which extends from the Arabian–Nubian Shield in the north to Dronning Maud Land in Antarctica in the south (Figure 6). In the examples discussed, the overestimation of the extent of oceanic crust is in the order of c. 20–60% for the conjugate margin pairs.

*The Appalachian–Caledonian orogenic bridge*

The western Irish and Newfoundland margins form prominent salients of continental crust (Figure 7; Chian *et al.*, 2001; Pe-Piper *et al.*, 2013; Yang *et al.*, 2021). The Newfoundland margin was subjected to Ordovician–Silurian contraction (up to Devonian in places) during the closure of the Iapetus and Rheic oceans, which resulted in the formation of the Appalachian Orogen (e.g., van Staal *et al.*, 2012; van Staal *et al.*, 2021). Offshore, Appalachian orogenic structures can

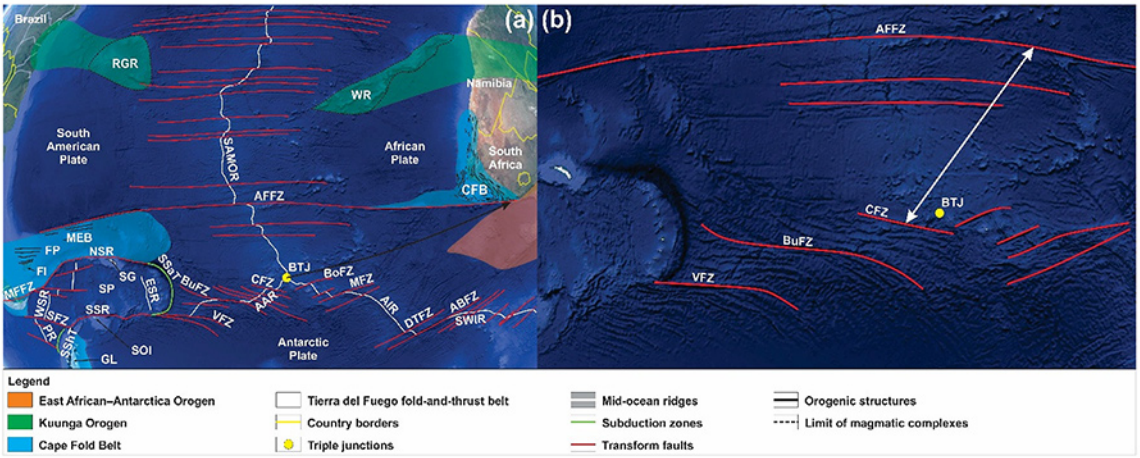


**Figure 5.** (**a**–**b**) Topographic–bathymetric map of the South Atlantic Ocean showing the ruptured Cape Fold Belt orogenic bridge. The black arrow in (**a**) links the Bouvet Triple Junction with the intersection of the Cape Fold Belt and East African–Antarctica Orogen prior to rifting. The orogenic structures of the Cape Fold Belt in the Falkland Islands, Falkland Plateau, and Maurice Ewing Bank are from Stanca *et al.* (2022). The extent of the Cape Fold Belt in Antarctica is from Elliott *et al.* (2019). Those in South Africa are from Paton *et al.* (2022). (**b**) better illustrates the parallelism between transform faults truncating the South Atlantic Mid-Ocean Ridge and those crosscutting the American–Antarctica Ridge, which is partly impeded in (**a**) due to the curvature of Earth's surface. The white double arrow in (**b**) shows that the eastern portion of the Agulhas–Falkland fault zone is parallel to the Conrad fault zone. Basemap is from © Google Earth. Abbreviations: AAR: American–Antarctic Ridge; ABFZ: Andrew Bain fault zone; AFFZ: Agulhas–Falkland fault zone; AIR: Atlantic–Indian Ridge; BoFZ: Bouvet fault zone; BuFZ: Bullard fault zone; BTJ: Bouvet Triple Junction; CFB: Cape Fold Belt; CFZ: Conrad fault zone; DTFZ: Du Toit fault zone; ESR: East Scotia Ridge; FI: Falkland Islands; FP: Falkland Plateau; GL: Graham Land; MEB: Maurice Ewing Bank; MFFZ: Magallanes–Fagnano Fault Zone; MFZ: Moshes fault zone; NSR: North Scotia Ridge; PR: Phoenix Ridge; RGR: Rio Grande Ridge; SAMOR: South Atlantic mid-ocean ridge; SFZ: Shackleton fault zone; SG: South Georgia; SP: Scotia Plate; SOI: South Orkney Islands; SSaT: South Sandwich Trench; SShT: South Shetland Trench; SSR: South Scotia Ridge; SWIR: Southwest Indian Ridge; VFZ: Vinogradov fault zone; WR: Walvis Ridge; WSR: West Scotia Ridge.

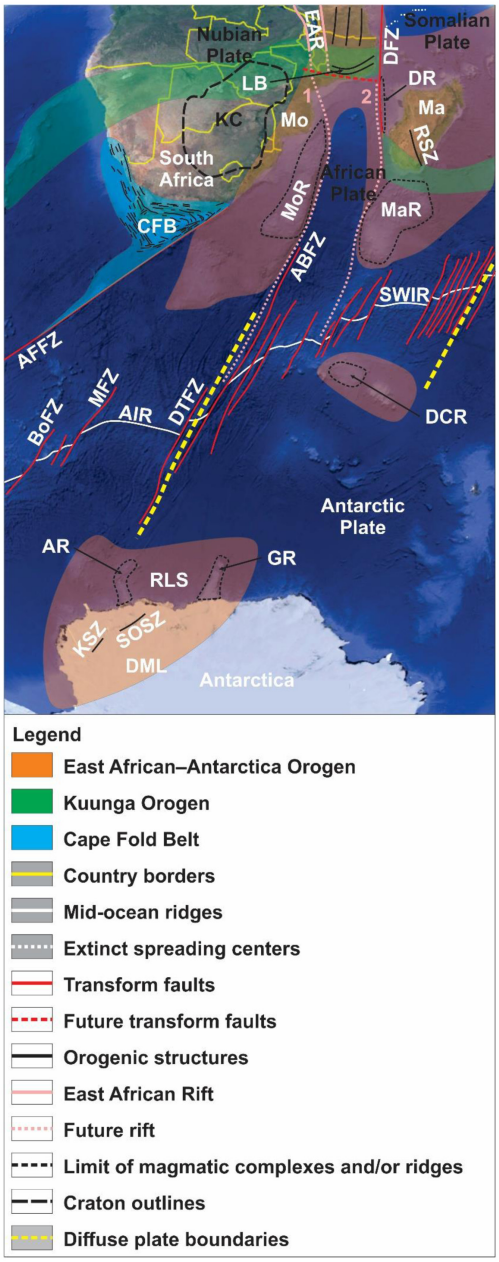


**Figure 6. Topographic–bathymetric map showing the ruptured East African–Antarctic orogenic bridge.** The orogenic bridge coincides with the Andrew Bain Fault Zone and other related major transform fault zones crosscutting the Southwest Indian Ridge. The orogenic structures in Antarctica, Africa, and Madagascar are from Jacobs (1999), Sacchi *et al.* (2000), Ruppel *et al.* (2015), Armistead (2019), and Paton *et al.* (2022). Basemap is from © Google Earth. Abbreviations: ABFZ: Andrew Bain Fault Zone; AFFZ: Agulhas–Falkland fault zone; AIR: Atlantic–Indian Ridge; AR: Astrid Ridge; BoFZ: Bouvet fault zone; DCR: Del Cano Rise; DFZ: Davie fault zone; DML: Dronning Maud Land; DR: Davie Ridge; DTFZ: Du Toit fault zone; GR: Gunnerus Ridge; KC: Kalahari Craton; KSZ: Kirwanveggen Shear Zone; LB: Lurio Belt; Ma: Madagascar; MaR: Madagascar Ridge; MFZ: Moshes fault zone; Mo: Mozambique; MoR: Mozambique Ridge; RLS: Riiser–Larsen Sea; RSZ: Ranotsara Shear Zone; SOSZ: South Orvin Shear Zone; SWIR: Southwest Indian Ridge.

be traced onto seismic reflection data up to Flemish Cap and Orphan Knoll, where they bend from a NNE–SSW to an ENE–WSW strike (Cawood *et al.*, 2021; Yang & Welford, 2023), i.e., into parallelism with the Charlie Gibbs fault zone (Keen *et al.*, 2014).

North of Orphan Knoll, the Charlie Gibbs fault zone can be traced on gravimetric and magnetic data, where it appears as an elongated negative gravimetric anomaly and truncates linear seafloor-spreading magnetic anomalies (Keen *et al.*, 2014 their figures 2 and 3). In seismic reflection data, the

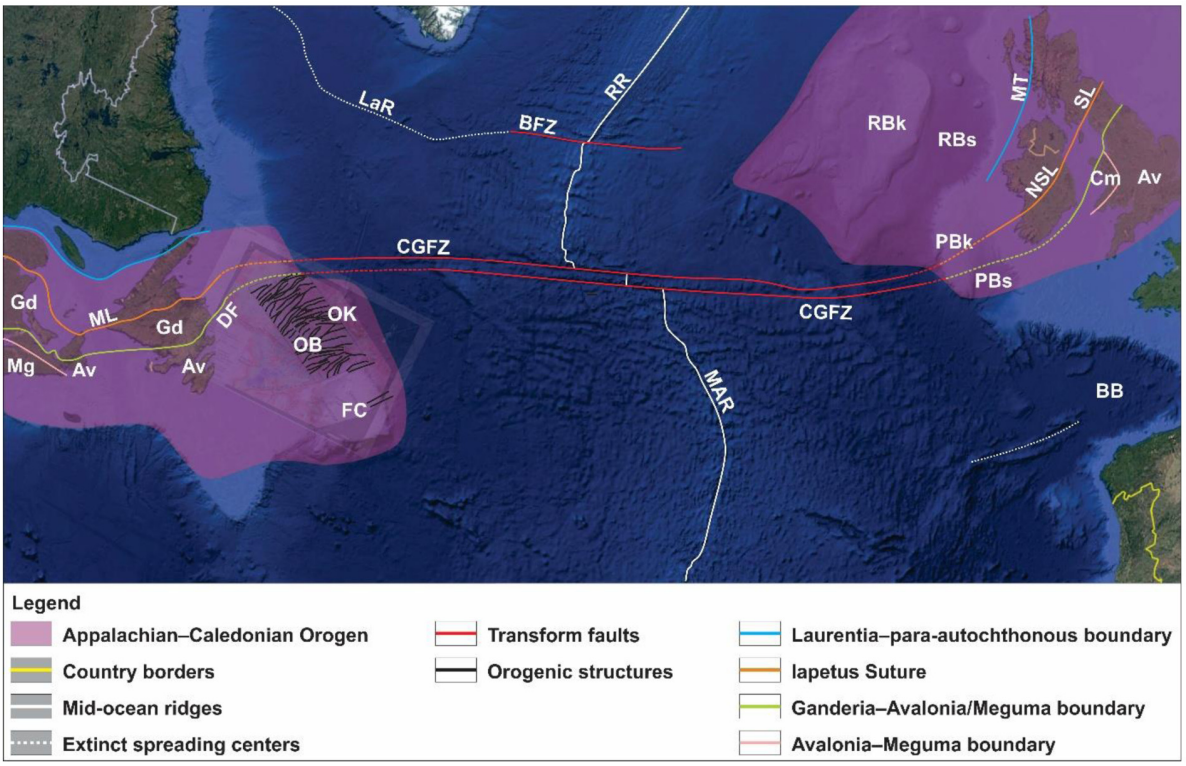


**Figure 7. Topographic–bathymetric map showing the ruptured Appalachian–Caledonian orogenic bridge and its relationship to the formation of the Charlie Gibbs fault zone.** The north-dipping Caledonian thrust systems at the Iapetus Suture west of Ireland and their correlation in Newfoundland, the Mekwe'jit Line (previously Red Indian Line), coincide with and their dip matches that of the northern segment of the Charlie Gibbs fault zone. The thickened orogenic crust at the rift-orthogonal Appalachian–Caledonian Orogen and related E–W-striking structures were unsuitably oriented to thin the crust and forced the Mid-Atlantic rift to step laterally and across the orogen. The main onshore tectonic boundaries are from van Staal *et al.* (2021). Offshore structures off Newfoundland are from Keen *et al.* (2014; Charlie Gibbs fault zone and Dover Fault). Offshore structures off western Ireland are from Klemperer *et al.* (1991). The Appalachian structures in the Orphan Basin and Orphan Knoll are from Cawood *et al.* (2021) and from Yang & Welford (2023, their figures 8 and 9) at Flemish Cap. Basemap is from © Google Earth. Abbreviations: Av: Avalonia; BB: Bay of Biscay; BFZ: Bight fault zone; CGFZ: Charlie Gibbs fault zone; Cm: Cimru terrane (correlative of Meguma); DF: Dover Fault; FC: Flemish Cap; Gd: Ganderia; LaR: Labrador paleo-mid-ocean ridge; MAR: Mid-Atlantic Ridge; Mg: Meguma; ML: Mekwe'jit Line; MT: Moine Thrust; NSL: Navan Silvermines Line; OB: Orphan Basin; OK: Orphan Knoll; PBk: Porcupine Bank; PBs: Porcupine Basin; RBk: Rockall Bank; RBs: Rockall Basin; RR: Reykjanes Ridge; SL: Solway Line.

Charlie Gibbs fault zone dips steeply to the north (Keen *et al.*, 2014 their figure 10). In its footwall, upward-curving seismic reflections delineate a c. 10–20 km wide anticline, which matches the strike of Appalachian structures in the area (Cawood *et al.*, 2021; Yang & Welford, 2023; Figure 7). In addition, basement rocks in the area show hundred meters to km-scale, asymmetric, wiggly, moderate- to high-amplitude reflections at a depth of 7.5–9.5 seconds (TWT) both in the footwall and hanging wall of the fault (Keen *et al.*, 2014 their figure 10). These are typically interpreted as asymmetric folds along mylonitic thrust systems (e.g., Koehl, 2021; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl & Stokmo, 2024; Koehl *et al.*, 2024). It is thus probable that the Charlie Gibbs fault zone formed along inherited Appalachian folds and thrusts.

It has been suggested that the northern segment of the Charlie Gibbs fault zone merges with the Paleozoic Dover Fault, which separates the Ganderia terrane from the Avalonia terrane onshore Newfoundland (Keen *et al.*, 2014; Figure 7). Given the similar strike and dip and proximity of the north-dipping Mekwe'jit Line (Iapetus Suture in Newfoundland; previously named Red Indian Line; van der Velden *et al.*, 2004), it is more probable that the northern segment of the Charlie Gibbs fault zone merges with the Iapetus Suture and that the southern segment merges with the Dover Fault (Figure 7).

In Ireland and the southern UK, the Ordovician–Silurian (to Early Devonian?) Caledonian Orogen developed E–W- to NE–SW-striking thrusts and folds (Chew & Stillman, 2009; Chew & Strachan, 2013). The westwards offshore continuation of the Iapetus Suture in western Ireland coincides with the Charlie Gibbs fault zone off Porcupine Bank, and both display comparable E–W strikes (e.g., Chew & Stillman, 2009; Tietzsch-Tyler, 1996; Figure 7). Seismic reflection data west of Ireland show that Caledonian thrust systems dominantly dip to the north, e.g., the presumed Iapetus Suture (Klemperer *et al.*, 1991),

which is consistent with seismic reflection data east of the UK (Freeman *et al.*, 1988). This attitude coincides with that of the north-dipping Charlie Gibbs fault zone, thus further supporting a controlling relationship of Caledonian thrust systems over this major transform fault.

Our interpretation is in agreement with Buiter & Torsvik (2014) who suggested that the Charlie Gibbs fault zone formed along a preexisting (Iapetus) suture zone. In this setting, E–W-striking Appalachian–Caledonian thrusts and related orogenic crust would have hindered rifting and delayed breakup between Newfoundland and Ireland. Repeated tectonic inversion of Appalachian–Caledonian structures may then have contributed to thinning the crust and to localize the formation of the Charlie Gibbs fault zone.

Alternatively, the ENE–WSW- to E–W-striking orogenic structures at Orphan Knoll and off western Ireland might be (partly?) Variscan (Lefort & Haworth, 1984; Lefort *et al.*, 1993; Miliorizos *et al.*, 2004). Thus, Appalachian–Caledonian and/or Alleghenian–Variscan preexisting orogenic structures may have controlled the formation of the Charlie Gibbs fault zone.

The Charlie Gibbs fault zone consists of two fault segments separated by a c. 40 km long spreading center (Figure 7). These faults offset the Mid-Atlantic Ridge by c. 340 km (Ligi *et al.*, 2022). A noteworthy feature of this fault zone is that the mid-ocean ridge to the north and in between the two fault segments produced little basalt and are thus less magmatic than the Mid-Atlantic Ridge to the south (Basch *et al.*, 2024; Skolotnev *et al.*, 2021a). Given the dominant north-dipping geometry of the inherited Caledonian thrusts at the presumed Iapetus Suture west of Ireland (Klemperer *et al.*, 1991), one may envision a formation of the Charlie Gibbs fault zone and related magmatism in a similar fashion to that suggested for the Molloy fault zone in the Fram Strait (Koehl *et al.*, 2021; Koehl *et al.*, 2025 awaiting peer review; Figure 8). In such a model, mantle is exhumed and partially melted in the footwall of the inverted Caledonian thrusts, i.e., south of the Charlie Gibbs fault zone.

In contrast, areas within and north of the inverted Caledonian thrust system are shielded by relatively dry and resistant continental crust because of the enrichment in tightly deformed and thus resistant mylonite along major thrusts. This model would explain the low degree of partial melting observed for recent igneous rocks within the Charlie Gibbs fault zone (Basch *et al.*, 2024; Sanfilippo *et al.*, 2024). Thus, the asymmetric amount of magmatism across major transform fault system may be controlled by the vergence of the preexisting thrust systems along which major transform faults develop. At Charlie Gibbs, such a trend seems to have persisted long after breakup (> hundred million years), thus suggesting that preexisting orogens have a long-term effect on partial melting of the mantle and, potentially, on its geochemistry. A hypothesis to be tested is that old (Appalachian–Caledonian) orogenic mylonitic shear zones also developed in the upper mantle and that part of these hyperextended shear zones remain near mid-ocean ridges and prevent rapid ascent of large amounts of melt at specific mid-ocean ridge segments, i.e., possibly compartmentalizing the mantle.

Yet another feature of interest is that the Charlie Gibbs fault zone is considered by some to be the southern boundary of the zone of influence of the postulated Icelandic plume. As such, the Charlie Gibbs was interpreted as a major geochemical and rheological boundary (Basch *et al.*, 2024; Sanfilippo *et al.*, 2024). However, the area extending from the Fram Strait to the Charlie Gibbs fault zone (including Iceland) was influenced by, and, in some area (e.g., Greenland–Iceland–Faroe Ridge), includes remnants of, the Appalachian–Caledonian Orogen (Cawood *et al.*, 2021; Horsfield, 1972; Klemperer *et al.*, 1991; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Yang & Welford, 2023). Thus, another possible interpretation is that the geochemical heterogeneity of the mantle between Iceland and Charlie Gibbs was inherited from the Appalachian–Caledonian Orogen and related tectonothermal processes, i.e., potentially further supporting a long-term influence of old orogens on the mantle.

At Orphan Knoll and Flemish Cap, continental to transitional crust potentially extends 80 km to the east (Welford *et al.*, 2020). Taking into account the c. 1100 km distance to the mid-ocean ridge, this suggests an overestimation of the amount of oceanic crust by c. 7.2%. In contrast, the lack of published studies of seismic reflection data between Porcupine Bank and the Charlie Gibbs fault zone (e.g., Peace *et al.*, 2019; Yang *et al.*, 2021) makes it difficult to assess the extent of oceanic crust at this margin. However, should continental crust extend all the way to the eastern tip of the Charlie Gibbs fault zone (i.e., for an extra 350 km farther west), this would imply an overestimation of the extent of oceanic crust by c. 30.4% along the western Ireland margin, given the c. 1150 km distance to the mid-ocean ridge.

*The Sergipano–Central African orogenic bridge*

In western Africa, the northern boundary of the Congo Craton with the West African Craton in the northwest and the Saharan Metacraton in the north is defined by the Central Africa Orogen (also called Oubangides; Figure 9). The orogen consists of arc-related intrusions, syn-tectonic volcano-sedimentary successions, and late-orogenic granitoids (e.g., Toteu *et al.*, 2022). It formed during the accretion of Gondwana in the late Neoproterozoic and was part of the Pan African Orogeny (Kouémo *et al.*, 2014; Kröner & Stern, 2004; Toteu *et al.*, 2022). It consists of several thousands km long, E–W- to ENE–WSW-striking, top-south thrusts, which were later reworked into dextral strike-slip mylonitic shear zones, e.g., ENE–WSW-striking Central African Shear Zone (Dorbath *et al.*, 1986; Ibrahim *et al.*, 1996; Kouémo *et al.*, 2014; Schandelmeier & Pudlo, 1990; Toteu *et al.*, 2022).

In northern Brazil, the Sergipano Belt defines the northeastern boundary of the Sao Francisco Craton and consists of late Neoproterozoic volcanics, and arc- and syn-orogenic granite and syenite plutons (D'el-Rey Silva, 1999; Oliveira *et al.*, 2010; Oliveira *et al.*, 2015; Oliveira *et al.*, 2017). The belt is

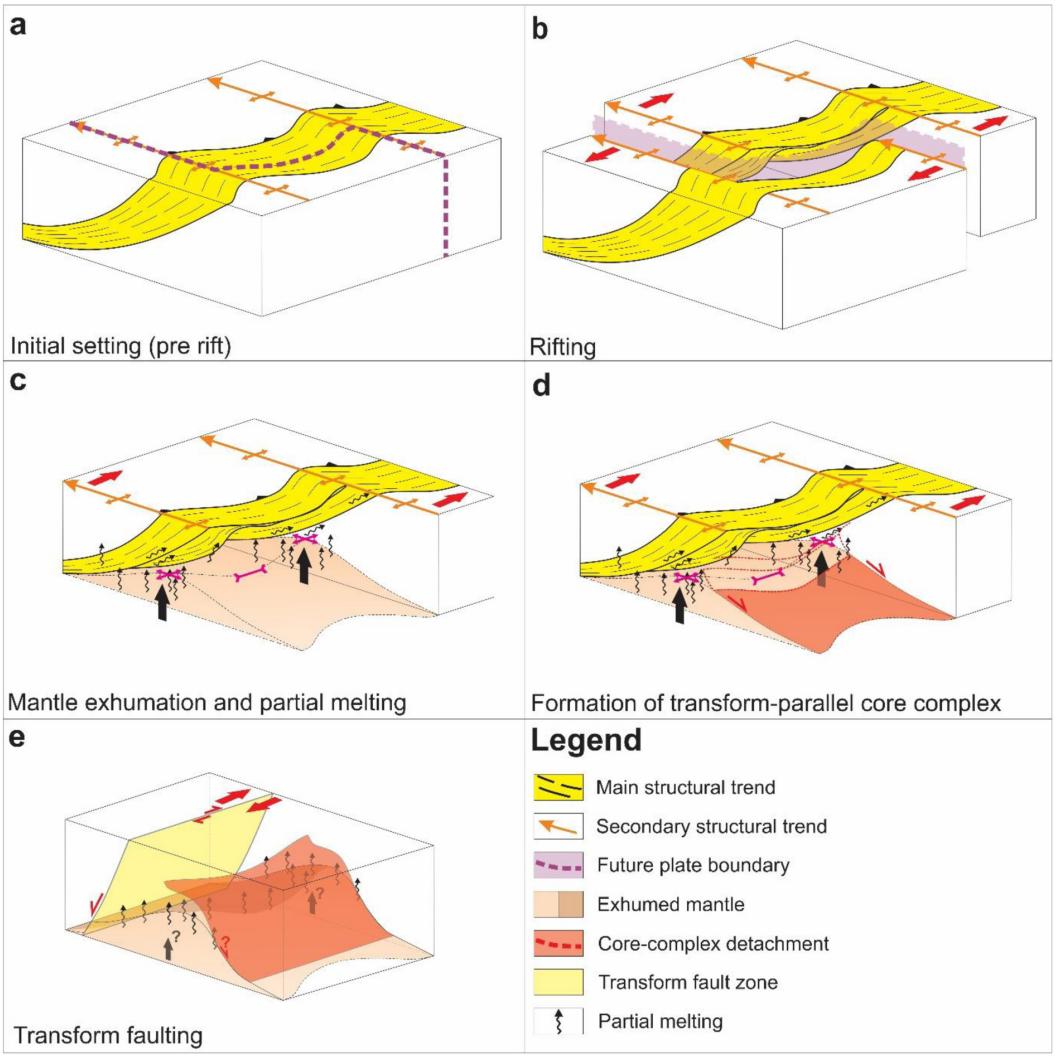


**Figure 8. Mantle exhumation along inherited rift-orthogonal thrust systems.** (**a**) The initial tectonic setting involves two sub-orthogonal structural trends, including major crustal-scale, mylonitic thrust systems and their reworking (e.g., folding) during a subsequent, suborthogonal contractional event. (**b**) Rifting thins the crust along the two inherited structural trends, cutting through the rift-orthogonal thrust systems in a step-like fashion, e.g., along the inherited thrusts and subsequent folds. (**c**) Exhumation of the mantle during breakup. Exhumation and partial melting preferentially occur in the footwall of inherited thrusts, with increased exhumation at anticlines where the combination of lateral (proto-transform) movements and erosion of the anticlinal hinge has a higher potential to create crustal imbalance. Magmatism occur dominantly in the footwall of the inherited rift-orthogonal thrust system, where the mantle is exhumed. The mylonitic character of the thrust system hinders the ascent of melt to the surface in the thrust hanging wall and preferentially channels magma along the thrust and in its footwall. (**d**) Hyperextension along the inverted rift-orthogonal thrust system leads to rift-orthogonal detachment faulting and the formation of transform-parallel oceanic core complexes. (**e**) Major transform faults form along the inherited crustal discontinuity, i.e., along the inverted rift-orthogonal thrust system.

deformed by major, E–W- to WNW–ESE-striking, mostly top-south mylonitic thrust systems reworked dominantly as dextral shear zone during the late stages of continental accretion (Oliveira *et al.*, 2010; Oliveira *et al.*, 2015). Thus, the kinematics of these structures are consistent with their counterparts in the Central African Orogen/Oubangides (D'el-Rey Silva, 1999; Kouémo *et al.*, 2014; Oliveira *et al.*, 2006; Oliveira *et al.*, 2010; Oliveira *et al.*, 2015; Toteu *et al.*, 2022). Farther west, the Segipano Belt bends into an NE–SW strike, i.e., following the northern edge of the Sao Francisco Craton, and merges with the Riacho do Pontal and Rio Preto belts. These belts are oriented NE–SW to E–W and show structures with corresponding top-south and dextral strike-slip kinematics and, respectively, define the northern and northwestern boundary of the craton (Caxito *et al.*, 2017). Notable structures of the Sergipano Belt include the Patos and Pernambucano

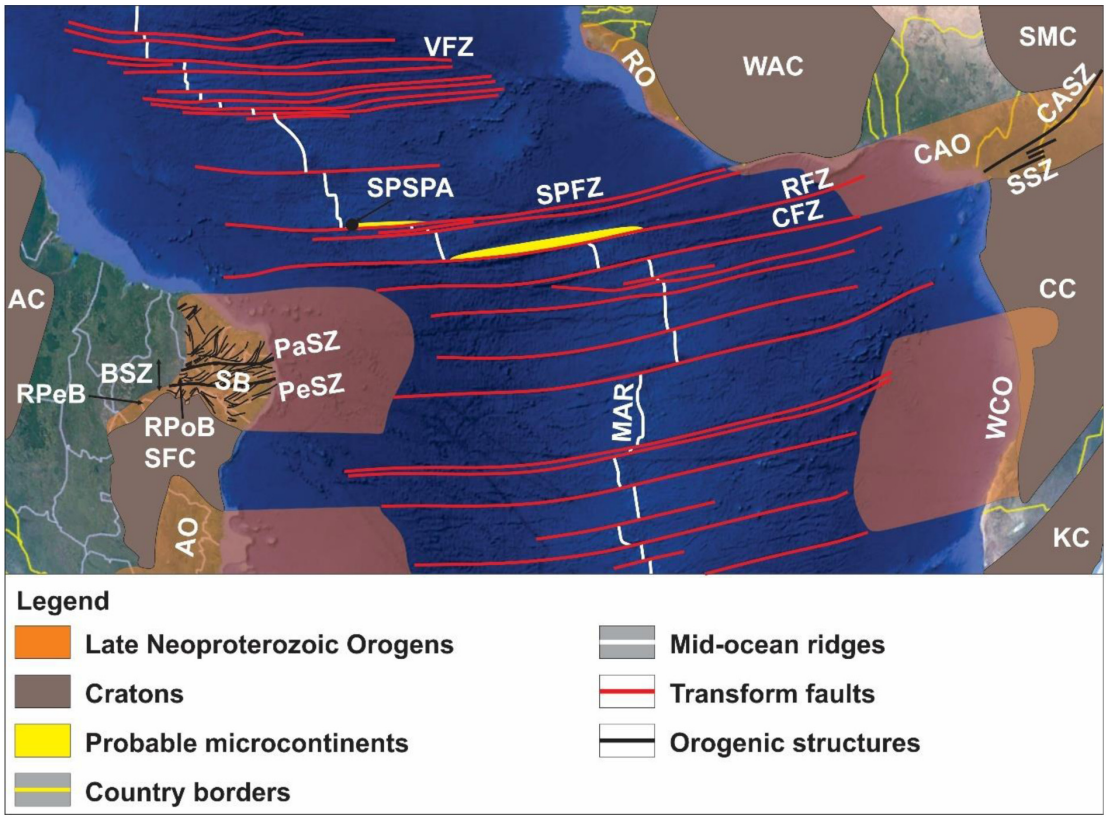


**Figure 9. Topographic–bathymetric map of the ruptured Sergipano–Central African orogenic bridge and its relationship to major transform faults.** Microcontinents and major transform faults between Africa and Brazil are parallel to north-dipping shear zones in the Sergipano Belt and Central African Orogen and probably initiated along such structures. The extent of the late Neoproterozoic orogens offshore is based on the lack of seafloor-spreading-related linear magnetic anomalies in these areas (James, 2010). Thus, it is possible that the cratons also extend farther offshore or that late Neoproterozoic belts (e.g., Araçuaí Orogen and Sergipano Belt) merge with one another offshore. The probable microcontinents along the Romanche and St Paul fault zones are based on Bonatti *et al.* (1994), Davison *et al.* (2015), Gasperini *et al.* (2001), and Melson *et al.* (1972). Orogenic structures in northeastern Brazil are from Oliveira *et al.* (2010) and from Kouémo *et al.* (2014) in western Africa. Basemap is from © Google Earth. Abbreviations: AC: Amazonia Craton; AO: Araçuaí Orogen; BSZ: Borborema Shear Zone; CAO: Central African Orogen; CC: Congo Craton; CFZ: Chain fault zone; KC: Kalahari Craton; MAR: Mid-Atlantic Ridge; PaSZ: Patos Shear Zone; PeSZ: Pernambucano Shear Zone; RFZ: Romanche fault zone; RO: Rockelide Orogen; RPeB: Rio Preto Belt; RPoB: Riacho Ponto Belt; SB: Sergipano Belt; SFC: São Francisco Craton; SMC: Sahara Metacraton; SPSPA: St Peter and Pt Paul Archipelago; SSZ: Sanaga Shear Zone; STFZ: St Paul fault zone; VFZ: Vema fault zone; WAC: West African Craton; WCO: West-Congo Orogen.

shear zones of the Borborema system, which are believed to represent the western continuation of the Central African Shear Zone (Finoto Bueno *et al.*, 2009; Fossen *et al.*, 2022; Oliveira *et al.*, 2006; Oliveira *et al.*, 2010).

The E–W-striking Saint Paul, Romanche, and Chain fault zones extend from western Africa to northeastern Brazil at the boundary of the central and southern segments of the Atlantic Ocean and offset the Mid-Atlantic Ridge by a total of c. 1800 km sinistrally (De Caprona, 1992; Gregory *et al.*, 2021; Heezen *et al.*, 1964; Searle *et al.*, 1994; Figure 9). The Romanche fault zone takes up half the total offset of the mid-ocean ridge and may be traced for ≥ 3500 km from a few hundred km off the coast of northeastern Brazil to a few hundred km south of Ivory Coast and Ghana (Figure 9). These transform faults are characterized by exhumed peridotite ridges (Bonatti *et al.*, 1994; Gregory *et al.*, 2021). The faults are thought to have formed during the opening of the Atlantic Ocean at ca. 50–45 Ma (Gregory *et al.*, 2021; Heezen *et al.*, 1964). The location of the Romanche and Chain fault zones coincides with that of segments of the Central African Shear Zone in Cameroon, e.g., Sanaga Shear Zone whose sinistral sense of shear matches that of the St Paul, Romanche, and Chain fault zones (Kouémo *et al.*, 2014). Thus, the late Neoproterozoic, ENE–WSW-striking orogens and related structures in western Africa and northeastern Brazil likely controlled the formation of these major transform faults.

This would explain the occurrence of potential, elongated microcontinents along the St Paul and Romanche fault zones (Davison *et al.*, 2015; Gasperini *et al.*, 2001; Figure 9). Such microcontinents may represent lenses of orogenic crust (e.g.,

nappes or thrust sheets) separated by mylonitic shear zones within major thrust systems (Figure 10). For example, mylonitized and serpentinized mantle rocks of the St Peter and St Paul Archipelago along the St Paul fault zone were interpreted as relic continental lithosphere (da Costa Campos *et al.*, 2005). This is supported by a ca. 835 Ma K–Ar age for hornblende in mylonitic rocks of the archipelago, which suggests that these igneous rocks were contaminated by continental material (Melson *et al.*, 1972). This age matches that of early Neoproterozoic metamorphism along NE–SW-striking shear zones and sutures in the Arabia–Nubia Shield (Abdelsalam & Stern, 1993; Collins *et al.*, 2021; Johnson, 2014; Johnson *et al.*, 2011; Robinson *et al.*, 2015), which are connected to the St Paul, Romanche, and Chain fault zones by the presumably late Neoproterozoic Central African Shear Zone (Ibrahim *et al.*, 1996; Schandelmeier & Pudlo, 1990). Thus, a hypothesis to be tested is that the early Neoproterozoic NE–SW-striking orogen in the Arabian–Nubian Shield extends across Africa into the Central African Orogen and to northeastern Brazil in the Sergipano Belt. Alternatively, the elongated peridotite ridges along the St Paul and Romanche fault zones may have formed as transform-parallel core complexes through exhumation of continental mantle along inherited rift-orthogonal thrust systems (e.g., Figure 8).

Depending on the location of the continent–ocean boundary in the Gulf of Guinea and off northeastern Brazil, the amount of oceanic crust could be overestimated by up to 34.0% off northeastern Brazil and 50.0% in the Gulf of Guinea. This is based on the lack of linear magnetic anomalies related to seafloor spreading in these parts of the central and southern Atlantic Ocean (James, 2010). This suggests that the continent–ocean boundary may be up to c. 850 km away from the coast of Brazil (with a 2500 km distance to the mid-ocean ridge) and c. 1200 km off the coast of Cameroon (assuming a 2400 km distance to the mid-ocean ridge; Figure 9). An extension of the late Neoproterozoic Central African Orogen farther offshore in the Gulf of Guinea is probable given the proximity of the coeval Rockelide Orogen in westernmost Africa (Culver *et al.*, 1991; Villeneuve *et al.*, 2015; Wildman *et al.*, 2022; Figure 9) and the prolonged connection between northeastern Brazil and western Africa (e.g., Jacobs *et al.*, 2024).

Note that the N–S-striking Araçuaí–West Congo Orogen separates the West Africa Craton from the Sahara Metacraton in western Africa and continues farther south along the coasts of eastern Brazil and western Africa (Meert & Lieberman, 2008; Figure 9). This orogen is parallel to the South Atlantic mid-ocean ridge and, thus, probably localized rifting, facilitating breakup up to the rift-orthogonal Sergipano–Central African Orogen. The latter likely hindered rifting and forced the rift to step to the west (Figure 9). However, the Araçuaí–West Congo Orogen belongs to the rift-parallel endmember of OrBiT and is therefore not further discussed in the present study.

*The Cape–Falkland orogenic bridge*

The composition of the crust beneath the Falkland Plateau and Maurice Ewing Bank has long been debated. However, recent studies have provided robust evidence that the crust is continental (Chemale Jr. *et al.*, 2018; Stanca *et al.*, 2022), albeit relatively thin at Maurice Ewing Bank (e.g., Schimschal & Jokat, 2018). Offshore drilling at Maurice Ewing Bank penetrated continental crust consisting of Mesoproterozoic paragneisses metamorphosed to granulite facies during the late Mesoproterozoic (Chemale Jr. *et al.*, 2018). Moreover, new interpretation of offshore seismic reflection, gravimetric, and magnetic data identified late Paleozoic fold and thrust structures on the Falkland Plateau and at Maurice Ewing Bank (Stanca *et al.*, 2022; Figure 5a). Considering the c. 3250 km distance between the previous continent–ocean boundary proposed by Schimschal and Jokat (2018; see also figure 1 in Stanca *et al.*, 2022) and the mid-ocean ridge and the c. 1900 km distance between the eastern tip of Maurice Ewing Bank (the continent–ocean boundary proposed in the present manuscript) and the mid-ocean ridge, the extent of oceanic crust on the South American side of this ruptured orogenic bridge is overestimated by c. 41.3%.

From plate paleogeographic reconstructions, folds and thrusts in the Falkland Plateau appear to have been parallel and adjacent to those of the Cape Fold Belt (e.g., Johnston, 2000; Martin *et al.*, 1981; McKay *et al.*, 2018; Mitchell *et al.*, 1986; Newton, 1993; Storey *et al.*, 1999; Veevers *et al.*, 1994; Figure 5a). Thus, the late Paleozoic contractional structures on the Falkland Plateau represent the prolongation of the Cape Fold Belt, which rifted away from southeastern South Africa during the opening of the South Atlantic. In the west, onshore southern South America, the Cape Fold Belt correlates with contemporaneous structures onshore Patagonia, which shows both comparable structural trends and similar timing of formation (Castillo *et al.*, 2017; du Toit, 1927; Falco *et al.*, 2022; Falco *et al.*, 2024; Grillo Vidal *et al.*, 2024; Pankhurst *et al.*, 2006; Figure 1 and Figure 5a).

The Cape Fold Belt in South Africa and the Falkland Plateau–Maurice Ewing Bank and its continuation onshore Patagonia parallel major transform faults in adjacent offshore areas. Hence, transform faults there all strike perpendicular to the active (East Scotia Ridge, American–Antarctic Ridge, and South Atlantic mid-ocean ridge) and paleo-mid-ocean ridges in the area (West Scotia Ridge and Phoenix Ridge; Figure 1 and Figure 5a). These transform faults include the Agulhas–Falkland fault zone in the South Atlantic (Barker, 1979; Ben-Avraham *et al.*, 1997; Uenzelmann-Neben & Gohl, 2004), and also all major transforms in the southernmost Atlantic Ocean (Conrad, Bullard, and Vinogradov fault zones; Ligi *et al.*, 1999; Mitchell *et al.*, 2000; Sandwell & Smith, 2001) and the Scotia Plate (North Scotia Ridge, South Scotia Ridge, and Shackleton fault zone; Klepeis, 1994; Livermore *et al.*, 2000; Ludwig & Rabinowitz, 1982; Pelayo & Wiens, 1989; Riley *et al.*, 2019; Thomas *et al.*, 2003; Figure 1 and Figure 5a). Notably, the Agulhas–Falkland fault zone parallels thrusts of the Cape Fold Belt both onshore and offshore southern South Africa (Paton *et al.*, 2022) and on the Falkland Plateau and Maurice Ewing Bank (Stanca *et al.*, 2022 their figures 4a, 5b, 12b–c, and 13a–c), which strike respectively NE–SW and E–W (Figure 5a). These late Paleozoic–earliest Mesozoic thrusts therefore likely

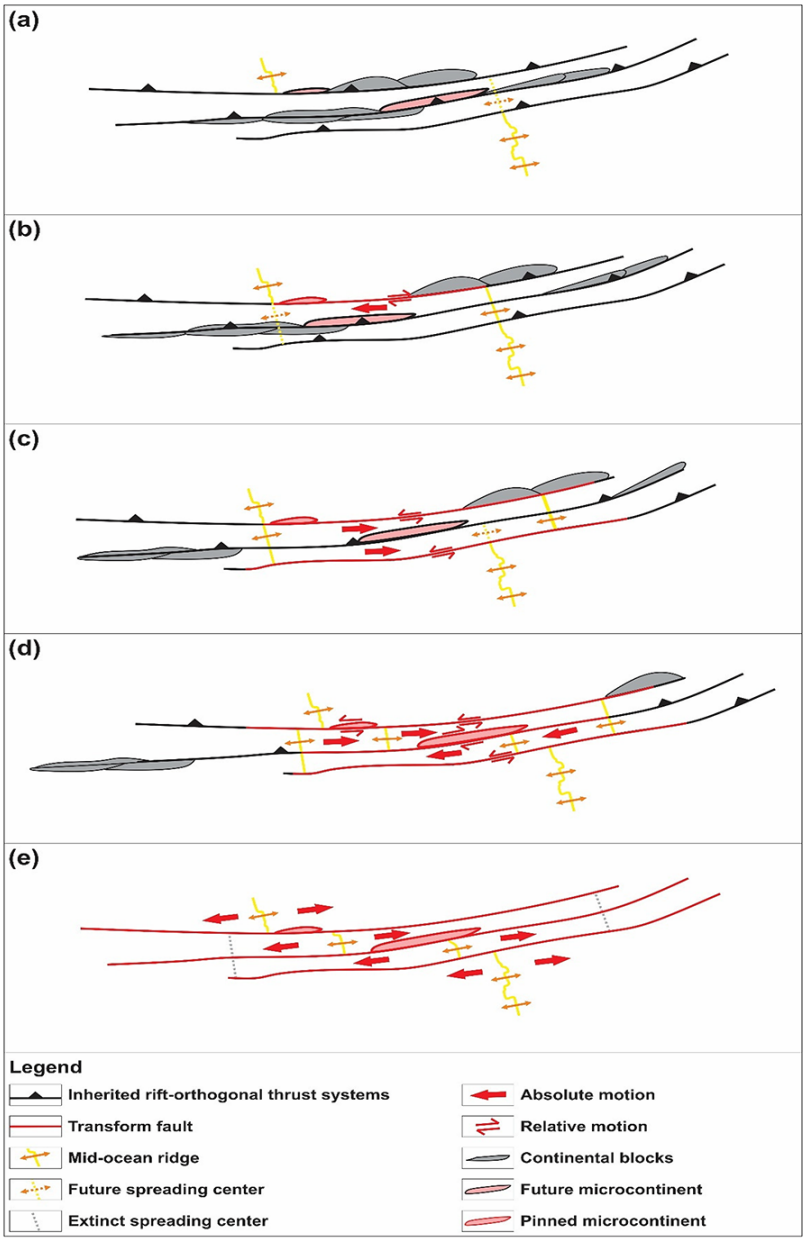


**Figure 10. Formation of transform-parallel microcontinents during oscillatory spreading.** (**a**) Inherited rift-orthogonal thrust systems (black lines) hinder rifting and initially force the rift (yellow lines) to step and bypass the area of orogenically thickened continental crust. The major thrusts consist of complex shear fabrics at lithospheric scale, which result in the formation of hundreds of km long lensoidal continental blocks (grey-filled blobs) separated by zones of intense deformation. (**b**) Over time, the rift slowly cuts through the orthogonal thrust systems from on end, thus initiating transform faulting (red line). Some narrow continental blocks along inherited thrusts immediately become pinned and incorporated to proto-transform fault segments due to their lensoidal shape (pink-filled red blob), which allows extruded oceanic crustal material to passively slide by without entraining the newly formed microcontinent (e.g., St Peter and St Paul Archipelago along the St Paul fault zone). (**c**) Since the inherited rift-orthogonal thrust systems are inefficient at thinning the crust because they are oriented parallel to the extension direction and are gently to moderately dipping (i.e., inefficient at transform faulting), the rift opens from both ends and spreading centers within the proto-transform fault system become offset. Some elongated continental blocks along proto-transform fault segments become trapped and oscillate between the main two spreading centers (pink-filled black blob). (**d**) As the rift repeatedly cuts through the rift-orthogonal orogen, oscillating continental blocks stabilize and become incorporated along transform fault segments (pink-filled red blob; e.g., Romanche fault zone). New spreading centers develop within the transform fault system and are potentially offset and moved towards the center of the transform fault system due to continued spreading at other spreading centers. Alternatively, the new spreading centers directly develop with an offset and towards the center of the transform fault system without the need of coeval spreading centers. (**e**) Fully developed transform fault system with narrow (tens of km wide), elongated (hundreds km long), transform-parallel microcontinents. The model was developed from the geometries of the St Paul, Romanche, and Chain fault zones but is potentially applicable to other major transform fault systems potentially including elongated microcontinents, such as the Charlie Gibbs, Vema, and Andrew Bain fault zones and the GIFR.

controlled the strike and geometry of the Agulhas–Falkland fault zone. This relationship was previously noted by Buiter & Torsvik (2014) who suggested that the Agulhas–Falkland fault zone formed along an inherited suture zone between the Falkland Plateau and South Africa. The Falkland Plateau and Maurice Ewing Bank are thus proposed to represent a ruptured, probably partly hyperextended, late Paleozoic orogenic bridge, which forced the opening Mesozoic rift to step along orogen-parallel transform faults.

The southernmost segment of the overall N–S-trending, Cenozoic South America Cordillera in southern Patagonia, the Tierra del Fuego fold-and-thrust belt bends into a WNW–ESE strike (Fuentes, 2023; Klepeis, 1994), i.e., into parallelism with the Cape Fold Belt (Figure 5a). The Tierra del Fuego fold-and-thrust belt may therefore also have helped control the formation of major transform faults in the area. However, its geometry may have been controlled by the preexisting late Paleozoic fold-and-thrust belt (Cape Fold Belt) in the first place, so although Cenozoic structures may very well have controlled the formation of the local transform faults, the cause of this inherited E–W strike is more likely to be found in the late Paleozoic Cape Fold Belt.

*The East African–Antarctica orogenic bridge*

The late Neoproterozoic East African–Antarctica Orogen is a well-studied branch of the Pan African Orogeny. (e.g., Abdelsalam *et al.*, 1998; Fritz *et al.*, 2013; Shackleton, 1996; Stern & Kröner, 1993). N–S- to NNW–SSE-striking shear zones in Madagascar and eastern Africa potentially extend into the Davie, Mozambique, and Madagascar ridges (Figure 6). These three N–S- to NNW–SSE-striking bathymetric highs are likely cored by continental crust as suggested by new gravimetric and magnetic data and from recent density and plate tectonics modeling (e.g., Klimke *et al.*, 2018; Ryzhova *et al.*, 2022; Sato *et al.*, 2022; Vormann *et al.*, 2020). The Davie and Madagascar ridges are believed to have once been connected to the Gunnerus Ridge (Figure 6) prior to the opening of the southwestern Indian Ocean (Davis *et al.*, 2016; Klimke *et al.*, 2018; Mueller & Jokat, 2019; Vormann & Jokat, 2021).

More specifically, continental material, namely c. 1 Ga granulite rocks, was dredged at the Mozambique Ridge, thus suggesting that at least the southern part of the ridge is continental (Hartnady *et al.*, 1992 and references therein). More recent geophysical studies then revealed that the northern part of the Mozambique Ridge consists of thinned continental crust and the southern part of intermediate crust, i.e., probably hyperextended continental crust as suggested by the southwards increase in the degree of extension and thinning of the crust, overlain by magmatism rocks (Evain *et al.*, 2021; Matsinhe *et al.*, 2021; Ryzhova *et al.*, 2022). As such, the extent of oceanic crust at the Mozambique Ridge is currently overestimated by c. 55.9 % using a distance of 3400 km between the northern tip of the Mozambique Ridge (i.e., previously proposed continent–ocean boundary) and the mid-ocean ridge and a c. 1500 km distance from the southern tip of the Mozambique Ridge to the mid-ocean ridge (i.e., new continent–ocean boundary).

The northern part of the Madagascar Ridge is thought to be continental and consists of a complex basement structure, where the crust is 26–22 km thick (Goslin *et al.*, 1981). The transition zone most likely consists of a thinned version of the northern segment since it is located at a rifted margin. In the southern part of the ridge, the 14-km thickness of the crust led previous workers to postulate thick oceanic crust despite the lack of bedrock samples in drilling attempts (Sato *et al.*, 2022). Similarly at the Del Cano Rise, the 16 km crustal thickness was assumed to result from plume magmatism (oceanic Large Igneous Province; Sato *et al.*, 2022). However, the lack of linear magnetic anomalies and thicker-than-normal character of the crust both in the southern Madagascar Ridge and Del Cano Rise clearly indicate that seafloor-related processes can be ruled out and the irregular magnetic anomalies may be explained by sporadic magmatic activity comparable to that which occurred at the continental Mozambique Ridge (Sato *et al.*, 2022). Thus, the thicker-than-normal crust and low residual Bouguer anomalies at the southern Madagascar Ridge and Del Cano Rise were interpreted to reflect continental crust capped by mafic volcanics (Sato *et al.*, 2022), a scenario also suggested for other areas of thickened offshore crust in the Indian Ocean, e.g., southern Kerguelen Plateau and Elan Bank (Jiang *et al.*, 2021 their figure 4). A likely scenario, which should be further tested is that the southern Madagascar Ridge and Del Cano Rise consist of hyperextended (i.e., very thin) continental crust and/or rafted continental blocks (e.g., Péron-Pinvidic *et al.*, 2015; Rime *et al.*, 2024). This is suggested because they occur at rifted margins and by the similar gradual southwards thinning of the continental crust at the Mozambique Ridge in adjacent areas (Hartnady *et al.*, 1992; Ryzhova *et al.*, 2022). Thus, the extent of oceanic crust at the Madagascar Ridge is overestimated by c. 43.5% using (a) a c. 1150 km distance between the previously inferred continent–ocean boundary at the transition zone between the northern and southern parts of the Madagascar Ridge at 31°S and the mid-ocean ridge and (b) a c. 650 km distance between the southern tip of the southern Madagascar Ridge (i.e., the presently proposed continent–ocean boundary) and the mid-ocean ridge.

In Antarctica, the Gunnerus and Astrid ridges represent salients of continental crust off the coast of Dronning Maud Land (Leitchenko *et al.*, 2008; Roeser *et al.*, 1996; Figure 6). Considering the strike of the former, i.e., parallel to major late Neoproterozoic shear zones in Dronning Maud Land, e.g., the South Orvin and Kirwanveggen shear zones (Bauer & Siemes, 2004; Golynski & Jacobs, 2001; Jacobs, 1999; Ruppel *et al.*, 2015; Figure 6), it is probable that structures of the East African–Antarctica Orogen extend offshore into the Gunnerus Ridge.

A relevant issue is the nature of the crust at the Astrid Ridge. Roeser *et al.* (1996) interpreted the northern part of the Astrid Ridge as oceanic. The authors of this work state (page 243, paragraph 1) that “seismic data were not obtained on the Astrid Ridge” and that they based their interpretation on existing magnetic data from Bergh (1987). The data show

E–W-striking magnetic anomalies in the northern part of the Astrid Ridge, i.e., parallel to the mid-ocean ridge (Bergh, 1987 his figure 6). Roeser *et al.* (1996) argued that "except for their greater amplitude and irregularity, they (the E–W-striking magnetic anomalies in the northern Astrid Ridge) resemble those in the Riiser-Larsen Sea" (page 253, paragraph 5). However, they were unable to correlate these anomalies with anomalies in adjacent oceanic domains in the Riiser–Larsen Sea. Roeser *et al.* (1996) stress that the magnetic anomalies in the northern Astrid Ridge display a "greater amplitude and irregularity" than those in the adjacent oceanic domain (Riiser–Larsen Sea; page 253, paragraph 5).

In the light of recent studies of high-resolution seismic reflection data and magnetic data off various rifted margins showing that the outermost linear magnetic anomalies reflect mafic intrusions in continental crust (e.g., southeastern Greenland, Faroe Islands, Namibia; Geoffroy *et al.*, 2022a their figure 1b, 3b–c, and 5; Geoffroy *et al.*, 2022b their figures 2 and 3; Koehl *et al.*, 2024 their figure 2e), it is more likely that the E–W-striking anomalies reflect mafic intrusions in continental crust. This reinterpretation is supported by the impossibility of correlating the magnetic anomalies in the northern Astrid Ridge with anomalies in adjacent oceanic domains (Riiser–Larsen Sea) and by their more irregular character and different amplitude from regular ocean-floor anomalies. The more irregular and high-amplitude character of seaward-dipping-reflector-related magnetic anomalies was specifically pointed out by Geoffroy *et al.* (2022a).

At the Astrid Ridge, the extent of oceanic crust could thus be overestimated by up to 20.6% using a c. 1700 km distance between the previously assumed continent–ocean boundary between the southern and northern parts of the Astrid Ridge (Roeser *et al.*, 1996) and a c. 1350 km distance from the northern tip of the Astrid Ridge (new continent–ocean boundary). At the Gunnerus Ridge, and taking into account the Del Cano Rise, oceanic crust extent may be overestimated by as much as 25.0% using a c. 2800 km distance between the southern tip of the Gunnerus Ridge and the mid-ocean ridge and c. 2350 km from the northern tip of the Gunnerus Ridge (new continent–ocean boundary) and including a c. 250 km wide continental crustal domain at Del Cano Rise (Sato *et al.*, 2022).

It is thus possible that late Neoproterozoic shear zones observed onshore Dronning Maud Land in Antarctica may extend into the (at least partly) continental crust at Del Cano Rise (Sato *et al.*, 2022; Figure 5). Further analysis of seismic reflection data at the Gunnerus Ridge and Del Cano Rise should help answer this. Regardless, the sinistral kinematics late Neoproterozoic shear zones in Dronning Maud Land are consistent with that of relative block movements on either side of the Andrew Bain Fault Zone (e.g., Peyve *et al.*, 2007; Sclater *et al.*, 2005), which strike parallel to major late Neoproterozoic faults in Antarctica and the East Africa Orogen (Abdelsalam *et al.*, 1998; Armistead, 2019; Bauer & Siemes, 2004; Boger *et al.*, 2015; Collins *et al.*, 2000; Collins *et al.*, 2012; De Waele *et al.*, 2011; Golynski & Jacobs, 2001; Hamimi *et al.*, 2022; Jacobs, 1999; Johnson, 2014; Key *et al.*, 1989; Mosley, 1993; Quick & Bosch, 1990; Ruppel *et al.*, 2015; Shackleton, 1996; Stern & Kröner, 1993; Figure 6).

This also applies to other major transform faults in the region, e.g., the Du Toit, Moshes, and Bouvet fault zones between South Africa and Antarctica (Figure 5a and Figure 6; Ligi *et al.*, 1999), and the Davie fault zone between Madagascar and eastern Africa (Figure 6; Davis *et al.*, 2016). The analysis of seismic reflection data in Klimke *et al.* (2018) clearly shows low-angle thrusts in the westernmost part of the Davie Ridge (the area labelled "compressed sediments" in their figure 6). These contractional structures may represent the offshore continuation of thrust systems of the East African–Antarctica Orogen between Madagascar and eastern Africa. It is therefore probable that the Mozambique, Madagascar and Gunnerus ridges and possibly the Del Cano Rise are part of a disrupted orogenic bridge.

This is further supported by the location of a narrow plate boundary and of a diffuse plate boundary between the Somalia and Nubian plates and possibly the Lwandle plate (DeMets *et al.*, 2010). This boundary was proposed by Chu & Gordon (1999) to help reconstruct past plate tectonics movements prior to the opening of the Indian Ocean, which is problematic at the Rodrigues Triple Junction (Minster & Jordan, 1978; Royer & Gordon, 1997). The narrow plate boundary coincides with major offsets of the Southwest Indian Ridge by the Andrew Bain Fault Zone and nearby transform faults, whereas the diffuse plate boundary matches the extent of the East African–Antarctica Orogen on either side of the Southwest Indian Ridge (Chu & Gordon, 1999; Meyzen & Schwarz-Schampera, 2023; Figure 1 and Figure 6).

The case of the Mozambique and Somali basins illustrate well the impact of orogenic bridges on rifting. Both basins host extinct, ENE–WSW-striking spreading centers and magnetic anomalies (e.g., Coffin & Rabinowitz, 1987; Davis *et al.*, 2016; Norton & Sclater, 1979; Sauter *et al.*, 2018; Simpson *et al.*, 1979; Figure 6). A tectonic evolution similar to that proposed by Seton *et al.* (2012 their figure 15) and Vormann & Jokat (2021 their figure 3) is considered likely. In such as model, the Indian rift attempted to cut through the East African–Antarctica Orogen at suitably oriented zones of weakness in the (Late Jurassic?–) Early Cretaceous. An area with suitably oriented structures is the Lurio Belt in northeastern Mozambique (Bingen *et al.*, 2009; Sacchi *et al.*, 2000; Viola *et al.*, 2008) and its counterpart in western India and Sri Lanka (Kuunga Orogen; Brandt *et al.*, 2014; Dharmapriya *et al.*, 2015; Ghosh *et al.*, 2004; He *et al.*, 2018; Hirayama *et al.*, 2020; Srinivasan & Rajeshdurai, 2010). Both of these orogens consist of ENE–WSW-striking structures (Figure 1 and Figure 6). These structures were oriented perpendicular to the c. N–S extension direction and were thus suitable to efficiently thin the thickened orogenic crust of the East African–Antarctica Orogen. However, upon meeting the unsuitably oriented, major orogenic structure of the East African–Antarctica Orogen, e.g., N–S-striking contractional structures at the Davie Ridge (Klimke *et al.*, 2018 their figures 2–6) and its southern prolongation, the

Madagascar Ridge, the rift may have been forced to step laterally, i.e., in the northern Mozambique Basin, where suitably oriented structures of the E–W-striking Kuunga Orogen occur in adjacent areas onshore southern Madagascar (Armistead, 2019; Collins *et al.*, 2003; Collins *et al.*, 2012). Nevertheless, upon meeting yet another unsuitably oriented N–S-striking structure at the Mozambique Ridge (e.g., Matsinhe *et al.*, 2021 their figures 2, 4, and 6), the Indian rift eventually stepped farther south into its present-day location at the South West Indian Ridge (Seton *et al.*, 2012; Figure 1 and Figure 6).

Large-offset, slow-spreading transform such as the Andrew Bain, Vema (southern Caribbean orogenic bridge), Romanche (Sergipano–Central African orogenic bridge; Figure 1) and Charlie Gibbs fault zones (Appalachian–Caledonian orogenic bridge), display multiple transform segments and oscillatory spreading. Thus, slivers of lithosphere switch from one plate to the other as the plate boundary jumps from one transform fault segment to another (e.g., Bonatti & Crane, 1982). These large-offset transforms are slower to adapt their geometry to new stress field and plate kinematics (Maia, 2019). OrBiT suggests that elongated lithosphere slivers within these transform fault systems are likely continental (Figure 10). This would facilitate the switch of the plate boundary to another fault segment and the switch of movement direction of the lithosphere sliver because it would already be decoupled from the surrounding oceanic lithosphere (Figure 10). This would explain the lack of seafloor-spreading-related magnetic anomalies in between the fault segments of large-offset transform fault systems, e.g., Charlie Gibbs fault zone (Skolotnev *et al.*, 2021b).

The presence of (hyper-) extended continental lithosphere could also explain the different thermal structure of large-offset, multi-segment transform fault systems. These fault systems involve cold crust and they are similar to continental strike-slip faults (Bonatti *et al.*, 2001; Ligi *et al.*, 2002) because they initially developed in continental crust. This agrees with the presence of rocks older than predicted by typical seafloor spreading within these transform fault system (Bonatti & Crane, 1982; Bonatti *et al.*, 1996). Figure 10). In such a scenario, transform-parallel ribbons of continental crust become detached from adjacent continental margins and are entrained along major transform faults due to the occurrence of transform-parallel, preexisting zones of the weakness in the continental crust, such as major (mylonitic) thrust systems. These preexisting structures would facilitate rupture and dislocation of the crust along an axis parallel to the proto-transform faults and allow the inclusion and entrainment of the transform-parallel continental ribbons into the oceanic crustal domain during seafloor spreading (Figure 10). This model explains the earliest Cretaceous (c. 140 Ma; i.e., pre-breakup) carbonates at the transverse ridge along the Romanche fault zone, which may be a microcontinent of hybrid (continental–gabbroic) crust (Davison *et al.*, 2015; Gasperini *et al.*, 2001).

In the northern part of the East African Orogen, the Red Sea rift presents some interesting relationships with preexisting sutures and shear zones in the Arabian–Nubian Shield (Figure 11). There, N–S-striking Neoproterozoic shear zones, such as the Barka (–Adobha) and (Onib–) Hamisana shear zones (Collins *et al.*, 2021; Johnson & Woldehaimanot, 2003; Stern & Kröner, 1993), coincide with zones of high seismicity and minor steps, bends/kinks, and narrowing of the Red Sea rift, which have been interpreted as potential (proto) transform faults (Bosworth *et al.*, 2005; Dixon *et al.*, 1987; Molnar *et al.*, 2020). N–S-striking, late Neoproterozoic shear zones also parallel the Aqaba–Dead-Sea–Levant fault zone, a major transform fault (Molnar *et al.*, 2020). Some of these shear zones have been reactivated in the order of km to tens of km and possibly localized the formation of the Aqaba–Dead-Sea–Levant fault zone and other proto-transform faults in the Red Sea (Bosworth *et al.*, 2005). Conversely, NW–SE-striking late Neoproterozoic shear zones, e.g., Rehba shear zone (Johnson & Woldehaimanot, 2003) and Najd fault system (Hamimi & Fowler, 2021; Moore, 1979; Stern, 1985), strike parallel to the segmented Rea Sea spreading center, thus suggesting opening of the rift along preexisting late Neoproterozoic zones of weakness in the crust (rift-parallel endmember of orogenic bridge theory; Figure 11).

***Passive margins***

At passive margins, linear magnetic anomalies near typically interpreted continent–ocean boundaries do not necessarily reflect the presence of oceanic crust but of (dominantly mafic) igneous intrusions in continental to hybrid crust. In many cases, the continent–ocean boundary is likely to be located farther oceanward (e.g., Geoffroy *et al.*, 2022b; Koopmann *et al.*, 2014). Data from exploration wells that penetrate continental crust offshore are rarely included in current plate tectonics reconstructions. As a result, the extent of oceanic crust has likely been overestimated in some areas along passive margins around the globe (Geoffroy *et al.*, 2022a), e.g., off the coast of Namibia (Geoffroy *et al.*, 2022b), the Newfoundland–Iberian margin (Lymer *et al.*, 2019; Shillington *et al.*, 2006), the Rockall Plateau north of Ireland (Dickin, 1992; Roberts *et al.*, 1973), and in the northeastern Atlantic and Arctic oceans (Foulger *et al.*, 2024).

**Namibia–Brazil margin**

Off the coast of Namibia, seismic reflection, magnetic, and gravimetric data show that the true continent–ocean boundary lies 100 to 300 km farther oceanward (Geoffroy *et al.*, 2022b). Given the c. 2800 km distance to the mid-ocean ridge in this area, this suggests an underestimation of the extent of continental crust of 3.5 to 10.7%. The mafic igneous rocks that comprise seaward-dipping reflectors produce linear magnetic anomalies that may be similar to mid-ocean-ridge-related anomalies (Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b; Koopmann *et al.*, 2014; Reeve *et al.*, 2021). Linear magnetic anomalies occur in highly thinned slivers of continental crust intruded by seaward-dipping reflectors along the Namibian passive margin (Geoffroy *et al.*, 2022b). Not only can linear magnetic anomalies not be relied upon to discriminate oceanic and continental crust, it is now necessary to reevaluate the extent of continental versus oceanic crust at volcanic passive margin.

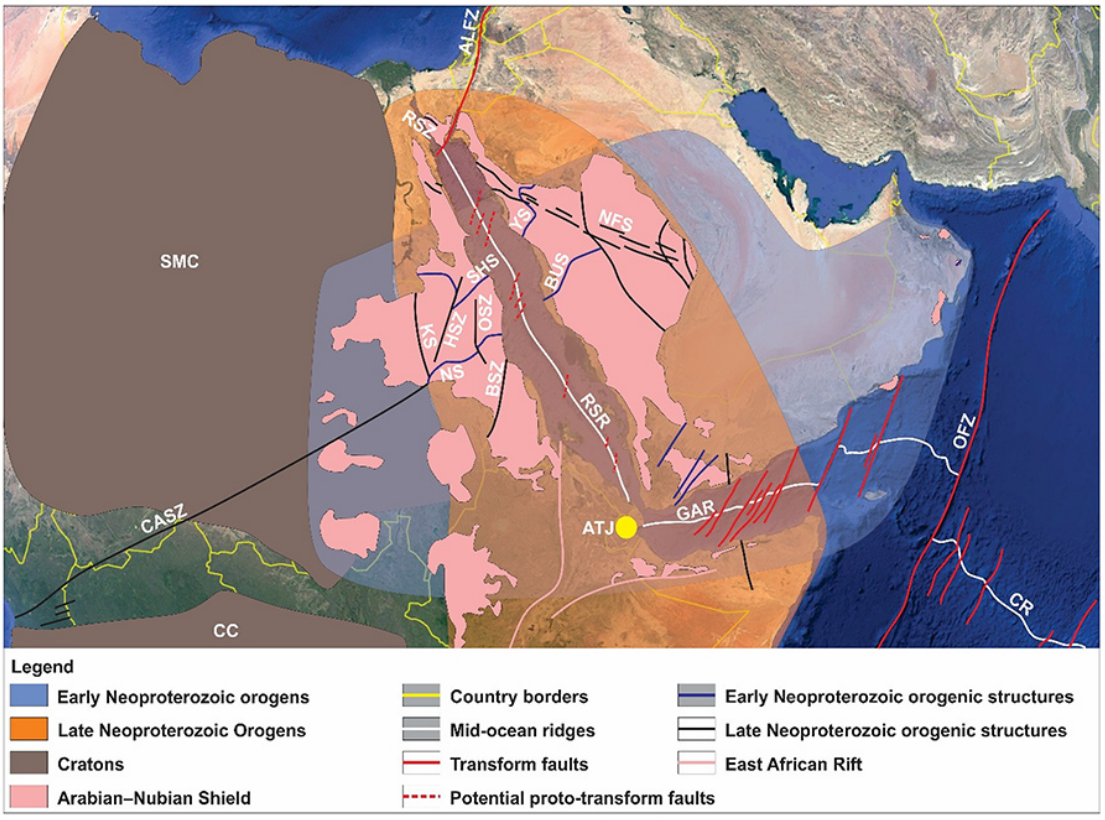


**Figure 11. Topographic–bathymetric map of the Arabian–Nubian Shield.** The map shows the relationship between the late Neoproterozoic, N–S-striking East African Orogen and the East African Rift and Red Sea Rift, which are parallel to one another. Another potential controlling relationship is that of early Neoproterozoic, NE–SW-striking orogenic structures with potential (proto-?) transform faults in the Red Sea rift and transform faults offsetting the Gulf of Aden Rift. Early and late Neoproterozoic orogenic structures are from Abdelsalam (2010), Alessio *et al.* (2017), Bosworth *et al.* (2005), Collins *et al.* (2021), Ibrahim *et al.* (1996), Johnson (2014), and Johnson & Woldehaimanot (2003). Basemap is from © Google Earth. Abbreviations: ALFZ: Aqaba–Dead-Sea–Levant fault zone; ATJ: Afar Triple Junction; BSZ: Barka (–Adobha) Shear Zone; BUS: B'ir Umq Suture; CASZ: Central African Shear Zone; CC: Congo Craton; CR: Carlsberg Ridge; GAR: Gulf of Aden Rift; HSZ: (Onib–) Hamisana Shear Zone; KS: Keraf Suture; NFS: Najd fault system; NS: Nakasib Suture; OFZ: Owen fault zone; OSZ: Oko Shear Zone; RSR: Red Sea rift; RSZ: Rehba Shear Zone; SHS: Sol Hamed Suture; SMC: Sahara Metacraton; YS: Yanbu Suture.

The crust below the Walvis Ridge shows a thickness and seismic velocities comparable to that below Iceland (Fromm *et al.*, 2017a; Fromm *et al.*, 2017b), which is likely continental (Foulger *et al.*, 2020a; Koehl *et al.*, 2024). In addition, basalts at the Walvis Ridge locally show traces of contamination by continental crust, which is similar to igneous province on continental crust, e.g., the Parana and Etendeka provinces (e.g., Eroshenko & Kharin, 2019).

On the conjugate South American margin, Proterozoic granite, gneiss, granulite, and gabbro were recovered from dredges on the Rio Grande Ridge (Santos *et al.*, 2019). The large variety of rock types in the dredged samples at Rio Grande Ridge and the lack of a thick manganese coating/encrustation, typical for rocks exposed to seawater for extended periods of time, calls for caution when interpreting the origin of these samples, as these features suggest ice-rafted debris from Antarctica. However, the absence of manganese coating may also suggest an origin from recent slumps and/or fault scarps, where fresh bedrock may be exposed and not yet encrusted. This is probable for most of the dredged samples, which were collected near a major bathymetric escarpment (see figure 2 in Ventura Santos *et al.*, 2019). The ca. 2.2–2.1 Ga, 1.4 Ga, 1.1 Ga, 540 Ma, and 480 Ma U–Pb zircon obtained for the samples at Rio Grande Ridge are typical for both Antarctica (Groenewald *et al.*, 1995; Liu *et al.*, 2014) and western Africa (which is a potential source for detrital zircon at Rio Grande Ridge) and Brazil (Basei *et al.*, 2008; Santos *et al.*, 2019). Thus, the geochronological record cannot distinguish the source area. Nevertheless, studies of the northern limit for icebergs and of circum-Antarctic currents in the South Atlantic Ocean suggest that only few icebergs (if any) make it to the Rio Grande Ridge area (e.g., Bornhold, 1983 his figure 1; Romanov *et al.*, 2017; England *et al.*, 2020 their figures 1 and 4; Starr *et al.*, 2021 their figure 1; Orheim *et al.*, 2023 their figures 1, 2, 6, and 7;

Barkley *et al.*, 2024 their figure 1; Bigg, 2024 his figures 2, 5, 6, and 7; van der Does *et al.*, 2024 their figure 4). An origin as ice-rafted debris from Antarctica is therefore unlikely and the samples probably reflect continental crust at Rio Grande Ridge.

These new results indicate that the Walvis–Rio Grande Ridge most likely consists of continental to hybrid crust and that the continent–ocean boundary is located 400–850 km farther oceanward on both margins. This suggests that large portions of the offshore areas are underpinned by continental crust. At Rio Grande Ridge, the extent of oceanic crust could be overestimated by as much c. 46.2% using a c. 2600 km distance from the previously proposed continent–ocean boundary at the western edge of the Rio Grande Ridge and the mid-ocean ridge and c. 1400 km distance from the eastern tip of the Rio Grande Ridge (new continent–ocean boundary). At Walvis Ridge, the overestimation could be up to 34.7% using a 2450 km distance from the continental shelf break east of Walvis Ridge to the mid-ocean ridge and a distance of 1600 km from the central Walvis Ridge (new continent–ocean boundary) to the mid-ocean ridge.

This is further supported by the (respectively clockwise and anticlockwise) bending of the seafloor flowlines in map view at the Walvis Ridge and Rio Grande Ridge, which indicates right- and left-lateral relative movement along the northern flank of the ridges in the order of a few tens to a hundred km (Fairhead & Wilson, 2005) since breakup at ca. 125–100 Ma (Eagles, 2007; Scotchman *et al.*, 2010), i.e., up to 1 mm per year. Such relative movements may be accommodated by either or a combination of bending (in map view) and strike-slip faulting. A possible cause for these relative movements is viscosity contrast between the continental-to-hybrid crust within the Walvis Ridge and Rio Grande Ridge and regular, c. 6 km thick oceanic crust in the north. A major limitation at Rio Grande Ridge and Walvis Ridge is that current seismic reflection data show poor reflectivity 1 second (TWT) into the bedrock (Sager *et al.*, 2021) and, thus, cannot definitively yield the nature of the crust there (oceanic versus continental/hybrid). Nevertheless, the irregular and high-amplitude character of the magnetic anomalies at those ridges (Sager *et al.*, 2021 their figure 17) is typical for intrusions (e.g., seaward-dipping reflectors) in continental crust (Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b).

**Newfoundland–Iberian margin**

Continental breakup at the Newfoundland and Iberian conjugate hyperextended margins is generally believed to have occurred later compared to the central and northern segments of the Atlantic rift (e.g., Causer *et al.*, 2022). In line with the findings of Geoffroy *et al.* (2022a; 2022b), the ages of the earliest anomalies (145 and 120 Ma; Srivastava *et al.*, 2000) contrast with the age inferred from drilling and dating the breakup unconformity (113 Ma; Boillot *et al.*, 1988; Tucholke & Sibuet, 2007). This suggests that the continent–ocean boundary lies farther seaward than previously proposed. Extreme thinning of the continental crust at passive margins due to extreme extension along low-angle detachments is particularly well illustrated along the Iberian margin (e.g., Lymer *et al.*, 2019; Pérez-Gussinyé, 2013). There, potential Variscan folds and thrusts in hyperextended continental basement seem to have controlled the formation of low-angle extensional detachments and show a top-east vergence (Lymer *et al.*, 2019 their figures 5a–d and 7b), i.e., comparable to Variscan structures in the geosyncline onshore northern Iberia (e.g., Franke, 2006; Pastor-Galan *et al.*, 2020; Shaw *et al.*, 2012).

In contrast to the drastically thinned Iberian continental crust, the broad Newfoundland passive margin displays a relatively thick wedge of continental crust. There, Alleghenian thrusts show a top-east vergence that matches that of coeval Variscan structures on the conjugate Iberian margin (Lefort & Haworth, 1984; Lefort *et al.*, 1993). The upper-plate geometry of the Newfoundland margin and lower-plate geometry (e.g., Lister *et al.*, 1986) of the Iberian margin suggest that Variscan thrusts controlled the breakup and the asymmetry of the margin.

**Rockall Plateau**

Basement rocks in the Rockall Plateau have now been penetrated by multiple exploration wells, many of which show that the crust there was metamorphosed to amphibolite to granulite facies during the Paleoproterozoic Laxfordian–Ketilidian Orogeny (Attfield, 1987; Dickin, 1992). Despite Mesozoic–Cenozoic extension and associated emplacement of thick igneous rock successions (Johnston *et al.*, 2001; Musgrove & Mitchener, 1996; Roberts *et al.*, 1973), which culminated with the opening of the southern North Atlantic Ocean in the Cretaceous, the entire block is believed to be underlain by Paleoproterozoic continental crust (Dickin, 1992). Despite the Paleoproterozoic ages obtained for the crust there, the Rockall Plateau is rarely included in Paleoproterozoic–Paleozoic plate tectonic reconstructions (e.g., Domeier, 2016), thus giving the continental plates and blocks in these reconstructions more space for movement or resulting in large overlaps of adjacent plates (e.g., Johnston *et al.*, 2001).

## Implications for RRR triple junctions

On restoration prior to breakup, all triple junctions linking three mid-ocean ridge segments (RRR), including paleo and failed triple junctions, appear to originate at the intersection of at least two major orogens that are oblique to one another. Most if not all RRR (may they be active-, paleo-, or failed-) triple junctions display a T-like geometry, that is two mid-ocean ridge segments parallel to one another and a third segment oblique to the other two. As such, of the three mid-ocean ridge segments involved at RRR triple junctions, two are crosscut by transform faults with the same strike. Given the control of rift-orthogonal orogens on the formation of major transform faults, a relationship between at least two orogens and RRR triple junctions is logical. OrBiT therefore predicts that RRR triple junctions form at the intersection of two preexisting orogens oblique to one another. To illustrate this, we explore the situation at the four currently active RRR triple junctions, the Bouvet, Rodrigues, Galapagos, and Pacific–Nazca–Antarctica

triple junctions, as well as at a paleo-RRR triple junction (Labrador–Reykjanes–Mid-Atlantic) and two failed RRR triple junctions (western Barents Sea and North Sea rift; Figure 1, Figure 5a–b, and Figure 6).

***Bouvet Triple Junction***

In the southern Atlantic Ocean, the Bouvet Triple Junction connects the southern segment of the Mid-Atlantic Ridge with the American–Antarctic Ridge in the southwest, and with the Atlantic–Indian Ridge in the southeast (Ligi *et al.*, 1999; Figure 1 and Figure 5a–b). Breakup at the southern Mid-Atlantic Ridge occurred at ca. 125–100 Ma (e.g., Eagles, 2007; Scotchman *et al.*, 2010), i.e., later than along the South-West Indian Ridge at ca. 160 Ma (DeMets *et al.*, 2021; Seton *et al.*, 2012). The southern part of the Mid-Atlantic Ridge is crosscut by E–W- to NE–SW-striking transform faults such as the Agulhas–Falkland fault zone (Figure 1 and Figure 5a–b; Barker, 1979; Ben-Avraham *et al.*, 1997; Uenzelmann-Neben & Gohl, 2004). The E–W-striking Agulhas–Falkland fault zone runs parallel to the late Paleozoic Cape Fold Belt in the Falkland Plateau and Maurice Ewing Bank (Johnston, 2000; Martin *et al.*, 1981; Mitchell *et al.*, 1986; Stanca *et al.*, 2022; Storey *et al.*, 1999) and onshore Patagonia (Castillo *et al.*, 2017; du Toit, 1927; Falco *et al.*, 2022; Falco *et al.*, 2024; Grillo Vidal *et al.*, 2024; Pankhurst *et al.*, 2006; Figure 1 and Figure 5a). In South Africa, the fault shows a NE–SW strike and runs parallel to the Cape Fold Belt near Cape Town and Port Elizabeth (Figure 5a; Johnston, 2000; McKay *et al.*, 2018; Newton, 1993; Veevers *et al.*, 1994).

In the southwest, the American–Antarctic Ridge is offset by a series of transform faults including the Conrad, Bullard, and Vinogradov fault zones (Ligi *et al.*, 1999; Mitchell *et al.*, 2000; Sandwell & Smith, 2001), which also parallel transform faults in the Scotia Plate, e.g., the North Scotia and South Scotia ridges (Klepeis, 1994; Livermore *et al.*, 2000; Ludwig & Rabinowitz, 1982; Pelayo & Wiens, 1989; Riley *et al.*, 2019; Thomas *et al.*, 2003; Figure 5a). All these faults also parallel the Cape Fold Belt; Figure 1 and Figure 5a). A potential hypothesis to be further tested for the West Scotia Ridge and Phoenix Ridge system in the west and the American–Antarctic Ridge in the east is a failed attempt of the West Scotia–Phoenix Ridge system to break the orogenically thickened continental crust between the Falkland Islands and Maurice Ewing Bank in the south and to merge with South Atlantic Mid-Ocean Ridge. Instead, seafloor spreading aborted there and the rift stepped to the west with seafloor spreading initiating at the American–Antarctica Ridge and succeeding in rupturing the orogenic bridge. This scenario is already supported by the left-lateral offset/step of the South Atlantic Mid-Ocean Ridge across the Agulhas–Falkland fault zone (Figure 5a–b) and by 137–93 Ma Ar–Ar ages for basalts at the northern tip of the West Scotia Ridge (Riley *et al.*, 2019). The latter suggest that magmatism along the northern tip of the West Scotia Ridge died out at 93 Ma, i.e., at the onset or soon after the breakup in the South Atlantic Ocean at ca. 100 Ma (Eagles, 2007).

East of the Bouvet Triple Junction, the Atlantic–Indian Ridge is truncated by NE–SW- to NNE–SSW-striking transform faults, which include the Andrew Bain Fault Zone (e.g., Peyve *et al.*, 2007; Sclater *et al.*, 2005) and other minor faults such as the Du Toit, Moshes, and Bouvet fault zones (Figure 5a; Ligi *et al.*, 1999). There, the transform faults parallel the East African–Antarctica Orogen and related shear zones, both in Antarctica (Bauer & Siemes, 2004; Golynski & Jacobs, 2001; Jacobs, 1999; Ruppel *et al.*, 2015), eastern Africa (Abdelsalam *et al.*, 1998; Hamimi *et al.*, 2022; Johnson, 2014; Key *et al.*, 1989; Mosley, 1993; Quick & Bosch, 1990; Shackleton, 1996; Stern & Kröner, 1993), and Madagascar (Armistead, 2019; Boger *et al.*, 2015; Collins *et al.*, 2000; Collins *et al.*, 2012; De Waele *et al.*, 2011; Figure 6).

Major transform faults offsetting the southern segment of the Mid-Atlantic Ridge and the American–Antarctic Ridge strike parallel to one another (Figure 5b), and both groups of transform faults parallel the late Paleozoic, E–W-striking Cape Fold Belt and its onshore continuation in Patagonia (Castillo *et al.*, 2017; Falco *et al.*, 2022; Falco *et al.*, 2024; Grillo Vidal *et al.*, 2024; Pankhurst *et al.*, 2006; Stanca *et al.*, 2022; Figure 5). However, major transform faults associated with the Atlantic–Indian Ridge (e.g., Andrew Bain Fault Zone) are oblique (c. 45°) to these transforms as they parallel the East African–Antarctica Orogen (Figure 5 and Figure 6; Collins *et al.*, 2000; Collins *et al.*, 2012; Ruppel *et al.*, 2015; Shackleton, 1996). When restored to prior to opening of the three mid-ocean ridge segments, the Bouvet Triple Junction lies at the intersection of the Cape Fold Belt and the East African–Antarctica Orogen near the eastern tip of Maurice Ewing Bank, the eastern tip of the Cape Fold Belt in South Africa, and between the Grunehogna and Kalahari cratons prior to rifting (black arrow in Figure 1 and Figure 5a; e.g., Mueller & Jokat, 2019; Tomasi *et al.*, 2021).

***Rodrigues Triple Junction***

Similar to the T-like Bouvet Triple Junction in the southern Atlantic Ocean (Figure 5a), the Rodrigues Triple Junction connects the NE–SW-striking Southwest Indian Ridge with the NW–SE-striking Southeast Indian and Central Indian ridges in the Central Indian Ocean (Figure 1 and Figure 12; Meyzen & Schwarz-Schampera, 2023; Munschy & Schlich, 1989; Patriat & Segoufin, 1988). The Southeast Indian and Central Indian ridges are crosscut by large NE–SW-striking transform faults such as the Marie Celeste fault zone (Figure 12; Chen *et al.*, 2017; Mahoney *et al.*, 1989; Mukhopadhyay & Iyer, 1993; Nauret *et al.*, 2006). In contrast, the Southwest Indian Ridge is truncated by NE–SW- to N–S-striking transform faults (e.g., Andrew Bain Fault Zone; Figure 5a and Figure 12; Peyve *et al.*, 2007; Sclater *et al.*, 2005) that strike parallel to late Neoproterozoic structures of the East African–Antarctica Orogen (see previous sections and Figure 6).

Transform faults associated with the Southeast and Central Indian ridges show a comparable strike to that of NE–SW-striking folds, thrusts, and shear zones of the late Neoproterozoic–Cambrian Kuunga Orogen, including the Lurio Belt in northeastern Mozambique (Figure 12; Bingen *et al.*, 2009; Collins *et al.*, 2003; Sacchi *et al.*, 2000; Viola *et al.*, 2008) and their counterparts in southern India and Sri Lanka (Figure 12;

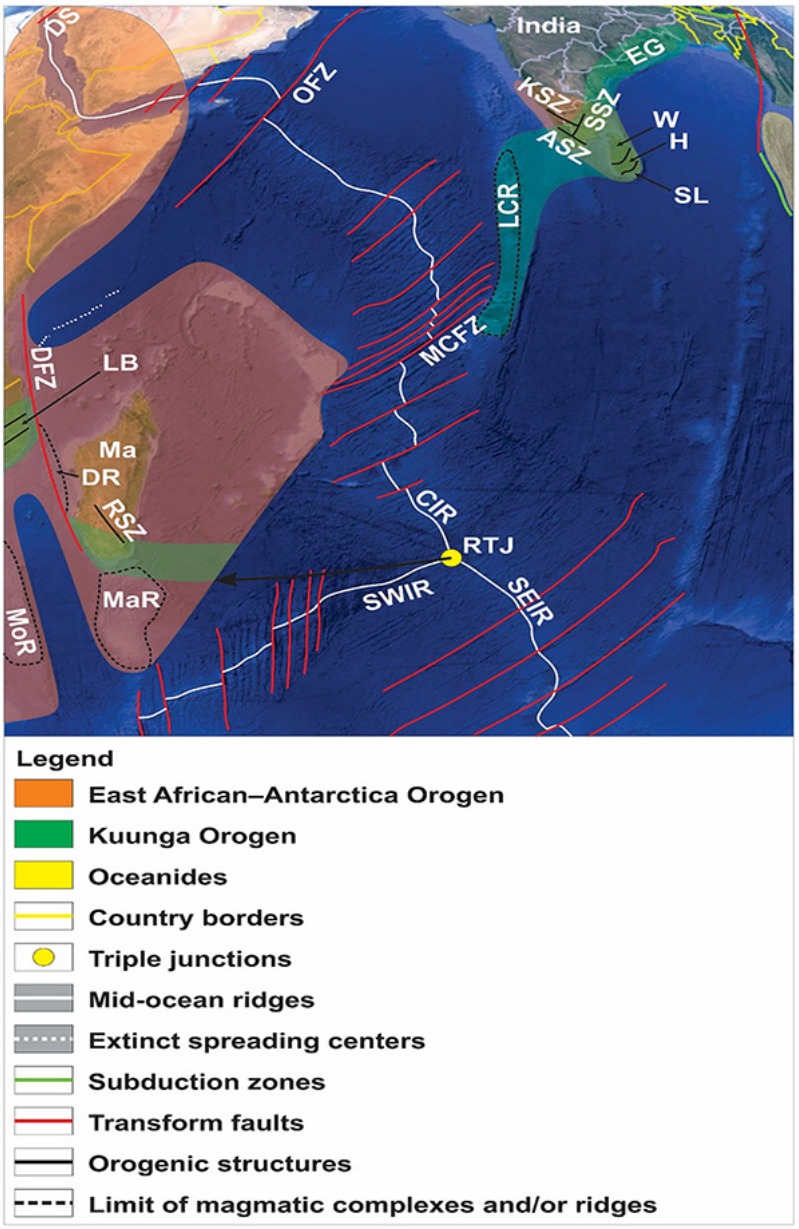


**Figure 12. Topographic–bathymetric map showing the relationship of major transform faults in the central and northern Indian Ocean with the East African–Antarctic and Kuunga orogens and related orogenic structures (e.g., Marie Celeste fault zone striking parallel to structures in the Lurio Belt in Mozambique).** When restored prior to the opening of the Indian Ocean, the Rodrigues Triple Junction coincides with the intersection of the Kuunga and East African–Antarctica orogens in southern Madagascar (black arrow). The orogenic structures in India, Madagascar, and Mozambique are from Sacchi *et al.* (2000), Collins *et al.* (2003), Brandt *et al.* (2014), and Armistead (2019). Basemap is from © Google Earth. Abbreviations: ASZ: Achankovil Shear Zone; CIR: Central Indian Ridge; DFZ: Davie fault zone; DR: Davie Ridge; DS: Dead Sea Transform; EG: Eastern Ghats; H: Highland Complex; KSZ: Karur–Kambam–Painavu–Trichur Shear Zone; LB: Lurio Belt; LCR: Laccadive-Chagos Ridge; Ma: Madagascar; MaR: Madagascar Ridge; MCFZ: Marie Celeste fault zone; MoR: Mozambique Ridge; OFZ: Owen fault zone; RSZ: Ranotsara Shear Zone; RTJ: Rodrigues Triple Junction; SEIR: Southeast Indian Ridge; SL: Sri Lanka; SSZ: Suruli Shear Zone; SWIR: Southwest Indian Ridge; W: Wanni Complex.

Axelsson *et al.*, 2020; Brandt *et al.*, 2014; Dharmapriya *et al.*, 2015; Ghosh *et al.*, 2004; He *et al.*, 2018; Hirayama *et al.*, 2020; Srinivasan & Rajeshdurai, 2010). The dominantly sinistral strike-slip, NE–SW-striking shear zones within the Lurio Belt bend E–W westwards, suggesting a possible link with the late Neoproterozoic, WNW–ESE-striking Ranotsara Shear Zone in southern Madagascar, which also displays evidence of sinistral strike-slip kinematics (Figure 6 and Figure 12;

Collins *et al.*, 2003; Tucker *et al.*, 2007). The latter was correlated with the Achankovil Shear Zone and/or the Karur–Kambam–Painavu–Trichur Shear Zone in southern India (Figure 12; Collins *et al.*, 2003; Ghosh *et al.*, 2004).

Since the NE–SW-striking, sinistral segment of the Karur–Kambam–Painavu–Trichur Shear Zone appears to continue southwards as the NE–SW-striking Suruli Shear Zone, it is probable that the Karur–Kambam–Painavu–Trichur Shear Zone and the Suruli Shear Zone correlate with NE–SW-striking sinistral shear zones in the Lurio Belt (Brandt *et al.*, 2014; Srinivasan & Rajeshdurai, 2010). Transform faults in the central Indian Ocean, such as the Marie Celeste fault zone, notably parallel the NE–SW-striking segment of the Karur–Kambam–Painavu–Trichur and NE–SW-striking Suruli shear zones in southern India, the NE–SW-striking Eastern Ghats in eastern India, and the NNE–SSW- to NE–SW-striking Highland and Wanni complexes in Sri Lanka (Figure 12; Axelsson *et al.*, 2020; Collins *et al.*, 2003; Dharmapriya *et al.*, 2015; Ghosh *et al.*, 2004; He *et al.*, 2018; Hirayama *et al.*, 2020; Kitano *et al.*, 2017; Meert, 2003).

Reconstruction of the Rodrigues Triple Junction prior to opening of the Indian Ocean shows that it most likely initiated near the southern tip of Madagascar and southern India, the northern tip of the Gunnerus Ridge, and just east of the Lurio Belt in northeastern Mozambique (e.g., Ghosh *et al.*, 2004; Mueller & Jokat, 2019). Thus, the Rodrigues Triple Junction probably formed at the intersection of the N–S-trending East African–Antarctica Orogen in Madagascar (see black arrow in Figure 12; possibly including the Mauritia microcontinent; Torsvik *et al.*, 2013), eastern Africa, and Dronning Maud Land in Antarctica with the NE–SW-striking Kuunga Orogen (e.g., Lurio Belt) in southern Madagascar (and Mauritia), southern India, and Sri Lanka (see black arrow in Figure 1 and Figure 12).

***Galapagos triple junction***

At the Galapagos triple junction, the transform faults crosscutting the E–W-striking Cocos–Nazca Rift (i.e., the Galapagos spreading center) are parallel to the Famatinian Orogen in Colombia and Ecuador (Garcia-Ramirez *et al.*, 2017; Ramos, 2018; Zuluaga *et al.*, 2017). The three major E–W-striking transform faults truncating the southern mid-ocean ridge segment are parallel to the bend in the late Cambrian–Ordovician Famatinian Orogen in Peru (Ramos, 2018). In the north, the E–W-striking transform faults crosscutting the East Pacific Rise are parallel to E–W-striking thrusts and shear zones and ophiolites (El Tambor Complex) of the Motagua Suture Zone in Honduras, Guatemala, and Mexico, a c. 400 km wide zone of contractional deformation including rocks metamorphosed up to blueschist and eclogite facies (Burke, 1988; Brueckner *et al.*, 2009; Martens *et al.*, 2007; Ratschbacher *et al.*, 2009; Tsujimori *et al.*, 2006). A major episode of metamorphism occurred in the earliest Cretaceous, but up to Grenvillian ages (ca. 1.1–1.0 Ga) were obtained, including early–mid Paleozoic metamorphic ages for E–W-striking igneous complexes (e.g., Chuacus complex) and shear zones. These suggest that the Motagua Suture Zone was part of the Taconic–Acadian orogen (Brueckner *et al.*, 2009; Martens *et al.*, 2007; Ratschbacher *et al.*, 2009).

Upon reconstruction to prior to seafloor spreading at the Cocos–Nazca Rift and in the Caribbean Plate, it is thus possible that the Galapagos triple junction initiated at the intersection of early–mid Paleozoic (Taconic–Acadian and Famatinian) or older (latest Mesoproterozoic–earliest Neoproterozoic Grenvillian and early–mid Paleozoic Famatinian) orogens. The location of this intersection is uncertain but was likely (or may still be) along the eastern prolongation of the Motagua Suture Zone, possibly near Puerto Rico, where it was partly reworked and overprinted during the Cuban Orogen (see black arrow in Figure 1). This is supported by latest Mesoproterozoic–earliest Neoproterozoic ages in Cuba and Hispaniola and early Paleozoic ages northwest of Cuba (Dallmeyer, 1984; Iturralde-Vinent, 1994; Kamenov *et al.*, 2011; Renne *et al.*, 1989), which suggest the presence of old continental crust from Mexico to at least Hispaniola (Dominican Republic and Haiti; Figure 1).

***Pacific–Nazca–Antarctica triple junction***

The mid-ocean ridge segments merging at the Pacific–Nazca–Antarctica triple junction are crosscut by transform faults that parallel the Cape Fold Belt and Sierra de la Ventana Fold-and-Thrust Belt in South America (Castillo *et al.*, 2017; Grillo Vidal *et al.*, 2024; Limarino *et al.*, 1999; Lopez-Gamundi, 2006; Pankhurst *et al.*, 2006; Rapela *et al.*, 2003; Stanca *et al.*, 2022; von Gosen *et al.*, 1990) and the late Paleozoic–Triassic fold belt in Indonesia (Brown *et al.*, 1979; Davies, 1980; Harahap, 2012; Hill & Raza, 1999; Page, 1976; Pigram & Davies, 1987) and in the Antarctic Peninsula (Graham Land) and Ellsworth Mountains in Antarctica (Curtis, 2001; Elliott *et al.*, 2019). In Papua (Indonesia) and Papua New Guinea, Silurian–Devonian rocks of the Omung Group were deformed into tight E–W-striking folds and metamorphosed to greenschist facies prior to the deposition of latest Paleozoic–Mesozoic sedimentary rocks and intrusion by Mesozoic igneous rocks (Brown *et al.*, 1979; Davies, 1980; Hill & Raza, 1999; Page, 1976; Pigram & Davies, 1987).

In Antarctica, gneisses and granitoids of Permian–Triassic age suggest deformation related to the Cape Fold Belt (Curtis, 2001; Elliott *et al.*, 2019). The mid-ocean ridge segments of the Pacific–Nazca–Antarctica triple junction are crosscut by only one trend of transform faults (Figure 1). Nevertheless, the triple junction occurs near the intersection of the E–W-striking, Permian Sierra de la Ventana Fold-and-Thrust Belt (Castillo *et al.*, 2017; Limarino *et al.*, 1999; Lopez-Gamundi, 2006; Rapela *et al.*, 2003; von Gosen *et al.*, 1990) and the N–S-striking, Cambrian–Ordovician Pampean and Famatinian orogens (Oriolo *et al.*, 2021; Ramos, 2018; Rapela *et al.*, 1998a; Rapela *et al.*, 1998b; Rapela *et al.*, 2001; Verdecchia *et al.*, 2011). This RRR triple junction is thus no exception

to the proposed controlling relationship and may have initiated at the intersection of Permian and Cambrian–Ordovician orogens.

Furthermore, the major transform faults crosscutting the East Pacific Rise in the southern Pacific Ocean strike parallel to late Paleozoic–early Mesozoic orogenic structures of the disrupted Gondwanide Orogen. In South America, they are parallel to structures of the Sierra de la Ventana Fold-and-Thrust Belt and Cape Fold Belt (Castillo *et al.*, 2017; Grillo Vidal *et al.*, 2024; Stanca *et al.*, 2022; von Gosen *et al.*, 1990). In Papua and Papua New Guinea, they are parallel to (Carboniferous–Permian?) E–W-striking the folds in the Omung Group (Brown *et al.*, 1979; Davies, 1980; Hill & Raza, 1999; Page, 1976; Pigram & Davies, 1987; Figure 1). In New Zealand and northeastern Australia, they parallel NW–SE- to WNW–ESE-striking belts of Carboniferous–Triassic igneous and metamorphic rocks of the Median Batholith and Tuhua Orogen, which extend well into the Pacific plate (Allibone *et al.*, 2009; Campbell *et al.*, 2020; Gibson, 1992; McCoy-West *et al.*, 2014; Mortimer *et al.*, 1999; Robertson *et al.*, 2019; Suggate, 1965).

***Labrador–Reykjanes–Mid-Atlantic paleo-triple junction***

The present-day Reykjanes Ridge, Mid-Atlantic Ridge, and paleo Labrador Ridge join at the Bight fault zone (Figure 1 and Figure 4). There, the E–W-striking Appalachian–Caledonian Orogen between Newfoundland and Great Britain (Chew & Stillman, 2009; van Staal *et al.*, 2009; Yang & Welford, 2023) intersects the NW–SE-striking Ketilidian–Laxfordian Orogen between Greenland and Rockall Plateau (Dickin, 1992; Garde *et al.*, 2002b; Hinchey, 2021; Figure 4).

A possible scenario to be further explored for this paleo-triple junction is that upon meeting the thickened orogenic crust of the WNW–ESE-striking, late Paleoproterozoic Ketilidian–Laxfordian Orogen towards Iceland, the rift tried to incise the continental crust along the Bight fault zone and then proceeded to open the Labrador Sea. There, the orogen incised the NE–SW-striking, late Paleoproterozoic Makkovikian–Ketilidian Orogen (Garde *et al.*, 2002b; Hinchey, 2021) separating the North Atlantic Craton in western Greenland from the Nain Province in northeastern Canada. In the Davis Strait, rifting met yet another barrier of orogenically thickened crust, the N–S- to E–W-striking Nagssugtoqidian–Torngat orogen (van Gool *et al.*, 2002a; van Gool *et al.*, 2002b; van Gool *et al.*, 2005; Figure 4), and stepped into Baffin Bay along the Ungava Fault Zone (e.g., Dafoe *et al.*, 2022; Oakey & Chalmers, 2012). Eventually, rifting died out in the Labrador Sea and Baffin Bay and rifting proceeded into the northeastern Atlantic along the Reykjanes Ridge (Figure 4).

***Western Barents Sea failed triple junction***

Examples of failed RRR triple junctions include the Hammerfest and Bjørnøya basins in the southwestern Barents Sea (Figure 13). These basins are located at the intersection of the NE–SW-striking Caledonian and WNW–ESE-striking Timanian orogens (Olovyanishnikov *et al.*, 2000; Roberts, 2003; Figure 13). Both basins and their boundary faults, e.g., Troms–Finnmark Fault Complex and Bjørnøyrenna Fault Complex, formed along Timanian thrusts and folds reworked into NE–SW-striking structures during the Caledonian Orogeny (Gernigon *et al.*, 2014; Gudlaugsson *et al.*, 1998; Koehl *et al.*, 2018; Koehl *et al.*, 2023a; Koehl & Stokmo, 2024). This suggests that rifting attempted to thin the crust along preexisting Caledonian (or reoriented Timanian) thrusts (Gernigon *et al.*, 2014; Koehl *et al.*, 2018; Koehl & Stokmo, 2024), but failed and merged with the Gakkel Ridge in the Arctic Ocean through delayed rifting in the Fram Strait (Koehl, 2020; Koehl & Mottram, 2024; Figure 4).

***North Sea failed triple junction***

The North Sea rift displays a triple-junction-like geometry in that it consists of three failed rift arm trends, including (a) an ENE–WSW-striking arm extending from Moray Firth to onshore the northern UK, (b) a WNW–ESE-striking arm extending from Denmark and including the Sorgenfrei–Tornquist Zone, and (c) a N–S to NNE–SSW-striking arm between the Shetland Islands and southern Norway (Figure 4). The N–S- to NNE–SSW- and ENE–WSW-striking arms clearly developed along inherited Caledonian structures as supported by numerous onshore field and offshore seismic reflection studies (e.g., Fazlikhani *et al.*, 2017; Fossen *et al.*, 2016; Fossen *et al.*, 2024; Osmundsen & Andresen, 1994; Serck *et al.*, 2022; Figure 4).

In contrast, the WNW–ESE-striking arm of the North Sea rift formed along the Laxfordian–Svecofennian Orogen. The latter includes WNW–ESE-striking Laxfordian shear zones onshore northern Scotland (Coward & Park, 1987), thrust systems around the Faroe Islands and in the Iceland–Faroe Ridge (Koehl *et al.*, 2024), Svecofennian shear zones onshore southern Sweden (Saintot *et al.*, 2011), and possibly the Sorgenfrei–Tornquist Zone (STZ; Ponikowska *et al.*, 2024). There is evidence that rift-related basins in the North Sea formed along reactivated segments of the Sorgenfrei–Tornquist Zone (e.g., Farsund Basin; Phillips *et al.*, 2018) and that these are related to WNW–ESE-striking late Paleoproterozoic thrust systems off the Faroe Islands and onshore northern Scotland (Koehl *et al.*, 2024). Thus, the North Sea rift seems to have been completely controlled by preexisting orogens.

***Afar triple junction***

In the Arabian–Nubian Shield, the N–S-striking late Neoproterozoic shear zones and sutures of the East African Orogen probably controlled the formation of the Aqaba–Dead-Sea–Levant fault zone and related proto-transform faults in the Red Sea (see East African–Antarctica orogenic bridge section; Bosworth *et al.*, 2005; Collins *et al.*, 2021; Dixon *et al.*, 1987; Johnson & Woldehaimanot, 2003; Molnar *et al.*, 2020; Stern & Kröner, 1993; Figure 11). In addition, it is well established that these inherited, late Neoproterozoic structures also controlled the geometry of the East African Rift in Nubian basement rocks, e.g., providing suitably oriented N–S-striking foliation, faults, shear zones, and intrusions (e.g., Chorowicz, 2005; Corti *et al.*, 2022). Furthermore, they also parallel the NNE–SSW-striking transform faults truncating the Gulf of Aden Rift, including

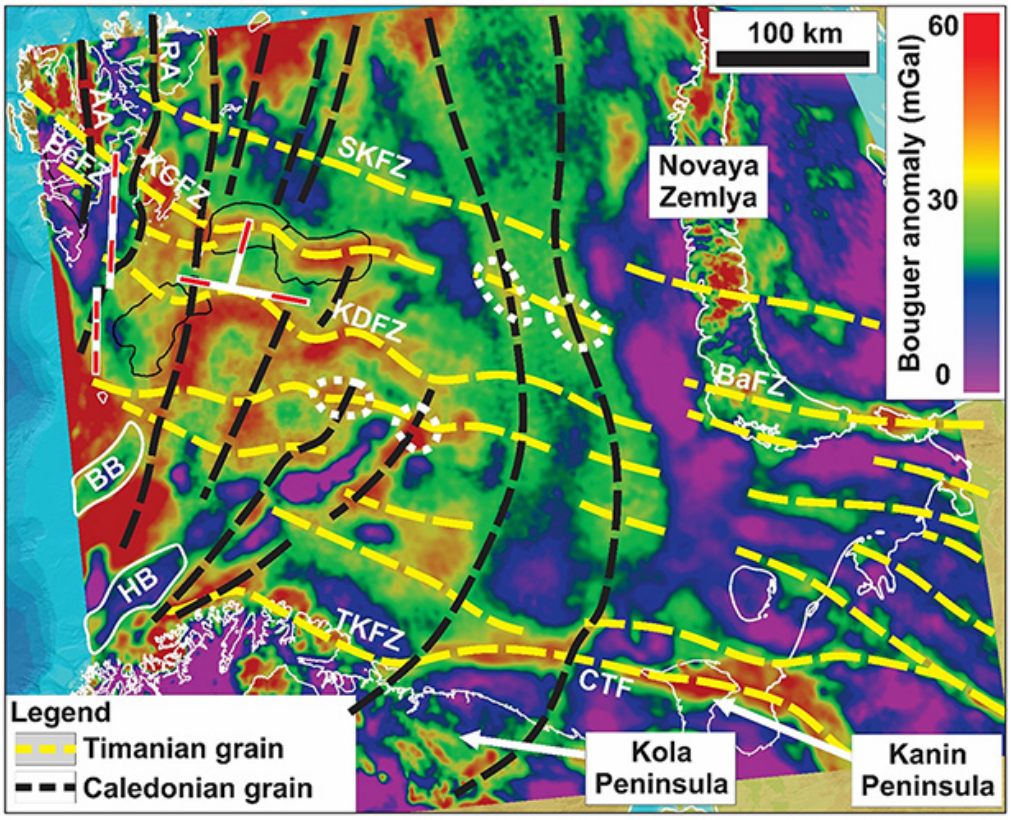


**Figure 13. Bouguer anomaly map of the Barents Sea.** The map shows the interaction of NE–SW- to N–S-striking Caledonian (dashed black) and Timanian (dashed yellow) structural trends in the Barents Sea. Notice how the Hammerfest Basin (HB) and Bjørnøya Basin (BB) in the west parallel preexisting Caledonian grain. The data is from BGR. Modified after Koehl *et al.* (2022).

the Owen fault zone (Fournier *et al.*, 2011) and, thus, may as well have controlled the formation of these structures.

In addition, the Arabian–Nubian Shield is transected by older, early Neoproterozoic, NE–SW-striking shear zones and suture zones, e.g., Yanbu-Sol Hamed, Bi'r Umq–Nakasib, and Ambur–Delgo sutures (Abdelsalam & Stern, 1993; Collins *et al.*, 2021; Johnson, 2014; Johnson *et al.*, 2011; Robinson *et al.*, 2015; Figure 11). These were reworked by E–W-oriented contraction during the late Neoproterozoic East African Orogeny, e.g., the NNW–SSE-striking sinistral Oko shear zone offsetting the NE–SW-striking Bi'r Umq–Nakasib suture (Abdelsalam & Stern, 1993; Abdelsalam, 2010). In addition, the location of some of these early Neoproterozoic structures coincide with that of late Neoproterozoic structures, e.g., the NE–SW-striking Bi'r Umq–Nakasib suture (Abdelsalam & Stern, 1993; Abdelsalam, 2010) and ENE–WSW-striking Central African Shear Zone (Ibrahim *et al.*, 1996; Schandelmeier & Pudlo, 1990 their figure 5; Figure 11). The latter is part of the Central African Orogen in western Africa, an oblique arm of the late Neoproterozoic Pan African Orogeny (Dorbath *et al.*, 1986; Kouémo *et al.*, 2014).

In Yemen, NE–SW-striking Neoproterozoic shear zones and/or sutures bound Archean–Mesoproterozoic crust of the Abas and Al Mahfid blocks from island-arc rocks of the Al Bayda block, which record late Neoproterozoic greenschist-facies metamorphism (Johnson *et al.*, 2011; Johnson, 2014; Whitehouse *et al.*, 2001; Yeshanew *et al.*, 2015; Figure 11). Similarly striking early Neoproterozoic structures also occur in Oman (Alessio *et al.*, 2017; Blades *et al.*, 2019). These zones of deformation strike parallel to the NE–SW-striking Gulf of Aden Rift. It is therefore possible that the rift was controlled by NE–SW-striking early Neoproterozoic orogenic structures. Thus, the Afar triple junction conforms with OrBiT in that it initiated at the intersection of the N–S-striking late Neoproterozoic East African Orogen with a NE–SW-striking early Neoproterozoic orogen and/or an oblique arm of the Pan African Orogeny (Central African Orogen; Figure 11).

## The plume model

Traditionally, offshore areas underlain by anomalously thick crust or shallow bathymetry where crustal thickness is unknown have been assumed to be oceanic crust thickened by extensive magmatism related to a nearby mantle plume. This has been

proposed for example for the GIFR in the northeastern Atlantic (Morgan, 1971; White & McKenzie, 1995) and the Madagascar and Mozambique ridges and Del Cano Rise in the Southwestern Indian Ocean (e.g., Jacques *et al.*, 2019; O'Connor *et al.*, 2019; Ryzhova *et al.*, 2022).

The Iceland area and the GIFR have been intensely researched for well over 50 years. The plume hypothesis for this feature, originally suggested in 1971 (Morgan, 1971) has been widely applied. Features such as the 25–40 km thick crust (e.g., Foulger, 2003), the extensive subaerial volcanism in Iceland with high surface temperature gradients at geothermal fields (50–100°C.km$^{-1}$; (Flovenz & Sæmundsson, 1993; Hermance & Grillot, 1974), and early magnetoteluric data Eysteinsson & Hermance, 1985; Hermance & Grillot, 1974) were interpreted to indicate enhanced magmatism and high temperatures. This interpretation is currently under scrutiny (e.g., Foulger, 2025).

At the Mozambique Ridge, similar geochemical signatures suggest a genetic link between local basalts and the Karoo–Vestfjella flood basalts, both of which had been interpreted to originate from the same mantle plume (Jacques *et al.*, 2019). At the Madagascar Ridge and the Del Cano Rise, the crust was interpreted to be of oceanic nature based on seismic refraction data, but previous studies could not explain the anomalously thick character of the crust there (Goslin *et al.*, 1980; Goslin *et al.*, 1981; Goslin & Diament, 1987; Suo *et al.*, 2016).

Although geochemical data have been interpreted as consistent with the mantle plume hypothesis (e.g., in Iceland and the Mozambique and Madagascar ridges; Jacques *et al.*, 2019; Kerr, 1995), not all data are reconciled by the model. In Iceland, there are several issues. For example, the thickness of the crust varies between 25 and 40 km (Darbyshire *et al.*, 1998; Foulger *et al.*, 2003). This is five times the thickness of typical 6-km-thick oceanic crust (Christeson *et al.*, 2019). Seismic attenuation shows that the 20–30-km-thick lower crust is anomalously cold (Menke & Levin, 1994). The distance separating the oldest rocks formed at rift zones is nearly twice (c. 500 km instead of 290 km) what is predicted by the full-plate spreading rate and plate modeling for the North Atlantic Ocean (Foulger, 2006).

Magnetic anomalies in the GIFR do not conform to the typical character of seafloor-spreading-related (Foulger *et al.*, 2020a; Gaina *et al.*, 2017). Instead of showing narrow, continuous, linear anomalies, the GIFR displays broader, distorted, curving and disrupted, anomalies (Foulger *et al.*, 2020a; Gaina *et al.*, 2017), which resemble more closely the pseudo-linear disrupted anomalies correlated with intrusions in thinned continental crust off southeastern Greenland, the UK, the Faroe Islands, and Namibia (Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b; Figure 14). Their locally anastomosing character, branching off and forking, their V- or Λ-shaped geometry, and, in places, their rift-oblique strike (Figure 14) suggest that the magnetic fabrics at the GIFR are not only the product of Cenozoic rift-related intrusions and may interact with older magnetic fabrics, e.g., older intrusions and/or folded magnetic metasedimentary beds. The V- and Λ-shaped anomalies likely correspond to tight, northeast-plunging Caledonian folds in (Paleoproterozoic?) basement rocks (black lines in Figure 14). Such geometries are typical for Caledonian fold structures on magnetic data on adjacent margins, where they show comparable width and strike (e.g., Koehl *et al.*, 2019 their figures 7e and 8a–b; Koehl & Stokmo, 2024 their figures 10–15). An interpretation of V- and Λ-shaped anomalies in the GIFR and Jan Mayen Microcontinent Complex is in agreement with recent work around the Faroe Islands, where dominantly NNE-dipping, late Paleoproterozoic thrust systems were reworked into northeast-plunging Caledonian folds (Koehl *et al.*, 2024). This tends to suggest that the Jan Mayen Microcontinent Complex is a remnant of a major Caledonian anticline (black lines in Figure 14).

Reinterpretation of the RRISP seismic profile on the Reykjanes Ridge (Gebrande *et al.*, 1980) also shows data compatible with cool, sub-solidus temperatures (e.g., Menke *et al.*, 1995), a result that provides little support for a hot plume model (Foulger *et al.*, 2003). Finally, ongoing seismic reflection mapping off the Faroe Islands and southeastern Greenland and within the GIFR suggest that basement-seated, late Paleoproterozoic thrust systems of the Laxfordian Orogen and Ammassalik Belt extend to Iceland (Koehl *et al.*, 2024; Koehl *et al.*, 2025). This most recent work suggests that the GIFR consists dominantly of continental crust and that breakup may not yet have occurred in Iceland despite the several km thick cap of lavas. A model for the thick Icelandic crust that includes a substantial component of continental material is thus currently under scrutiny (e.g., Yuan *et al.*, 2020).

South of Africa and Madagascar, the Mozambique Ridge was arbitrarily assumed to be of volcanic origin (i.e., oceanic crust) with only weak geophysical evidence (magnetic data; König & Jokat, 2010). A continental composition of the crust thus cannot be excluded. This influenced later work (e.g., Jacques *et al.*, 2019) and non-volcanic models for the Mozambique Ridge have been neglected. Seismic refraction and bathymetric data alone are insufficient to establish crustal affinity (e.g., Goslin *et al.*, 1980; Goslin *et al.*, 1981) as demonstrated by an early erroneous interpretation of the Falkland Plateau as oceanic crust (e.g., Schimschal & Jokat, 2018) and of the GIFR as thickened oceanic crust (e.g., White & McKenzie, 1995). This oceanic interpretation was invalidated by the penetrating of Mesoproterozoic continental crust by offshore drill holes (Chemale Jr. *et al.*, 2018) and by evidence of the continuation of the late Paleozoic Cape Fold Belt into the Falkland Plateau and Maurice Ewing Bank (Stanca *et al.*, 2022; Figure 5a). Moreover, the interpretation of gravimetric data leading to the assumption of anomalously thick oceanic crust had been based on the assumption that a mantle plume was present near the Mozambique Ridge (e.g., Goslin & Diament, 1987; Suo *et al.*, 2016), an example of circular reasoning. It is now clear that both the Mozambique Ridge and the Madagascar Ridge are underlain by 15–30 km-thick continental (to hybrid?) crust (Ryzhova *et al.*, 2022; Sato *et al.*, 2022).

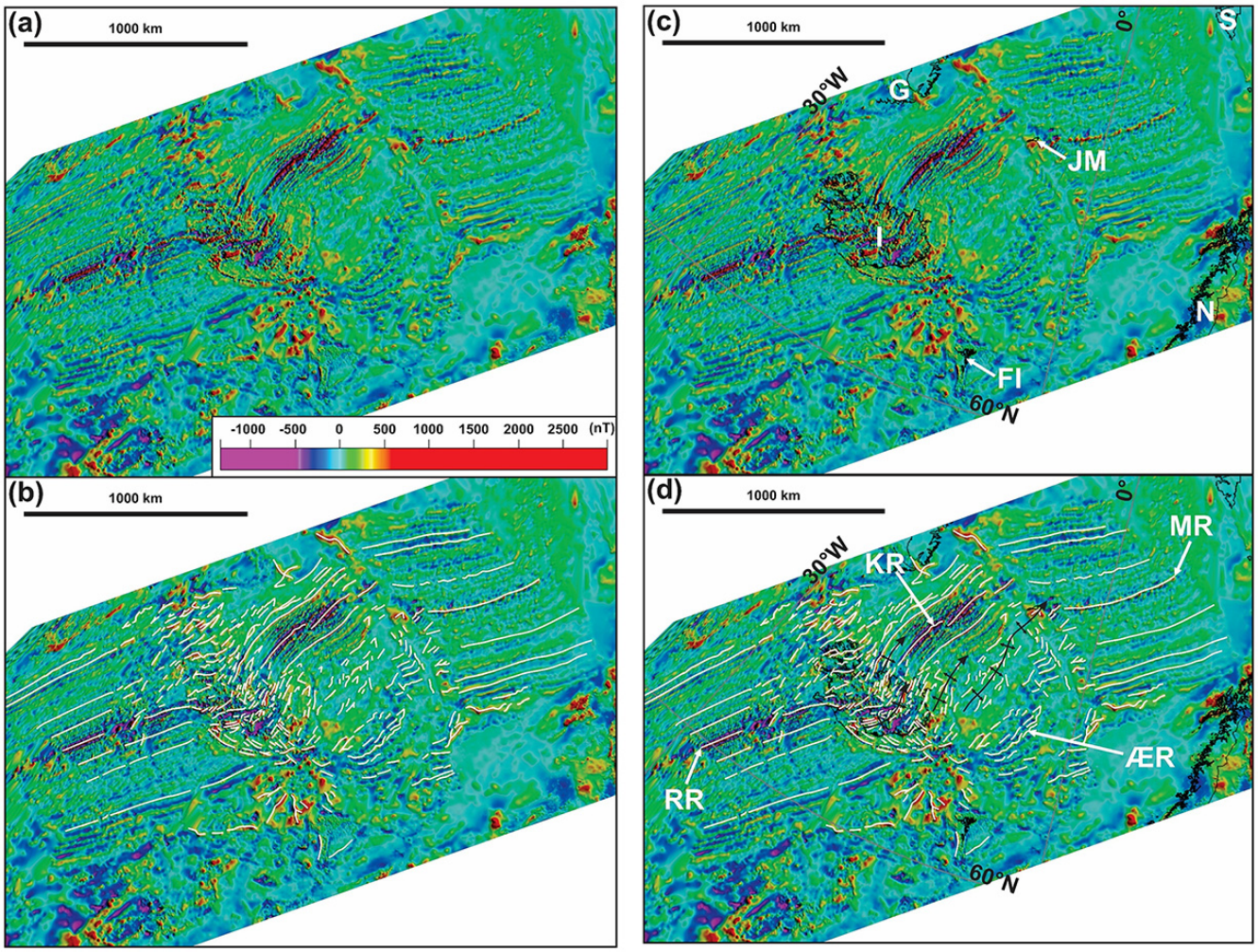


**Figure 14. NAG-TEC magnetic anomaly map of the Northeastern Atlantic Ocean.** The data show that magnetic anomalies at the GIFR clearly differ from typically linear seafloor-spreading anomalies, which can be traced for hundreds to thousands of km. Instead, magnetic anomalies at the GIFR are typically < 100 km long and display anastomosing, splaying, and V- and Λ-shaped geometries, which are more typical of deformation structures and intrusions in continental crust. (**a**) and (**b**) respectively show the data uninterpreted and interpreted without coastlines and geographic coordinates to illustrate the contrast between the character of magnetic anomalies at GIFR and within the three rectangular oceanic crustal basins around the Reykjanes Ridge, Kolbeinsey Ridge, and Mohns Ridge (possibly also including a narrow oceanic domain at the Ægir Ridge). (**c**) and (**d**) respectively show the data uninterpreted and interpreted with the coastlines and geographic coordinates. The data are from Gaina *et al.* (2017). Abbreviations: FI: Faroe Islands; G: Greenland; I: Iceland; JM: Jan Mayen; KR: Kolbeinsey Ridge; MR: Mohns Ridge; N: Norway; RR: Reykjanes Ridge; S: Svalbard; ÆR: Ægir Ridge.

Geophysical evidence unambiguously suggests that, although theoretical mantle plumes may produce thick lava flows, they are unlikely to have formed thickened oceanic crust at the GIFR, Mozambique and Madagascar ridges, and Del Cano Rise (Foulger *et al.*, 2003; Foulger *et al.*, 2020a, Foulger *et al.*, 2020b; Geoffroy *et al.*, 2022a; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Ryzhova *et al.*, 2022; Sato *et al.*, 2022). A genetic link between igneous rocks at the Mozambique and Madagascar ridges and those of the Karoo–Vestfjella province is not precluded by our model (e.g., East African–Antarctic Orogen; Figure 6). Nevertheless, certain issues need to be further studied, e.g., the tracking of old orogenic structures into these areas of anomalously thick offshore crust on seismic reflection data.

The wet" versus "dry" rift classification by Dunbar & Sawyer (1989) related the intensity of magmatism and width of the resulting rift with the existence of preexisting weaknesses in the crust and/or mantle. For example, preexisting mantle weaknesses would tend to form narrow "wet" rifts with intense magmatism (e.g., Iceland), whereas crustal weaknesses lead to the development of broad "dry" rifts (e.g., Iberia–Newfoundland). This work assumes that breakup has occurred at the Greenland–Iceland–Faroe Ridge, which is not (yet) the case (Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, if the magma-rich Greenland–Iceland–Faroe Ridge is a through-going orogenic bridge where breakup has not yet occurred whereas breakup has occurred at magma-poor margins, e.g., in the Arctic Ocean (ultra-slow-spreading Gakkel Ridge), then intense magmatism

and preexisting mantle weaknesses or plumes have less effect on breakup than previously assumed. Other factors, e.g., rift-parallel and rift-orthogonal orogens, must therefore be at play.

Progress in geophysical imagery tools, the gradual release of private geophysical data, and the increasing amount of offshore drill cores and exploration wells are generally revealing that the extent of oceanic crust on Earth has been overestimated. In other words, the extent of continental and hybrid crust (i.e., continental crust extensively intruded by mafic magma) has been significantly underestimated. Such crust should be considered a candidate in many areas where thick crust has traditionally been assumed to be entirely mafic and plume-generated (i.e., oceanic; e.g., Foulger *et al.*, 2020a; Geoffroy *et al.*, 2022a).

## Predictions using OrBiT

***Propagation of the Gakkel Ridge towards northern Russia along the Verkhoyansk Orogen***

OrBiT predicts that the Gakkel Ridge in the Arctic Ocean will propagate towards northern Russia along the parallel Verkhoyansk Orogen and then step along the E–W-striking segment of the Verkhoyansk Orogen, where a major transform may form (Figure 15a–b). Existing data suggest that this is already happening. Seismic data between the Russian tip of the Gakkel Ridge and northern Russia show numerous $M_w \geq 5.0$ earthquakes suggesting normal focal mechanisms along major fault systems parallel to the Gakkel Ridge in the Laptev Sea and nearby onshore areas (e.g., Cook *et al.*, 1986; Engen *et al.*, 2003; Franke *et al.*, 2001; Imaeva *et al.*, 2018; Imaeva *et al.*, 2019). These indicate extension off axis (Figure 15b). Rifting may thus be proceeding along the same trend as the Gakkel Ridge towards Tiksi in northern Russia, where the Verkhoyansk Orogen and associated structure strike N–S, i.e., parallel to the Gakkel Ridge (Kuzmichev & Danukalova, 2023; Pavlovskaia *et al.*, 2022; Figure 15a).

Farther south, the Verkhoyansk Orogen bends c. 90° to an E–W to WNW–ESE strike (Pavlovskaia *et al.*, 2022; Figure 15a). There, the focal mechanisms of $M_w \geq 5.0$ earthquakes commonly involve a major component of sinistral strike-slip movement along a WNW–ESE-trending axis (e.g., Cook *et al.*, 1986; Fujita *et al.*, 1997; Imaeva *et al.*, 2018; Imaeva *et al.*, 2019), suggesting active, steep, strike-slip faults in the area (Figure 15b). These faults may be related to a major, dominantly sinistral transform plate boundary north of the Sea of Okhotsk possibly related to the Ulakhan fault system (Figure 1; see notably Fujita *et al.*, 1997; Hindle *et al.*, 2006; Hindle *et al.*, 2019; Hindle & Mackey, 2011; Kozhurin *et al.*, 2023; Parfenov *et al.*, 1988).

Although these earthquakes may be related to westwards movements of the Pacific Plate towards the Sea of Okhotsk (e.g., Gorbatov *et al.*, 1994; Gorbatov *et al.*, 1997), should the Gakkel Ridge propagate to the E–W-striking arm of the Verkhoyansk Orogen (Figure 15a), it will meet sub-orthogonal folds and thrust structures crosscut by steeply dipping strike-slip faults in thickened, orogenic continental crust (probably an orogenic bridge). This will hinder the direct linear propagation of rifting (e.g., Molnar *et al.*, 2017). Propagation of the Gakkel Ridge into northern Russia and to the Sea of Okhotsk has already been proposed (e.g., Cook *et al.*, 1986; Fujita *et al.*, 1997). OrBiT explains the variations in earthquake focal mechanisms in the area – normal movement along N–S-striking faults in the Laptev Sea and N–S-striking segment of the Verkhoyansk Orogen under E–W extension, and strike-slip movements at the E–W segment of the orogen where E–W-striking faults are parallel to the extension direction (Cook *et al.*, 1986; Imaeva *et al.*, 2018; Imaeva *et al.*, 2019; Figure 15b). This suggests that the Gakkel Ridge will step along a major sinistral transform fault (Ulakhan fault system?) in the Verkhoyansk Orogen (Figure 15a) rather than propagate linearly through northern Russia as suggested by earlier works (e.g., Cook *et al.*, 1986; Imaeva *et al.*, 2019; Parfenov *et al.*, 1988).

From the E–W-striking segment of the Verkhoyansk Orogen and the potential parallel future/proto transform related to the Ulakhan fault system, the Gakkel Ridge may step to the west and merge with the NE–SW-striking segment of the Baikal Rift (which is opening parallel to the late Neoproterozoic and Late Devonian–Mississippian Baikal–Patom Fold-and-Thrust Belt; e.g., de Boisgrollier *et al.*, 2009) and late Paleoproterozoic Akitkan Orogen (Donskaya, 2020; Sears & Price, 2000). Alternatively, it may reactivate preexisting Devonian–Mississippian, NE–SW-striking rift-related structures of the Vilyui Rift in central Siberia (e.g., Kiselev *et al.*, 2012; Polyansky *et al.*, 2017; Ricci *et al.*, 2013; see alternative "1" in Figure 15a). However, there is no indication in present-day data that this is occurring, and the Baikal Rift bends ENE–WSW to the northeast (e.g., Huang & Zhao, 2022; Klyuchevskii *et al.*, 2022; Radziminovich *et al.*, 2013; Figure 15a). Another possibility is that the Gakkel Ridge will step to the east towards the Kuril–Kamchatka volcanic arc possibly in a future backarc setting (alternative "2" in Figure 15a), where the Pacific Plate is subducted below the Sea of Okhotsk (Fujita *et al.*, 1997; Gorbatov *et al.*, 1994; Gorbatov *et al.*, 1997; Parfenov *et al.*, 1988; Rhea *et al.*, 2010).

Farther south, the ridge may continue along the southern N–S-striking segment of the Verkhoyansk Orogen (i.e., south of the E–W-striking segment; Figure 15a). There it may follow preexisting late Paleoproterozoic structures of the Ulkan Orogen/Suture (Didenko *et al.*, 2015; Donskaya, 2020; Sears & Price, 2000) and step back to the west to merge with the ENE–WSW-striking arm of the Baikal Rift across another major E–W-striking transform fault, the sinistral South Tukuringra fault in the Aldan Stanovoy Block (e.g., Imaeva *et al.*, 2017; Ovsyuchenko *et al.*, 2010; Parfenov *et al.*, 1988; Figure 15a), which runs parallel to the E–W-striking Cis–Stanovoy Orogen (Donskaya, 2020). Thus, both proto-transform faults in the area (Ulakhan fault system and Tukuringra fault) also follow preexisting orogenic structures and fabrics (Figure 15a).

***Southwards propagation of the East African Rift along the East African Orogen***

The East African Rift is likely to propagate farther south along existing late Neoproterozoic–Cambrian structures of the East African Orogen (Figure 6). In northeastern Mozambique, it may

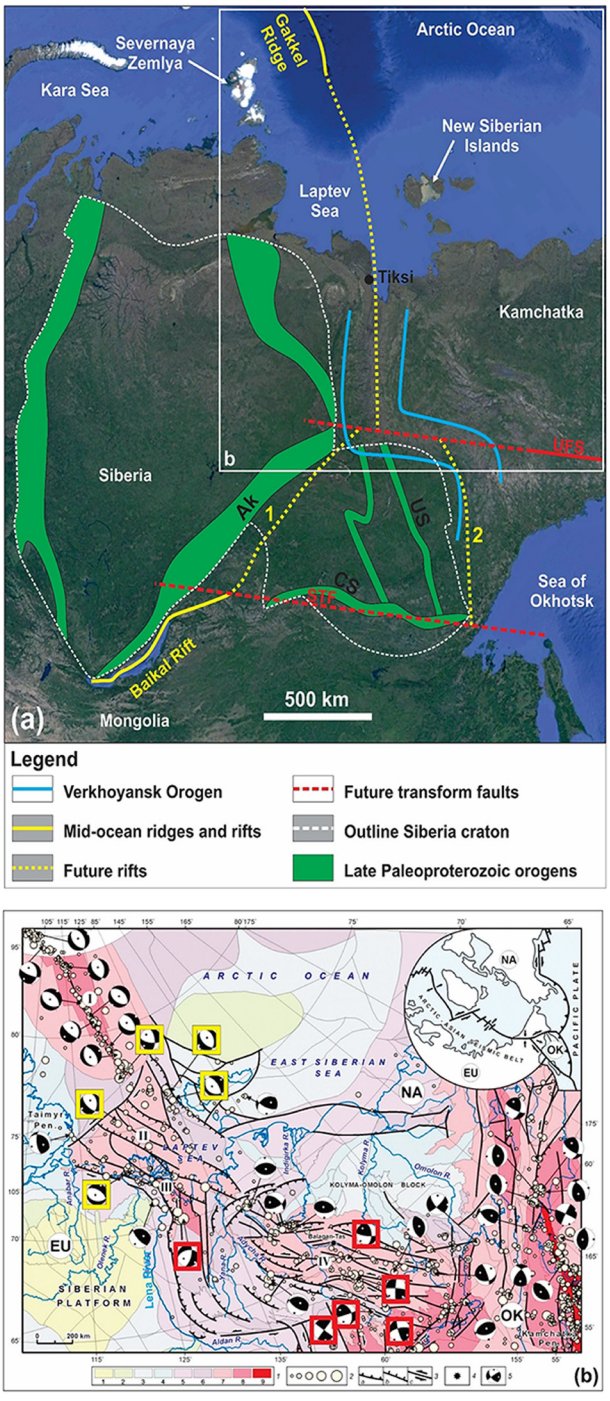


**Figure 15.** (**a**) Location map of the Gakkel Ridge, its termination in the Arctic Ocean, and possible future propagation (dotted yellow line) on the edge of the Siberian craton. The possible future propagation could occur along the N–S-striking segment of the Verkhoyansk Orogen in northern Russia, stepping sideways along a major future/proto transform fault (e.g., Ulakhan fault system) to form parallel to the E–W-striking segment of the orogen. Southward, the Gakkel Ridge may merge with the Baikal Rift either by stepping to the west along preexisting orogenic fabrics of the late Paleoproterozoic Akitkan Orogen (1) or along the southern continuation of the Verkhoyansk Orogen, i.e., following preexisting late Paleoproterozoic fabrics such as that of the Ulkan Orogen/Suture (2), and via another major step across another transform fault (the South Tukuringra fault). The outline of the Siberian craton and related orogens is from Donskaya (2020). Abbreviations: Ak: Akitkan Orogen; CS: Cis–Stanovoy Orogen; STF: South Tukuringra fault; UFS: Ulakhan fault system; US: Ulkan Orogen/Suture. (**b**) Seismicity related to neotectonic structures in the Laptev Sea and Verkhoyansk Orogen in northern Russia. This shows the dominance of normal movements along the N–S-striking arm of the Verkhoyansk Orogen (yellow squares) and strike-slip kinematics along the E–W-striking segment (red squares) at the location of the predicted future/proto transform fault. 1: Colored areas indicating increasing seismicity; 2: Earthquake epicenters by magnitude (≤ 4.0, 4.1–5.0, 5.1–6.0, 6.1–7.0); 3a: Thrust faults; 3b: Normal faults; 3c: Strike-slip faults; 4: Balagan–Tas volcano; 5: focal mechanisms of earhquakes (lower hemisphere). Modified after Imaeva *et al.* (2019).

either (1) propagate south into the N–S-striking Mozambique Ridge (alternative "1" in Figure 6) or (2) step east or west along suborthogonal structures of the Kuunga Orogen in northeastern Mozambique (alternative "2" in Figure 6). Propagation into the continental crust of the Mozambique Ridge (Ryzhova *et al.*, 2022), which was likely deformed by the late Neoproterozoic East African Orogen like adjacent onshore rocks (e.g., Fritz *et al.*, 2013; Shackleton, 1996; Stern & Kröner, 1993), seems the most likely scenario. This is supported by the coincidence of the narrow plate boundary between the Nubian and Somalia plates (Chu & Gordon, 1999) with the potential propagation of the East African Rift along the Mozambique Ridge and the Andrew Bain Fault Zone (Figure 6).

Initially, the NNW–SSE-striking East African Rift would have to propagate through the thickened continental crust of the late Neoproterozoic, NE–SW-striking Lurio Belt (Kuunga Orogen; Bingen *et al.*, 2009; Sacchi *et al.*, 2000; Viola *et al.*, 2008; Figure 6). This may be problematic if the crust is thick. From there, it is hindered from stepping west since those areas comprise long-lived and dry continental crust of the Kalahari Craton (e.g., Oriolo & Becker, 2018; Figure 6). That crust is therefore difficult to extend and cut across (e.g., Peslier *et al.*, 2010). A possible scenario is that the East African Rift steps east (along a major future transform formed parallel to the Lurio Belt?) and further propagates along potential late Neoproterozoic contractional structures of the East African Orogen in the Davie Ridge, Madagascar, and the Madagascar Ridge (Armistead, 2019; Boger *et al.*, 2015; Collins *et al.*, 2000; Collins *et al.*, 2012; De Waele *et al.*, 2011; Klimke *et al.*, 2018; Sato *et al.*, 2022; Vormann & Jokat, 2021), possibly also reusing younger structures (e.g., Davie fault zone; Davis *et al.*, 2016; alternative "2" in Figure 6).

Regardless of whether it propagates through the Mozambique Ridge or the Davie and Madagascar ridges, the East African Rift would propagate within the diffuse plate boundary between the Somalian and Nubian plates inferred to comprise a prolongation of the East African–Antarctica Orogen across the Southwest Indian Ridge (Chu & Gordon, 1999; Meyzen & Schwarz-Schampera, 2023; yellow dashed lines in Figure 6). OrBiT may therefore help predict the location of future plate boundaries (e.g., future rifts and mid-ocean ridges) and explain the existence of diffuse plate boundaries as transitional plate boundaries, i.e., existing prior to full separation of two or more plates.

According to OrBiT, the new plate boundary and triple junction at the Southwest Indian Ridge would probably not consist exclusively of mid-ocean ridges, since RRR triple junctions likely form at the intersection of two orogens. In the southwestern Indian Ocean, only one orogen is known in the area where the East African Rift is believed to propagate towards the Southwest Indian Ridge, the East African Orogen (Figure 6). Thus, it is probable that part of the new plate boundary would comprise a transform fault segment, e.g., the Andrew Bain Fault Zone (Figure 6).

***Testing the existence of tentative (paleo) transform faults***

OrBiT can help test the plausibility or likelihood of tentative (paleo-) transform faults should any doubts be cast on their existence or kinematics. The theory predicts that the formation of major transform faults is controlled by orogens striking (sub-) orthogonal to propagating rifts. Any transform or paleo-transform fault that does not fulfill this condition is therefore unlikely according to OrBiT. Should the theory be further tested and substanciated, it would allow quick and smooth testing/troubleshooting of specific transform faults worldwide. Transform and paleo-transform faults not obeying OrBiT's principles (i.e., formation parallel to preexisting rift-orthogonal orogen) could thus be discarded as a (paleo) transform faults or even in some cases as faults. Two such examples are the De Geer Zone in western Svalbard and the Wegener Fault between Greenland and Ellesmere Island (Figure 4).

**The De Geer Zone**

The De Geer Zone is a 1000-km-long, early Cenozoic paleo-transform fault that was assumed to run along the western Svalbard–Barents Sea margin and its postulated conjugate margin in northern Greenland (du Toit, 1937; Faleide *et al.*, 1993; Faleide *et al.*, 2008; Harland, 1961; Harland, 1967; Harland, 1969; Horsfield & Maton, 1970; Piepjohn *et al.*, 2016; Wegmann, 1948; Figure 4). The existence of such a physiographic lineament was first proposed based on the linear geometry of both margins (De Geer, 1926). It was subsequently adopted with little criticism as a major paleo-transform fault and became broadly accepted as a fact (e.g., du Toit, 1937; Harland, 1961; Harland, 1967; Harland, 1969; Horsfield & Maton, 1970; Wegmann, 1948). Plate tectonic modeling over the last few decades has usually included the De Geer Zone to explain the opening of the northeastern Atlantic and Arctic oceans (e.g., Cianfarra & Salvini, 2015; Faleide *et al.*, 1993; Harland, 1969; Torsvik & Cocks, 2016). During extension, the De Geer Zone was proposed to have accommodated c. 400 km of lateral movement of Svalbard to the south (Breivik *et al.*, 1998; Faleide *et al.*, 1993; Faleide *et al.*, 2008; Håkansson & Pedersen, 2001; Harland, 1969).

Nevertheless, the De Geer Zone hypothesis does not take into account that nearly half of the transform movement (c. 200 km) was accommodated by the Spitsbergen and Molloy fault zones in the Fram Strait, which are oblique to the De Geer Zone (Figure 4), i.e., that the De Geer Zone cannot have accommodated more than 200 km displacement. Both the Molloy and the Spitsbergen fault zones are observed on various datasets (e.g., Crane *et al.*, 1982; Johnson & Eckhoff, 1966; Myhre & Thiede, 1995; Thiede *et al.*, 1990).

Recent interpretations of geophysical data in the Fram Strait, Svalbard, and the Barents Sea suggest that (1) the Timanian

thrust systems continue into the Fram Strait and are found on the conjugate northeastern Greenland passive margin (Koehl, 2020; Koehl *et al.*, 2021; Koehl & Mottram, 2024; Figure 2), (2) Timanian thrust systems west of Svalbard can be traced continuously without any lateral offset across the presumed De Geer Zone (Figure 4; Koehl, 2024b), and (3) N–S-striking listric fault segments of the De Geer Zone such as the Hornsund Fault Complex are extensional normal faults rather than strike-slip faults (e.g., Austegard *et al.*, 1988; Eiken, 1994; Gabrielsen *et al.*, 1990; Riis & Vollset, 1988; Schaaf *et al.*, 2020). These observations also conflict with the presumed 400 km of dextral movements of Svalbard considered to have occurred along the N–S-striking De Geer Zone.

The postulated De Geer Zone strikes NNW–SSE (du Toit, 1937; Faleide *et al.*, 1993; Faleide *et al.*, 2008; Harland, 1961; Harland, 1967; Harland, 1969; Horsfield & Maton, 1970; Piepjohn *et al.*, 2016; Wegmann, 1948), i.e., oblique to the WNW–ESE-striking Timanian Orogen and related thrust systems in Svalbard, the Barents Sea, and the Fram Strait (Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl, 2024b; Koehl & Mottram, 2024). Thus, in addition to the arguments presented by Koehl (2024b), based on OrBiT's global correlation of major transform faults with inherited rift-orthogonal orogens on adjacent margins, the De Geer Zone is unlikely to have accommodated transform movements.

**The Wegener Fault**

The Wegener Fault is a hypothetical major early Cenozoic sinistral strike-slip fault proposed to exist on the basis of the linear morphology of the Nares Strait and the potential sinistral offset of rock units across the Strait (e.g., Taylor, 1910; Figure 4). It was later proposed to have formed as a major transform during the opening of the Labrador Sea and Baffin Bay (e.g., Piepjohn *et al.*, 2016; Saalmann *et al.*, 2005).

The latter is likely almost fully underlain mostly by continental crust (e.g., Welford *et al.*, 2018) and, furthermore, late Neoproterozoic dykes are continuous across the proposed Wegener Fault (e.g., 627 Ma Kap Leiper Dyke) across the Nares Strait with no trace of lateral offset (Dawes, 2008; Hansen *et al.*, 2011; Oakey & Damaske, 2006; Oakey & Stephensen, 2008; Rasmussen & Dawes, 2011). This fault is thus no longer a viable working hypothesis. Nevertheless, some studies continue to use the Wegener Fault hypothesis in tectonic models (e.g., Gilotti *et al.*, 2018; von Gosen *et al.*, 2019).

Structural trends of the Eurekan Orogen (and, more speculatively, of the Ellesmerian Orogen) in Arctic Canada and northern Greenland strike ENE–WSW (Piepjohn *et al.*, 2016; Saalmann *et al.*, 2005), i.e., oblique to the postulated Wegener Fault (Taylor, 1910). OrBiT suggests that since the Wegener Fault is not parallel to any known rift-orthogonal orogens in nearby areas (Figure 4), it is unlikely to have accommodated any transform movements. The Wegener Fault is not parallel to the other transform faults in the Labrador Sea and Baffin Bay either (e.g., Ungava Fault Zone; Figure 4). In addition, the absence of any offset of corresponding bedrock units and magmatic intrusions across the Nares Strait (Dawes, 2008; Hansen *et al.*, 2011; Oakey & Damaske, 2006; Oakey & Stephensen, 2008; Rasmussen & Dawes, 2011) suggests that the Wegener Fault does not exist and that the negative topography characterizing the Nares Strait may not have been created by a fault. OrBiT can therefore be used to (1) predict the orientation of future transform and paleo-transform faults, and (2) test the plausibility of existing models and transform fault hypotheses.

## Implications for plate tectonics and modeling

We propose the existence of long-lived, continuous orogenic bridges, e.g., the late Neoproterozoic Timanian orogenic bridge in the Fram Strait, late Paleoproterozoic Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and late Paleoproterozoic Nagssugtoqidian–Laxfordian Greenland–Iceland–Faroe orogenic bridge at the GIFR (Foulger *et al.*, 2020a; Koehl & Mottram, 2024; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Peace *et al.*, 2018; Figure 3a–d and Figure 4). The theory suggests that past plate tectonics were less dynamic than commonly assumed in current plate models. Models involving the repeated opening of through-going Phanerozoic oceans, which split/unzipped continental blocks cleanly and completely at an early stage are too simplistic and are no longer viable solutions. Some continents are now known to be still connected by continuous (or recently ruptured) Precambrian orogenic bridges. Other orogenic bridges may have persisted for tens of Myr, and then subsided beneath sea level whilst progressively stretching of continental crust persisted, prior to rupturing relatively late.

The Iapetus Ocean and the northeastern Atlantic Ocean both opened between Norway and Greenland as suggested by Cambrian ophiolites and Caledonian metamorphism and thrusting in mid-Norway (e.g., Furnes *et al.*, 1988; Slagstad *et al.*, 2020). However, despite blueschist metamorphism of Caledonian age suggesting rapid subduction of mafic rocks to great depth in western Svalbard (Horsfield, 1972; Kosminska *et al.*, 2014), it is unlikely that these two oceans fully opened between Svalbard and Greenland. This is because it would require rupture of a possibly still continuous late Neoproterozoic orogenic bridge (e.g., Timanian orogenic bridge between Svalbard and northern Greenland; Figure 4). This is supported by the mapping of late Neoproterozoic Timanian thrust systems without any offset or truncation (Koehl, 2020; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl & Mottram, 2024; Koehl, 2024b) across Caledonian/Iapetus sutures in the Barents Sea and western Svalbard (Breivik *et al.*, 2005; Horsfield, 1972; Kosminska *et al.*, 2014). It is also supported by the delayed opening of the Fram Strait at ca. 24 Ma (Engen *et al.*, 2008) or later (present study and Koehl *et al.*, 2021), i.e., much later than the opening of the Mohns Ridge between Greenland and Norway and Gakkel Ridge in the Arctic Ocean at ca. 56 Ma (Faleide *et al.*, 1993; Faleide *et al.*, 2008; Gaina *et al.*, 2002; Srivastana, 1985).

If the late Neoproterozoic Timanian orogenic bridge had already been ruptured by opening of Iapetus, breakup in the Fram Strait would not have taken more time (or at least not much longer) to achieve than between Norway and Greenland.

This also applies to the Iapetus Ocean and northeastern Atlantic Ocean at the GIFR. If breakup had already occurred at the GIFR, transform faulting at the Tjörnes fault zone accommodating sliding of late Paleoproterozoic (or older) continental crust in the southwest against Cenozoic oceanic crust in the northeast would not have been required. Thus, although Iapetus did open and close in some places (e.g., between Norway and Greenland), it clearly did not in others (GIFR and Fram Strait).

Less magmatism at (both present-day and paleo) mid-ocean ridges does not necessarily imply less tectonic extension since orogenic bridges contract (during orogenesis) and extend (during rift-related stretching) together with adjacent oceanic domains (Figure 3). However, the recognition of orogenic bridges providing continental connections between continental blocks formerly assumed to be entirely separated by oceanic crust pins these blocks together. Examples are Baltica and Laurentia, which have been connected for the past 1.8 Gyr via a continuous late Paleoproterozoic orogenic bridge at GIFR, thus greatly restricting the amount of relative and absolute paleo plate movements of these two cratons This suggests significantly less dynamic plate tectonics. The Iapetus Ocean was probably much narrower than the previously suggested 5000 km (Fortey & Cocks, 2003; Torsvik & Trench, 1991). A ≤ 1000 km width similar to that of the present-day Northeastern Atlantic Ocean is more plausible because it would not have resulted in rupture of the Timanian and Greenland–Iceland–Faroe orogenic bridges. For example, if the late Paleoproterozoic Greenland–Iceland–Faroe orogenic bridge had ruptured, it would include traces of intense Caledonian deformation with possible suture zones, tight folds, and segments of oceanic crust. This is neither in line with current crustal thickness estimates across the GIFR (25–40 km), which suggest continental crust in Iceland's lower crust (Foulger *et al.*, 2003; Foulger *et al.*, 2020a), nor with the open character of the Caledonian folds reworking the late Paleoproterozoic thrust systems at the GIFR, which indicate mild Caledonian deformation (Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, models such as the rotation of Baltica in the Cambrian–Ordovician (e.g., Torsvik & Rehnström, 2001; Trench & Torsvik, 1992) are no longer viable alternatives.

This has implications for ophiolites and eclogite- and blueschist-facies metamorphism. It may indicate that some presumed ophiolites, e.g., km-wide blueschist units in western Svalbard (Agard *et al.*, 2005; Horsfield, 1972; Kosminska *et al.*, 2014), may simply correspond to lava flows and/or igneous rocks intruded into continental crust, which were later imbricated during subsequent (Caledonian) orogenesis. Thus, some presently assumed ophiolites may not necessarily reflect the closure of paleo-oceans (sutures) and may not even be ophiolites (e.g., Hamilton, 2019). If these presumed ophiolites were indeed deposited onto or intruded into and incorporated in together with continental crust (e.g., through tectonic imbrication), they would have been difficult to quickly subduct to great depth (≥ 50–70 km) due to the relative buoyancy of continental crust. Thus far, rapid subduction to great 50–70 km depth has generally been considered necessary to explain blueschist metamorphism (e.g., Agard *et al.*, 2005; Agard *et al.*, 2009). Hence, alternative models may need to be further considered for the formation of some high-pressure metamorphic rocks (Jamtveit *et al.*, 2018; Luisier *et al.*, 2019; Moulas *et al.*, 2013; Yamato & Brun, 2016), and the interpretation of some rock units as ophiolites may need to be reexamined.

Models involving large lateral movements of terranes hundreds to thousands of kilometers in different directions over a few tens of million years (e.g., Harland *et al.*, 1992; Majka *et al.*, 2021) can no longer be used to explain local heterogeneities in basement rocks in continuous or recently disrupted orogenic bridges (e.g., Timanian orogenic bridge; Koehl, 2020; Koehl *et al.*, 2022). A continuous/recently ruptured late Neoproterozoic orogenic bridge through the Barents Sea, Svalbard, and the Fram Strait suggests that such presumably early Paleozoic terrane movements are unlikely. Had they occurred the Timanian Orogen would have been disrupted and breakup in the Fram Strait would have been achieved quicker, which was not the case (Koehl, 2020; Koehl, 2024b; Koehl *et al.*, 2021; Koehl *et al.*, 2022; Koehl & Mottram, 2024).

The overestimation of the extent of oceanic crust on Earth, especially at orogenic bridges (e.g., Foulger *et al.*, 2003; Foulger *et al.*, 2020a; Foulger *et al.*, 2020b; Foulger *et al.*, 2024; Geoffroy *et al.*, 2022a) and magmatic passive margins (e.g., Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b; Koopmann *et al.*, 2014; Reeve *et al.*, 2021), suggests that the intensity, amount, and speed of seafloor spreading at mid-ocean ridges may have been overestimated in many paleogeographic reconstructions. These reconstructions are in need of updating to incorporate the deformation and incorporation of continental crust in the oceans as hybrid crust. Future reconstructions should therefore address this issue by including updated (extended) domains of continental (including hybrid) crust.

An additional consequence of OrBiT already noted is its impact on faunal barriers (Koehl, 2024a), the use of faunal assemblages in paleogeographic reconstructions, e.g., to infer continental block separation (Fortey & Cocks, 2003), and faunal spreading between the continents via orogenic bridges, which remain emerged longer than adjacent areas along the strike of the rift (Jacobs *et al.*, 2024). Previous works have argued that discrete faunal assemblages on two continents implied ≥ 1000 km distance between those continental blocks (Fortey & Cocks, 2003; Popov & Cocks, 2017). An example is the distinct trilobite assemblages of Svalbard and Laurentia with Baltica. Svalbard and Laurentia were dominated by Olenellus svalbardensis Kielan in the early Cambrian (Birkenmajer, 1978; Birkenmajer & Orlowski, 1977; Fritz, 1972; Kielan, 1960; Poulsen, 1974)

and by Bathyurid trilobites in the Early Ordovician (Fortey & Bruton, 2013). Baltica was dominated by Holmia, Schmidtiellus, and Kjerulfia genera and Ptychopariid trilobites in the early Cambrian (Ahlberg, 1980; Ahlberg *et al.*, 1986) and Asaphid trilobites in the Early Ordovician (Fortey & Cocks, 2003). The continuous character of late Neoproterozoic Timanian thrust systems through the Barents Sea, Svalbard, and possibly the Fram Strait indicates that Svalbard, Laurentian, and Baltica have been connected since at least the late Neoproterozoic (Koehl *et al.*, 2022; Koehl, 2024b; Koehl & Mottram, 2024). Koehl (2024a) further illustrated the potential role of WNW–ESE-striking late Neoproterozoic thrust systems of the Timanian Orogen in forming a series of faunal barriers. These impeded exchange and mixing between fauna in Laurentia and Svalbard in the northern part of the Timanian Orogen and Baltica, which is mostly south of the Timanian Orogen (Koehl, 2024a). The impact of climatic belts on faunal distribution may also have been underestimated in previous paleogeographic reconstructions (Koehl, 2024a).

Further considerations need to be given to preexisting orogens when producing new paleogeographic reconstructions. Many of these commonly include cryptic, unrealistic transform plate boundaries (e.g., Cao *et al.*, 2021; Domeier, 2016; Domeier, 2018; Domeier & Torsvik, 2014; Merdith *et al.*, 2021; Torsvik & Cocks, 2016; Young *et al.*, 2019). These cryptic transform boundaries generally do not fulfill the requirement set by OrBiT, i.e., formation of major transform faults parallel to preexisting, rift-orthogonal orogens, and should be reconsidered and/or speculated with greater care from now on.

## Conclusions

1) Orogenic bridge theory suggests that the formation of major transform faults is controlled by preexisting structures in orogenically thickened continental crust oriented perpendicular to propagating rift axes. These are referred to as orogenic bridges.

2) Existing orogenic bridges oriented suborthogonal to a propagating rift form barriers of thickened continental crust that hinder the opening of a rift and delay full continental breakup.

3) Rupturing of orogenic bridges results in the formation of major transform faults and in lateral stepping of the propagating rift.

4) RRR triple junctions form at the intersection of (at least) two orogens.

5) Orogenic bridge theory permits large-scale predictions about the tectonic evolution of entire regions, e.g., rift stepping and propagation, and testing the existence of tentative (paleo-) transform faults.

6) Orogenic bridge theory suggests that the extent of oceanic crust has been overestimated, that more hybrid crust lies in the oceans than hitherto thought, and that therefore the extent of oceanic crust and nature (e.g., intensity, amount, and speed) of seafloor spreading should be reconsidered and decreased in many locations in future paleogeographic reconstructions.

## Ethics and consent

Ethical approval and consent were not required.

## Data availability

No new data are associated with this article.

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# Open Peer Review

## Current Peer Review Status: ✗ ✗ ? ✗ ✗ ✗ ? ?

**Version 2**

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?

**Juan I Soto**
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1. The manuscript presents a tectonic hypothesis rather than a theory. A hypothesis is a preliminary explanation that invites further testing, while a theory is a well-established model supported by substantial and consistent evidence. I recommend consistently using the term “hypothesis” throughout the manuscript.
2. The description of the ocean–continent boundary could be strengthened by incorporating additional geophysical constraints, such as seismic refraction profiles, tomographic imaging, and gravity modeling, alongside the magnetic anomaly data used that the authors rely on extensively (see additional references in the accompanying list, point no. 1)
3. Introducing the concept of diffuse plate boundaries could provide a more comprehensive framework for interpreting some of the regions discussed, particularly where deformation is distributed over broad zones (see references point no. 2). The global compilation of plate tectonic structures and boundaries by Roberts and Bally (in addition to Bird, 2003; see point no. 3) might also be a useful resource, particularly their maps and terminology.
4. The terminology used to describe rift types might be refined. Referring to “hot” and “cold” rifting modes, rather than “wet” and “dry,” could offer a more physically grounded classification (see references in point no. 4).
5. I consider that the concept of hyperextended margins and the associated processes, could be improved by using (and referring) to some of the key references on this issue (see point no. 5).
6. It would be helpful to distinguish more explicitly between transform faults and oceanic fracture zones, which differ in geometry and kinematics (see point no. 6).
7. The section titled “Implications for RRR triple junctions” could be expanded to include a broader range of examples and references (see point no. 7), which would provide additional depth and context.
8. The manuscript would benefit from a more detailed consideration of mantle dynamics in rifting settings. In particular, the role of the asthenosphere and the thermal regime could be more fully integrated into the discussion of extensional and rifting processes.

I include below a list of specific suggestions:

- Introduction, first paragraph: The hypothesis is presented too early. Key references should support the individual claims.
- Introduction: The sentence “Large areas of (hyper-) extended continental crust have now been discovered offshore. New offshore continental blocks generally not included in full-plate-tectonic reconstructions” is presented without enough explanation, making it hard for the readers to understand despite citations. Clarification is needed.
- Introduction: The sentences “Despite the apparent correlation of the location of some of the proposed orogenic bridges with that of so-called land bridges, orogenic bridges are clearly different from land bridges. While land bridges imply continent fixity, orogenic bridges work in symbiosis with plate tectonics and extend and contract together with adjacent plate segments undergoing seafloor spreading” are too categorical, lack connection with the previous text, and need supporting references.
- Introduction: The last sentence here: “Land bridges were once proposed by knowledgeable geoscientists in the early 20th Century. It is therefore not surprising that they may hold some truth after all”, is too informal and speculative, and is not suitable for a scientific manuscript.
- Introduction, next paragraph: Ensure all abbreviations (e.g., OrBiT) are introduced before use.
- Figure 3: The extension arrows in panel (b) should be perpendicular to the arrows currently shown and point outward. Also, indicate the positions of the different orogenic bridges on the figure.
- Structure of the manuscript: In my view, the introduction is overly long and divided into too many subsections, followed immediately by the discussion. It may be advisable to include an intermediate section—between the Introduction and the Discussion—summarizing the key observations and considerations that support the proposed hypothesis.
- Discussion – Sections on OrBs: Review the structure and wording of the first two sections, “Potential orogenic bridges (OrBs)” and “Continuous orogenic bridges (OrBs),” which currently use the same abbreviation. Clarify the distinction between the two concepts, as the current text focuses on their implications before clearly defining what they are.
- Discussion – “Ruptured orogenic bridges”: Add references to support the opening statement of this section, which currently lacks citation.
- Figure 8 caption: The expression “step-like fashion” is somewhat vague in this context. Consider revising or rephrasing to clarify the intended meaning.
- Figure 10 caption: The caption is clear and informative, but the explanation it provides might be better integrated into the main text as well, to ensure the concept is fully developed within the discussion.
- Discussion – “The plume model” section: The opening sentence would benefit from key references supporting this statement (“Traditionally, offshore areas underlain by anomalously thick crust or shallow bathymetry where crustal thickness is unknown have been assumed to be oceanic crust thickened by extensive magmatism related to a nearby mantle plume.”).
- Discussion – “Implications for plate tectonics and modeling” section: The meaning of “modeling” is unclear and could be clarified. Additionally, I suggest the authors specify the time span during which these bridges may remain active to provide more precision (e.g., in the sentence, “We propose the existence of long-lived, continuous orogenic bridges…”).
- Discussion – Faunal barriers: The manuscript briefly mentions faunal barriers toward the end of the discussion, but this aspect does not appear to be developed earlier in the text (in the paragraph starting with “An additional consequence of OrBiT already noted is its impact

on faunal barriers…"). I suggest the authors clarify this topic further and consider adding a dedicated subsection within the discussion to properly address it.
- Final paragraph of Discussion: The terms "cryptic" and "unrealistic" applied to transform boundaries seem overly negative and are not sufficiently supported or demonstrated within the manuscript. I recommend reconsidering this language or providing stronger evidence to justify such strong negative terms.
- Refer to 1,2,3,4,5,6,7

**References**

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**Is the work clearly and accurately presented and does it cite the current literature?**
Partly

**Is the study design appropriate and does the work have academic merit?**
Partly

**Are sufficient details of methods and analysis provided to allow replication by others?**
Partly

**If applicable, is the statistical analysis and its interpretation appropriate?**
Not applicable

**Are all the source data underlying the results available to ensure full reproducibility?**
Yes

**Are the conclusions drawn adequately supported by the results?**

Partly

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Structural geology and tectonics. Shale and salt tectonics

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

Reviewer Report 11 September 2025

https://doi.org/10.21956/openreseurope.21383.r59119

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?

**Zhong-Hai Li**
University of Chinese Academy of Sciences, Beijing, China
**Fengyuan Cui**
University of Chinese Academy of Sciences, Beijing, Beijing, China

This manuscript attempts to introduce a new perspective within plate tectonic theory—the Orogenic Bridge Theory (OrBiT), which can be briefly summarized as follows: within post-collisional orogenic belts, rifts are more likely to develop parallel to the orogenic strike, whereas rift propagation orthogonal to the orogen could be hindered, often resulting in rift or ridge jumps, with major transform faults preferentially localized within these belts. The authors present numerous global examples, discussing existing orogenic bridges (e.g., the Greenland–Iceland–Faroe Ridge orogenic bridge), ruptured orogenic bridges (e.g., the Appalachian–Caledonian orogenic bridge), as well as the role of orogenic bridges along passive margins and triple junctions. They further attempt to use this framework to predict future rifting trajectories in several regions, and propose that the theory may also serve as a tool for evaluating the existence of ancient transform faults. Moreover, the authors argue that the present-day global extent of oceanic lithosphere has been substantially overestimated, suggesting that many continental blocks remain connected through orogenic bridges rather than being fully separated.

We find this theory interesting and somewhat innovative. From geodynamic perspective, it is conceptually straightforward: orogens contain abundant faults and sutures that serve as pre-existing weak zones, which can be exploited during rifting. In contrast, propagation orthogonal to the orogen strike encounters thicker and stronger lithosphere, which hinders rifting and ridge propagation. In other words, the anisotropy of orogens strongly influences rift propagation. This framework enriches plate tectonic theory by replacing overly simplified models of continental breakup with more complex scenarios shaped by lithospheric heterogeneity. It is worth noting that current geodynamical numerical modeling has scarcely addressed this issue, and this manuscript has the potential to stimulate further modeling efforts as well as broader research

within the plate tectonics community. Moreover, the manuscript provides a comprehensive review of the tectonic history of multiple regions, with an extensive reference list that will be useful to geodynamic researchers. We believe that indexing of this theory could stimulate further studies on continental breakup.

However, we must acknowledge that the manuscript still presents several non-negligible issues. We outline these concerns below; if the authors are able to adequately address or resolve them, we believe the work could merit indexing.

(1) Possible overemphasis on the role of orogens. According to the theory, the anisotropy in orogenic strength is presented as the key factor that either promotes or hinders rift propagation and the formation of transform faults. In other words, what truly controls rift propagation is lithospheric heterogeneity. During rift propagation, if the rift encounters a weaker terrane, it may preferentially tear through it; conversely, if the terrane is mechanically stronger, the rift may be forced to deviate from its initial path, leading to transform faulting and rift jumps. Beyond orogens, however, there are many other processes that generate such mechanical heterogeneities in the lithosphere—for example, island arc volcanism, lithospheric thinning, hydration, and thermal weakening by mantle plumes can all reduce lithospheric strength, while cratons, as ancient and relatively cold lithosphere, are generally regarded as mechanically strong anomalies. The presence of such terranes could also influence rift propagation. The authors may consider a discussion on this broader spectrum of lithospheric heterogeneities into the framework of Bridge Theory, which would significantly complement and extend its applicability.

Accordingly, statements such as “The theory predicts that the formation of major transform faults is controlled by orogens striking (sub-) orthogonal to propagating rifts. Any transform or paleo-transform fault that does not fulfill this condition is therefore unlikely according to OrBiT” may be too arbitrary. For instance, rift jumps observed in the East African Rift are thought to be associated not with orogeny but with the presence of the Tanzania Craton. Reframing the control as lithospheric heterogeneity rather than strictly orogenic belts may enhance the robustness and general applicability of the theory.

(2) The authors dedicate a separate section to discuss the role of mantle plumes, primarily emphasizing that the anomalously thick crust beneath Iceland and southern Madagascar may not be plume-derived, or in other words, that these regions may not represent large igneous provinces but instead consist of continental or hybrid crust. However, this does not conclusively demonstrate that these areas are entirely unaffected by mantle plumes. For example, the Greenland–Iceland–Faroe land bridge, Mauritia between India and Madagascar, as well as the Rio Grande Rise and Walvis Ridge in South America—all of these widely distributed fragments of continental lithosphere may have formed with some degree of plume involvement. Even if, as the authors argued, mantle plumes did not directly generate the anomalously thick crust, the presence of mantle plumes could still have dynamically facilitated the formation of orogenic bridges? While this remains an open question, we believe the manuscript would benefit from a more balanced discussion of the potential dynamic effects of mantle plumes, rather than simply dismissing their role.

(3) Regarding the description of the tectonic settings and histories of individual regions, we find that it is kind of difficult to follow, especially for readers who are not already familiar with these areas. We strongly recommend reducing the use of abbreviations in the figures, as these make

geographic labels less clear and force readers to repeatedly check the abbreviations with their definitions. In addition, the presentation of tectonic histories should be streamlined. I would suggest adding some concise summary statements at the beginning and/or end of these sections, enabling unfamiliar readers to quickly get the key points.
There are also issues with the arrangement of figures. For example, in the section of ruptured orogenic bridges, the text introduces the Appalachian–Caledonian, Sergipano–Central African, Cape–Falkland, and East African–Antarctica orogenic bridges in that order. However, the corresponding figures appear as Figures 7, 8, 5, and 6. This inconsistency in figure order creates unnecessary confusion.

There are also several minor issues in the manuscript that need revision:
(1) Figure 3d and 3e appear identical, and the caption does not mention 3e at all. It seems likely that Figure 3e was incorrectly pasted and may need to be replaced with the intended figure.
(2) Many statements remain overly arbitrary. This issue was repeatedly raised by reviewers of Version 1 and is still present in the current version. We recommend that the authors carefully constrain the applicability and scope of the proposed theory rather than making sweeping generalizations.
(3) All maps should include latitude/longitude and colorbar.
(4) Figure 7 contains extraneous base-map information that should be removed.
(5) On page 12, the first paragraph of Ruptured orogenic bridges states that only two examples (Figs. 5 and 6) are discussed, but the text actually covers four, which are inconsistent.
(6) The discussion of triple junctions influenced by orogenic bridges would benefit from an additional schematic figure. Relying solely on text makes it difficult to get the conceptual link between orogens and triple junction geometry.

**Is the work clearly and accurately presented and does it cite the current literature?**
Yes

**Is the study design appropriate and does the work have academic merit?**
Yes

**Are sufficient details of methods and analysis provided to allow replication by others?**
Yes

**If applicable, is the statistical analysis and its interpretation appropriate?**
Partly

**Are all the source data underlying the results available to ensure full reproducibility?**
No source data required

**Are the conclusions drawn adequately supported by the results?**
Yes

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Structural geology, Tectonics, Geodynamics

**We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.**

Reviewer Report 28 August 2025

https://doi.org/10.21956/openreseurope.21383.r57080

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**Gabriela Fernández-Viejo**
University of Oviedo, Oviedo, Spain

General assessment:
The manuscript presents an ambitious hypothesis termed the *Orogenic Bridge Theory (OBT)*, which proposes that the breakup of continents and subsequent plate movements are strongly influenced by the orientation of pre-existing orogenic belts—particularly when these structures strike perpendicular to the direction of rifting.
While the attempt to bring new perspectives into the field of plate tectonics is commendable, the manuscript falls short in several critical areas. The theory is not clearly defined, lacks a robust foundation of supporting evidence, and misuses or overlooks a considerable body of well-established geological and geophysical knowledge. Overall, the manuscript reads as speculative rather than scientific, and in its current form, it is not suitable for indexing.
The main impression is that the article in its form should not be accepted. However, I did enjoyed reading it and seeing that every now and then someone tries to produce new ideas or recycle old ones to explain the -still left to explain- challenges of plate tectonics theory. In that side I would encourage the authors to pursue those ideas but in a more rigorous and scientific manner and starting in a particular area, gathering all the evidences, and producing a sound and tested hypothesis that can hold up to attempts of disproving it.
Right now, I cant find the way to disprove it as most of it is based on intuitions and causality but with little geological or geophysical support. However, I truly appreciate the authors' enthusiasm and would encourage further development of their ideas—starting from a regional case study with thorough data integration, and only after that, attempting global extrapolations.

Major concerns:

1. Terminology and conceptual clarity
   - The central concept—*"orogenic bridge"*—is never clearly defined. What exactly constitutes "orogenic crust" or an "orogenic bridge"? Since much of the continental crust has undergone orogenic processes at some point, this term becomes overly broad and vague. The use of different orogenies with their respective times with respect to the rifting and ocean formation should be taken into account .
   - The interchangeable and sometimes contradictory use of fundamental concepts such as rifting, sea-floor spreading, transform faults, transitional crust, and hybrid crust adds confusion. These terms have established meanings in the literature and should not be

redefined without rigorous justification.
- The use of the word *"theory"* is premature. OBT should be presented as a hypothesis. Scientific theories require testable predictions, supporting data, and counter evidences dismissed, which are currently lacking in this manuscript.

2) Lack of supporting data:
- The manuscript makes bold claims (e.g., reinterpreting the extent of oceanic crust, redefining transform fault origins, and even implications for plate kinematics), but does not present any new data—either geological, geophysical, or geochemical—to support these assertions.
- One important caveat of the whole article is that lack of data to support the hypothesis. There is plenty of DSDP, ODP , deep drilling legs in the ocean by now to, at least, show some of them supporting their statement of continental crust along transform faults. There is not a paragraph dedicated to the first order evidence that drilling provides when talking on the composition or nature of the ocean floor. In an article where the authors say statements as bold as to say that the oceanic crust is much less than what we think, and change the plate tectonics theory some first degree data to support it would be welcome.
- Also, that this fact would change the kinematic reconstructions is also quite daring. Kinematic reconstructions based on sea floor anomalies are one of the most important proofs of the actual theory and the confirming evidence for the previous continental drift hypothesis of A. Wegener.
- That stretched continental crust hyperextended, exhumed mantle domains in rifted margins may show similar magnetic anomalies to truly oceanic crust is also not new, and they can be included in kinematic reconstructions with a bigger error and a bit more caution. Serpentinized mantle and extremely hyperextended crust can show magnetic anomalies and they are included in reconstructions in fact. This lack of engagement and omission with existing data from ocean drilling programs (DSDP, ODP, IODP), which provide critical constraints on the nature and evolution of oceanic and transitional crust is a serious shortcoming.
- The authors claim a scarcity of reflection and refraction seismic data, which is incorrect for many regions. While distinguishing stretched continental crust from oceanic crust is indeed challenging with seismic velocities alone, abundant data do exist and have been used extensively in the literature. It is true that deep reflection seismics are unable to distinguish with accuracy among oceanic or continental stretched and intruded crust. Also refraction data, which are a bit more resolutive according to the velocities, they also give a good amount of data to base their theories on. But the authors seem to ignore them.
- In general, the main problem is that velocities of oceanic crust sensu stricto and stretched or intruded rifted crust are very similar and the distinction by geophysical means is so far impossible unless there is some cores. Therefore, this point is highly speculative

3. Misrepresentation or Oversimplification of Established Knowledge:
- The manuscript sometimes appears to misrepresent or ignore foundational concepts in plate tectonics, particularly in relation to the nature of transform faults, the formation of oceanic crust, and the role of pre-existing structures in rifting. I am also surprised because they talk about continental breakup, transform faults, sea-floor spreading, rift, and many other concepts which at times give the impression that they mix and match. At the beginning the theory works on the supercontinent breakup, later it works on the position of transform faults. The initial breakup of a supercontinent and the inception of transform faults in an ocean are separated by millions of years.  Even assuming that we don't fully understand when and how transform faults appear transecting ridges, that the influence of

a long gone orogen strike is of major importance in the development of these oceanic structures is simply puzzling. I can agree about the influence of the rifted margins structures partly in their development later but this aspect needs a sound amount of data to be supported. Very few of them reach out to the continental margins in the actual oceans. And the idea simply overlooks the role of plate geometry and spherical Earth constraints on its formation.

- Concepts traditionally diffuse such as transitional crust, hybrid crust, hyperextended rifted crust, ocean-continent transition, that have been used to define more or less the same parts of the margin to ocean types of crusts, and also the inheritance concept, that are already abundant in the literature, and served to “define” those areas of the margins and ocean floor that did not fall completely into the definition of oceanic and continental crust, treat them like something new calling them orogenic crust or orogenic bridges. I think that brings still more confusion.
- The influence of structural grain and inherited weaknesses in continental crust on rift orientation is already well known and widely discussed in the literature. Simply stating that rifting follows pre-existing orogens is neither novel nor sufficient to form the basis of a new theory.

4. Absence of Predictive Capability and geological inconsistencies:
   - Despite claiming that OBT allows for large-scale predictions, the manuscript provides no quantitative models, simulations, or even kinematic data to support or illustrate these predictions.
   - The authors do not incorporate GPS data, which could help evaluate present-day strain patterns in relation to proposed orogenic controls in actual rifting and presumed “orogenic bridges” areas
   - Statements such as “OBT predicts the location of major transform faults” are unsubstantiated. No examples are rigorously demonstrated or tested.
   - Above all, plate tectonics is a theory that DO predict, and DO explain most of the geological aspects of our planet. However, we all know that each area is unique and has different history, structures, rocks and deep thermal characteristics. After all, the deep mantle and nucleus are still big unknowns for the most part. A global theory cant explain each and every geological setting to its roots but it should serve as the basis for the detailed studies of each one.
   - This orogenic bridge theory is not well explained, definitely not supported by data, and finally not predicting anything as the authors do not even try to make a model that fits their statements
   - The formation of *blueschist facies* in rift settings is particularly problematic. While accepting that some of the ophiolitic outcrops around the world may be overinterpreted, the experimental and laboratory evidences show that this facies and indicative minerals do require high-pressure, low-temperature conditions, which are incompatible with the high thermal gradients expected in extensional regimes. Making such a claim without petrological or thermodynamic modeling is scientifically unfounded. This aspect seems totally disconnected from the literature and existing models.

Some minor comments
- The manuscript contains a high density of references, but many are not properly cited or contextualized.

- Some statements rely heavily on intuition or anecdotal observation rather than testable scientific reasoning.
- A clearer structure, with definitions up front, would help the reader navigate the proposed ideas more easily.

Final remarks and constructive suggestions
While the manuscript reflects creative thinking and a commendable desire to tackle unresolved questions in tectonics, it does not meet the standards of scientific rigor required for indexing. The hypothesis remains speculative, lacks empirical support, and does not offer a coherent or testable framework. If permitted I would like to make a few suggestions to continue their work, which again, I encourage sincerely.

1. Reframe the *Orogenic Bridge Theory* as a hypothesis, and define key concepts with precision.
2. Choose a specific rifted margin or tectonic setting to test the hypothesis in detail using available geological, geophysical, and drilling data.
3. Present quantitative models or predictions that can be evaluated and potentially reproduced or at least not crash with current evidences.
4. Engage with the vast body of existing literature on transitional crust, hyperextension, inheritance, and transform margin evolution. No margin is equal to other and continental breakup is one of the most complicated processes of plate tectonics and its evolution probably unpredictable with the actual knowledge. Even in the African rift with all its activity seems difficult to predict how it will break up in the end.
5. Avoid making broad global claims until supported by local-scale, data-rich studies.

**Is the work clearly and accurately presented and does it cite the current literature?**
No

**Is the study design appropriate and does the work have academic merit?**
Partly

**Are sufficient details of methods and analysis provided to allow replication by others?**
No

**If applicable, is the statistical analysis and its interpretation appropriate?**
Not applicable

**Are all the source data underlying the results available to ensure full reproducibility?**
No

**Are the conclusions drawn adequately supported by the results?**
Partly

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** active seismology, passive margins, geology

**I confirm that I have read this submission and believe that I have an appropriate level of**

**expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.**

Reviewer Report 25 June 2025

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**Zhikun Ren**
Institute of Geology, China Earthquake Administration, Beijing, China

The authors are too ambitious to present a new theory—Orogenic Bridge Theory (OrBiT)—challenging fundamental aspects of plate tectonics, particularly supercontinent breakup, transform fault formation, and the distribution of continental vs. oceanic crust. The authors try to compile global evidence to argue that pre-existing orogens orthogonal to rifts act as barriers, delaying breakup, forcing rift jumps/localization of transform faults, and creating "orogenic bridges" of hyperextended continental crust. However, the manuscript requires strengthening in defining core concepts (OrBs), providing mechanistic validation beyond correlation, quantifying the oceanic crust overestimation more robustly, and more fully integrating the role of mantle dynamics.

**The main comments are as following:**

1. OrBiT introduces a first-order control (rift-orthogonal orogens) on supercontinent breakup dynamics, complementing traditional drivers (subduction, plumes). However, orogenic bridge is actually not the first-order issues in plate tectonic theory. The term "orogenic bridge" is applied variably: a) Continuous*unruptured crust (Fram Strait Timanian), b)Ruptured crustal blocks (Falkland Plateau), c) Hybrid crust (GIFR, Walvis Ridge). Clear, diagnostic criteria (e.g., crustal thickness range, seismic velocity structure, geochemical signatures, structural inheritance demonstrably hindering breakup) are needed to distinguish OrBs from standard rifted margins or volcanic provinces.
2. While correlations between transform faults and orthogonal orogens are well-documented, demonstrating that the orogen caused the delay/jump/transform formation (vs. being a passive feature) remains correlative. The proposed mechanism (thickened crust + unsuitable fabric orientation hindering thinning) needs stronger mechanical validation.
3. The central claim of significant overestimation of oceanic crust is crucial but relies heavily on reinterpretations of geophysical data and localized samples. Some estimates (e.g., 20-60% overestimation for conjugate margins) appear speculative without systematic global reassessment.
4. OrBiT emphasizes structural inheritance but potentially underplays the role of mantle heterogeneity, plumes, and inherited mantle lithosphere weaknesses in localizing rifts/transforms. The "wet" vs. "dry" rift discussion (Dunbar & Sawyer, 1989) is acknowledged but not fully integrated. The Charlie Gibbs magmatism asymmetry example hints at mantle-crust interplay needing deeper exploration.
5. The implications of reduced plate motions (e.g., narrower Iapetus, restricted Baltica-

Laurentia motion) are profound but require clearer articulation. How much smaller should these oceans be? How does this reconcile with existing paleomagnetic and faunal data? The critique of terrane transport models needs specific examples.

**Figures and Presentation:**

1. Introduce "Orogenic Bridge Theory (OrBiT)" at first mention in the abstract/introduction.
2. Consistently use "rift-orthogonal" (preferred) or "rift-perpendicular"; avoid mixing. Define "hybrid crust" explicitly early on.
3. Section 6.2: Briefly mention potential climatic/topographic feedback influencing African Rift path selection alongside structural control.
4. Fig 3: Please consider adding a panel showing the final OrB stage (stretched continental bridge flanked by ocean). Some figures are overloaded (Fig 1, 4, 5, 6, 12). Schematic models (Fig 8, 10) could be slightly simplified. Fig 14 (GIFR magnetics) needs clearer annotation of the proposed fold structures.

**Is the work clearly and accurately presented and does it cite the current literature?**
Partly

**Is the study design appropriate and does the work have academic merit?**
Partly

**Are sufficient details of methods and analysis provided to allow replication by others?**
Partly

**If applicable, is the statistical analysis and its interpretation appropriate?**
Partly

**Are all the source data underlying the results available to ensure full reproducibility?**
Partly

**Are the conclusions drawn adequately supported by the results?**
No

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Geology，Active Tectonics

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.**

**Version 1**

Reviewer Report 14 October 2024

https://doi.org/10.21956/openreseurope.18630.r40775

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**Willian Sager**
University of Houston, Houston, Texas, USA

I am happy with a well-developed and documented contrarian paper because it makes us think about our assumptions and interpretations. But, the logic and arguments must be sound. This review was difficult because the current manuscript is poorly focused, at times bombastic, and at times misleading. The authors make overly broad statements, often without explaining or giving rationale. It took me a long time to do the review because I found myself thinking of some citations “that paper doesn’t say that, does it?” So I ended up looking up dozens of the references. Often they supported the authors claims, but many times they did not. It seems that when there is uncertainty or ambiguity, the authors take this as evidence supporting their hypothesis. This caused me to mistrust the arguments that the authors were trying to make (even though I agree with the basic idea). I think the same will happen with many readers. For this and reasons outlined below, I cannot recommend this manuscript for publication. I think it should be extensively re-written.

As above, I found the paper to be poorly focused for the following reasons. What is this paper about? The authors claim that rifting of continents will have offsets where the rift tries to cross an orogenic bridge (OB), an area of crust thicker than normal. Their definition of orogenic bridge is extended or hyperextended continental crust with perhaps some volcanism added at volcanic rifted margins. There are indeed places in the oceans where there are major offsets of the mid-ocean ridge. This has been noted by many others (e.g., you can see this in the global reconstructions of Seton et al., Earth Sci Rev, 2012). Some researchers think that the oceanic transforms are related to major transforms in the continents (e.g., Eagles, GJI, 2007). The idea is that when a rift tries to cross the thicker crust of the OB, it is offset to places where weaknesses and structural grain in the pre-existing crust allow easier rift nucleation. This was modeled by Dunbar and Sawyer (JGR, 1989), a reference that is curiously missing here. Thus, I think the central idea of the current manuscript is basically correct.

Why do I think this manuscript is not well focused? It seems to be doing at least two things. One focus is a review of OB in the Atlantic and Indian Oceans in order to point out offsets in places where there is oblique continental structure. Another seems to convince the reader that extended continental crust is everywhere underestimated, so oceanic crust is therefore overestimated. This leads to much of the manuscript reviewing examples of passive margins to say that the extent of continental crust is greatly underestimated. Another is to convince the reader that fault and fold trends are continuous from one continent, across the OB, and into the conjugate continent. Further, an issue is the citation of references. The authors bury their arguments with the number of references. Rather than citing the best reference or two, they give many more. Some paragraphs are >50% references. Sometimes I need to read a paragraph several times to extract the meaning.

I think that the discussion of oceanic vs. continental crust is overblown and biased. Everywhere the

authors conclude that oceanic crust should be banished and replaced with continental crust. I think this comes from two things. I think the authors feel the need to have all OB be all continental crust all the way across the ocean (as portrayed in Figure 2). I don't see why this is necessary because major transform faults, once established during continental rifting, tend to stay in place unless there is a major plate motion reorganization. So the OB idea works as long as you are satisfied that there was structural grain in the continent that caused an offset of the rift when rifting began. Indeed, in most of the arguments made by the authors, this seems to be the case – i.e., the rift offset formed as the rift formed. One does not need a continuous bridge of continental crust across the entire ocean. This is difficult to prove.

My issues with the integrity of the arguments mostly stem from this attempt to conclude that there are areas of continuous continental crust. Below are some examples.

Cape-Falkland OB
The statement that the Falkland Plateau (FP) and Maurice Ewing Bank (MEB) are continental crust is not supported by cited references. Schimschal & Jokat (2018) interpret seismic data to show continental crust slightly offshore of Falklands islands but oceanic farther seaward (on the FP). Chamale et al. (2018) do indeed study zircons in continental rock cored by DSDP. This hole penetrated <10 m of continental rock. Even Chamale et al. sketch this rock as a cap on the MEB crust (but give no evidence to support the sketch). The authors interpret this evidence to indicate that the entire FP is continental. This is an overinterpretation unsupported by data.

The authors show E-W late Paleozoic fault trends north of the Falklands Islands and on the northern Falklands plateau in Figure 4. These trends are cited as being from Stanca et al. (2022). I checked that paper and I could not find these lineaments. That paper analyzed seismic data and shows late Paleozoic folds in deep sediments, but I could not find any definition of lineaments. The survey also does not cover much of the area where the lines in Figure 4 are shown. The authors claim that Paleozoic faults at Falklands Plateau reconstruct parallel to those in Cape Fold Belt in South Africa. I cannot tell this from Figure 4, but if you move the former to the latter along the fracture zone, it does not look like this is true. The authors claim a connection between contractional belt of Southern South American cordillera and subsequent formation of transform faults. This is not shown in Figures 1 or 4 nor is it explained.

East African-Antarctic OB
To argue that the OB is mostly continental, the authors claim that the Mozambique, Madacascar, and Davies ridges (Africa) and Gunneris and Astrid ridges (Antarctica) are continental. At best, these ridges are partly continental, not entirely as implied. Klimke et al. (2018) studied Antarctic margin and connection to Africa for plate motion. They do not mention Mozambique Ridge, but instead say that the Gunneris Ridge is possibly continental. The Gunneris Ridge connects to Mozambique Ridge. Vorman & Jokat investigate Davies Ridge near Africa and they find that it has continental core part way from African margin towards Madagascar. Leithenkov et al (2008) says that marginal part of Astrid Ridge is continental, but they cannot tell about segment farther offshore. Roeser et al. (1996) interprets seismic data to show that the northern Astrid Ridge is oceanic. The authors also claim that Sato et al. (2022) show that the Del Cano Rise (oceanic rise between continents) is continental. Those authors said nothing of the sort. They only said that their data did not allow them to rule out that Del Cano is continental. In sum, the authors have taken some partial evidence of continental affinity and assumed that all of the ridges and Del Cano Rise are continental. This is misleading.

The authors cite Chu and Gordon (1999) to delineate a diffuse plate boundary that intersects the Southwest Indian Ridge (SWIR) at a major offset. They claim that this shows that major transform faults are where such boundaries intersect the ridge. Chu and Gordon do not show where the boundary is. I followed other references, and this got complicated. Meyzen and Schwarz-Schampera (2023) show two diffuse boundaries intersecting the SWIR, but incorrectly attribute their sketch. These two boundaries are used in the plate model of DeMets et al. (2010), but their attribution is also incorrect. The result is that I can't find where the definition of these boundaries originated. I think one of the claims is probably correct, one correlates with the Andrew Bain FZ, but the other does not correlate to a major offset. The authors say that these FZ are colder than normal oceanic faults. They cite Ligi et al. (2002) and imply that those authors said the wide, multi-fault FZ are similar to continental crust because they involve cold crust. They then extrapolate this idea to the fact that the rocks of these FZ are older than predicted by SFS. This is not what I would conclude from that reference and these observations. The authors claim these plate boundary-transform connections show that this area between Antarctica and Africa is an OB, but the rationale is not made clear.

Passive Margins
The authors claim that 20-100% of crust categorized as oceanic is in fact continental. They cite Geoffroy et al. (2022) in the Warren Hamilton GSA volume. This paper and this volume were intended to be provocative to honor Hamilton, an iconoclast. In the Geoffroy paper figure was meant to apply to the north Atlantic between Greenland and Europe, not everywhere as implied. The text suggests that similar uncertainty exists in the width of the Newfoundland margin. I checked both Shillington et al. (2006) and Lymer et al. (2019) and do not see that they said this. These authors discussed margin width and the uncertainty of whether transitional crust is continental. Their work may enlarge the defined margins slightly, but do not support the 20-100% number.

Namibia-Brazil
Paragraph 2 of this section states that Walvis Ridge is continental affinity. This statement is incorrect. Fromm et al 2017a does not say this (the seismic line is over the volcanic ridge). Fromm et al. 2017b analyzes a seismic profile that starts on the continent. They do not say that Walvis is continental, but instead show the transition between continent and the oceanic ridge. The authors cite the paper by Ventura Santos et al. (2019) to say that Rio Grande Rise (conjugate to Walvis) is continental. Ventura Santos et al. indeed found continental rocks but these rocks are usually fresh and lack the Mn coating of rocks that have been lying on the seafloor for tens of millions of years (I know because I have seen them). The type of rock is highly variable (unexpected from a single dredge or ROV pick-up). These rocks are likely dropstones carried by icebergs from Antarctica. Navigational charts show that Rio Grande Rise is south of the northern limit for icebergs. In sum, there is no reliable information that suggests Walvis Ridge is continental. Once again, the authors have taken a biased view to conclude that continental crust is the foundation of this ridge. The author cites Fairhead and Wilson (2005) as evidence that there has been significant strike slip motion along Walvis Ridge. This paper is an outlier. It was a crude analysis of structural features, but provided no solid evidence of strike-slip faulting. It is true that Walvis Ridge is associated with transform faults. The Frio Ridge (eastern part) is aligned with and next to a FZ that probably had a large offset (few hundred km) and this fault may have offset the continent during the Cretaceous (see Eagles, GJI, 2007). Near the end of the Cretaceous, this fault broke up and reformed as other transforms farther south (Sager et al., G-cubed, 2021). So the idea that there is a throughgoing

transform is incorrect.

RRR Triple junctions
The authors say that triple junctions must be related to OB because the latter control fracture zones. Not much rationale is provided. The RRR triple junctions (Bouvet and Rodrigues) probably started with the separation of continents in Gondwana. When three blocks pull apart, you get a triple junction and this is where those triple junctions likely started. It is plausible that orogens dictated where the continents split, so yes, continental faulting probably initiated the TJ.

Bouvet Triple junction
The authors state that Agulhas-Falkland FZ is parallel to trends in the Cape Fold Belt near Cape Town. The authors say its strike is SW-NE. The Cape Fold belt trends are N-S and E-W, so this appears erroneous. Arguments about fracture zone trends matching is unconvincing because some of those are on the Scotia backarc (a microplate) and we are talking two separate ridge systems (South America-Antarctic & Africa-Antarctic). The author cites Figure 4 which does not seem to support these claims. Another claim is that FZ on the southern MAR and SA-ANT ridge are parallel. This is clearly shown to be incorrect by Figure 4.

Plume model
Paragraph 5. The authors take anti-plume approach and argue that available data unambiguously support that thickened crust is continental and not from hotspot volcanism. I think this is overstatement because there is ambiguity about crustal type in many of the places mentioned. The authors cast doubt on the widely-accepted hotspot model for Walvis Ridge formation because the ridge does not parallel MAR fracture zones. They conflate plate-plate relative motion (the FZ) with plate-mantle (hotspot) motion. The two do not need to be the same. Paleomagnetic data shows that Africa has changed paleolatitude during Walvis Ridge formation, so the continent has had some N-S motion relative to the mantle and hotspots. Hotspots themselves may have moved relative to the mantle. I don't know why one must argue against mantle plumes here. I don't think that they invalidate the OB idea. This is another example of lack of focus.

Testing the Existence of tentative paleo transforms
The authors say that the OB theory can predict whether a paleo transform is valid or not. They are not clear how exactly, but apparently make the judgment whether or not the TF parallels orogenic trends. I don't disagree entirely, but the authors have not demonstrated that all TF must be dictated by continental orogenic trends. Comparison with plate reconstructions seems a fruitful method.

Over the top rhetoric
The authors make claims that this paper is a major revision of plate tectonics and that it confirms the old land bridge hypothesis for fauna crossing the oceans. By the way, after the introduction, the land bridge is hypothesis is not addressed again and certainly unsupported by the paper discussion. The OB idea is called a "theory" rather than a hypothesis, as if it is a major cornerstone for understanding plate tectonics. I think these claims are bombastic and set a poor tone for the manuscript. As stated above, the idea of major offsets being inherited from continents is not new. The idea that a rift will be deflected by a zone of thick crust with oblique fabric is not new. The idea that this paper forces a major rethinking of plate tectonics is over the top.

Some examples:

p.5, paragraph 1: This relationship has received little attention despite the potential ground breaking implications that it may have.

Minor points
p. 4, last paragraph. Major transform faults are defined as those having an offset of a few km or more. That is most transforms. I thought this must be a typo, but the same appears elsewhere. Maybe >100 km

p.8, paragraph 7: “Other orogens worldwide show similar 90° bends (e.g., Verkhoyansk Orogen in northeastern Russia; Figure 1).” Significance of 90° bends is not explained.

p. 9, paragraph 6: “Hence, they strike perpendicular to the active (East Scotia Ridge, American–Antarctic Ridge, and South Atlantic mid-ocean ridge) and paleo-mid-ocean ridges in the area
(West Scotia Ridge and Phoenix Ridge; Figure 1 and 4.” These figures do not demonstrate this relationship and one would not expect different plate boundaries to have the same orientation.

p. 10, paragraph 1: “This contractional belt may therefore also have helped control the formation of major transform faults in the area, though its geometry may have been controlled by the preexisting late Paleozoic fold-and-thrust belts.” Connections unclear.

p. 11, last paragraph: This paragraph writes about these ill-defined plate boundaries (Lwandle plate from DeMets et al. 2010) and uses this to infer an OB? The rationale is not explained.

p. 11, paragraph 2: The authors write about large offset transforms having “oscillatory spreading”, which I think means that the transform can jump from one side to another of a block within the transform domain. The conclusion is then that these must be continental. Why? No rationale is given.

p. 13, paragraph 3: “Given the control of rift orthogonal orogens on the formation of major transform faults, a relationship between at least two orogens and mid-ocean-ridge-related triple junctions is unavoidable.” Rationale is not given. “unavoidable” is probably hyperbole.

p. 13 paragraph 3: “…the OrBiT predicts at least two discrete strikes of transform faults at any RRR triple junction.” I don’t know why. Rationale not given.

p. 13, paragraph 6: “East of the Bouvet Triple Junction, the Atlantic–Indian Ridge is truncated by NE–SW-to N–S-striking transform faults, which include the Andrew Bain Fault Zone (e.g., Peyve et al., 2007; Sclater et al., 2005) and other minor faults such as the Du Toit, Moshes, and Bouvet fault zones (Figure 4; Ligi et al., 1999).” According to the provided figure (and a check with Google Earth), none of these faults is oriented N-S.

p. 13, paragraph 7: “Major transform faults offsetting the southern segment of the Atlantic mid-ocean ridge and the American–Antarctic Ridge strike parallel to one another, and both groups of transform faults parallel the late Paleozoic, E–W-striking Sierra de la Ventana Fold-and-Thrust Belt…” I believe this refers to the southern Mid-Atlantic Ridge (Atlantic mid-ocean ridge). These transforms do not appear parallel in the figure 4 and the figure does not clearly show this fold belt. The transforms on different plate boundaries should not be parallel.

p. 15, paragraph 5: “typical 10-km thick oceanic crust”. Oceanic crust is typically much thinner. Christensen, Rev. Geophys., 2019 gives an average of slightly more than 6 km.

p. 15, paragraph 5: The authors repeat a statement by Foulger in her 2020 paper about the Greenland-Iceland-Faroe Ridge to say that polarity reversal magnetic anomalies do not occur in the ridge and therefore it is continental in nature. I think that is an overstatement. The anomalies are distorted, but can be traced through; although, it is true that because of this distortion, analysts trace magnetic anomalies from the sides and connect them over the GIFR.

p. 15, paragraph 6: “Geophysical evidence unambiguously suggests that mantle plumes are unlikely to have formed the thickened oceanic crust at the GIFR, Mozambique and Madagascar ridges, and Del Cano Rise.” Foulger (2020) argues that the entire GIFR is continental. Although that paper is well-crafted and thought provoking, I don’t think the case is unequivocal. The others are certainly not unequivocal as claimed.

p. 17, paragraph 2: “The OrBiT explains the variations in earthquake focal mechanisms in the area.” Perhaps it does, but this is not explained.
p. 19, paragraph 2: “…suggests that the dynamism of seafloor spreading at mid-ocean ridges and the extent of hybrid continental crust should be reexamined.” What does dynamism mean? BTW, the next sentence is basically the same statement (repetitious).

p. 19, conclusions, point 6: “The orogenic bridge theory suggests less dynamism in paleo-plate tectonics than current models show.” I have no idea what this means – and besides, this point was discussed in one sentence. This seems an odd conclusion.

**Is the work clearly and accurately presented and does it cite the current literature?**
No

**Is the study design appropriate and does the work have academic merit?**
No

**Are sufficient details of methods and analysis provided to allow replication by others?**
No

**If applicable, is the statistical analysis and its interpretation appropriate?**
Not applicable

**Are all the source data underlying the results available to ensure full reproducibility?**
Partly

**Are the conclusions drawn adequately supported by the results?**
No

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Marine geophysics, plate tectonics

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.**

Author Response 20 Feb 2025

**Jean-Baptiste Koehl**

Dear Prof. Sager,
thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

**Comments by the reviewer**
Comment 1: I am happy with a well-developed and documented contrarian paper because it makes us think about our assumptions and interpretations. But, the logic and arguments must be sound. This review was difficult because the current manuscript is poorly focused, at times bombastic, and at times misleading. The authors make overly broad statements, often without explaining or giving rationale. It took me a long time to do the review because I found myself thinking of some citations "that paper doesn't say that, does it?" So I ended up looking up dozens of the references. Often they supported the authors claims, but many times they did not. It seems that when there is uncertainty or ambiguity, the authors take this as evidence supporting their hypothesis. This caused me to mistrust the arguments that the authors were trying to make (even though I agree with the basic idea). I think the same will happen with many readers. For this and reasons outlined below, I cannot recommend this manuscript for publication. I think it should be extensively rewritten.
Response: Agreed in that various parts the manuscript should be extensively rewritten. The reviewer is obviously affected by the "dilution effect" ( https://www.ted.com/talks/niro_sivanathan_the_counterintuitive_way_to_be_more_persuasive/transcript?su in that many arguments are presented in the present manuscript, some of which the reviewer argues are doubtful because of inappropriate referencing. For now, these arguments with presumably inappropriate references act as the broken pieces of the larger dinnerware set in the attached TED Talk: they reflect negatively on the whole new theory despite not outweighing the sum of the other positive arguments. The authors of the present manuscript would like to point out that the dilution effect is the reason why short, "Nature"- or "Science"-like publications had and (unfortunately) still enjoy relatively high citation metrics: they do not dilute and present only the main argument(s) supporting entire theories. However, such contributions have major flaws in that they can never include the actual proofs supporting a theory, nor all the arguments in favor or against the theory presented. Thus, should there be grounds to question an existing theory due to new technological development (like in the present case, improvements in seismic reflection imaging and interpretation), the readers are left trying to piece things together from the cited contributions in these short publications, which is tedious and wasteful and is not in line with modern practices on Open Science such as reproducibility and replicability. Thus, despite the fact that the authors of the present manuscript must expose their work to the risk of dilution effect, it is their duty to present all the arguments supporting their theory to

facilitate further testing and validating or invalidating of the theory. To attempt to move past the bias introduced by the dilution effect, the authors of the present manuscript clarify each of the contested references in their response to subsequent comments and hope that the logics of their citing specific work becomes clearer to the reviewers and readers. See response to comments 5, 7, 8, 9, 10, 11, 12, and 13.
Changes: See response to comments 5, 7, 8, 9, 10, 11, 12, and 13.

Comment 2: As above, I found the paper to be poorly focused for the following reasons. What is this paper about? The authors claim that rifting of continents will have offsets where the rift tries to cross an orogenic bridge (OB), an area of crust thicker than normal. Their definition of orogenic bridge is extended or hyperextended continental crust with perhaps some volcanism added at volcanic rifted margins. There are indeed places in the oceans where there are major offsets of the midocean ridge. This has been noted by many others (e.g., you can see this in the global reconstructions of Seton et al., Earth Sci Rev, 2012). Some researchers think that the oceanic transforms are related to major transforms in the continents (e.g., Eagles, GJI, 2007). The idea is that when a rift tries to cross the thicker crust of the OB, it is offset to places where weaknesses and structural grain in the pre-existing crust allow easier rift nucleation. This was modeled by Dunbar and Sawyer (JGR, 1989), a reference that is curiously missing here. Thus, I think the central idea of the current manuscript is basically correct.
Response: The authors of the present manuscript thank the reviewer for suggesting relevant works to include in the manuscript. Regarding the definition of “orogenic bridges”, the authors of the present manuscript concede that it is not crystal in the manuscript. Orogenic bridges are portions of orogenically thickened crust with orogenic structures striking dominantly oblique to orthogonal to the active rift. These structures are therefore unsuitable to accommodate crustal thinning and hinder rifting, forcing the rift to jump or bypass certain areas (e.g., Greenland–Iceland–Faroe Ridge). While oceanic crust forms on either side of orogenic bridges, the continental crust at orogenic bridges continues to be stretched until break up occurs there too. Examples of ruptured orogenic bridges, which, in their time, forced the active rift to jump or reorient include the Kuunga Orogen in southern Brazil (Dom Feliciano Belt) and Namibia (Damara Belt) and the Cape Fold Belt in South Africa and at the Falkland Plateau and Maurice Ewing Bank (see Figure 1 in present manuscript). See response to comment 13.
Regarding the modelling work by Dunbar and Sawyer (1989), this is an interesting work, which is partly in line with the present manuscript. Their “wet” versus “dry” rift classification relates the intensity of magmatism and width of the resulting rift with the existence of preexisting weaknesses in the crust and/or mantle. However, the work of Dunbar and Sawyer (1989) for example assumes that breakup has occurred at the Greenland–Iceland–Faroe Ridge. This is not the favored hypothesis in the present manuscript. Instead, the present manuscript discusses recent and ongoing mapping of late Paleoproterozoic thrust systems around the Faroe Islands and in the Greenland–Iceland–Faroe Ridge (Koehl et al., 2024, 2025) suggesting that breakup is yet to occur there. Thus, in the present manuscript, the occurrence of intense magmatism has no or little effect on breakup. For example, the magma-rich Greenland–Iceland–Faroe Ridge is a through-going orogenic bridge (i.e., breakup has not yet occurred), whereas the Gakkel Ridge is a magma-poor mid-ocean ridge where breakup has occurred. The authors of the present manuscript concede that the modelling study by Dunbar and Sawyer (1989) is an

important piece of work that should be discussed in the present manuscript.
Changes: Added two new paragraphs after paragraph 4 in the “Orogenic bridge theory” section: “Despite the apparent correlation of the location of some of the proposed orogenic bridges with that of so-called land bridges, orogenic bridges are clearly different from land bridges. While land bridges imply continent fixity, orogenic bridges work in symbiosis with plate tectonics and extend and contract together with adjacent plate segments undergoing seafloor spreading. This is due to the fact that preexisting thrust systems at orogenic bridges strike dominantly oblique to orthogonal to the active rift. As such, these structures are unsuitable to accommodate crustal thinning. Thus, they hinder rifting, forcing the rift to jump or bypass certain areas (e.g., Greenland–Iceland–Faroe Ridge). While oceanic crust forms on either side of orogenic bridges, the continental crust at orogenic bridges continues to be stretched until break up occurs there too.
Clear evidence of the reworking of orogenic bridges during orogenesis and rifting are shown in Koehl *et al.*, (2024, 2025). Notably at the GIFR, WNW–ESE-striking late Paleoproterozoic thrust systems of the Laxfordian–Nagssugtoqidian Orogen interpreted within the GIFR and adjacent continental margins of the Faroe Islands and southeastern Greenland were reworked as 100–200 km wide open anticlines during the Caledonian Orogeny (i.e., shortened orogenic bridge) and were later inverted during post-Caledonian extension, thus contributing to thinning the crust (extending orogenic bridge; Koehl *et al.*, 2024 their figure 2e; Koehl *et al.*, 2025).”.
Added a new paragraph at the end of the “Previous work” section: “Another relevant study is the modelling of the influence of preexisting zones of weakness in the crust and mantle on rifting ( Dunbar & Sawyer, 1989). While mantle weaknesses were suggested to explain the formation of “wet” rift with intense magmatism and narrow passive configurations, crustal weaknesses were associated to the formation of “dry” rifts and broad passive margins. Like Lundin & Doré (2005), this study attempted at relating zones of intense magmatism with preexisting structural fabrics.”. Also added a new paragraph at the end of the “Issues with mantle plumes” sub-section: “The wet” versus “dry” rift classification by Dunbar & Sawyer (1989) related the intensity of magmatism and width of the resulting rift with the existence of preexisting weaknesses in the crust and/or mantle. For example, preexisting mantle weaknesses would tend to form narrow “wet” rifts with intense magmatism (e.g., Iceland), whereas crustal weaknesses lead to the development of broad “dry” rifts (e.g., Iberia–Newfoundland). This work assumes that breakup has occurred at the Greenland–Iceland–Faroe Ridge, which is not (yet) the case ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, if the magma-rich Greenland–Iceland–Faroe Ridge is a through-going orogenic bridge where breakup has not yet occurred whereas breakup has occurred at magma-poor margins, e.g., in the Arctic Ocean (ultra-slow-spreading Gakkel Ridge), then it follows that intense magmatism and preexisting mantle weaknesses or plumes have less effect on breakup than previously assumed. Other factors, e.g., rift-parallel and rift-orthogonal orogens, must therefore come into play.”.
See also response to comment 13.

Comment 3: Why do I think this manuscript is not well focused? It seems to be doing at least two things. One focus is a review of OB in the Atlantic and Indian Oceans in order to point out offsets in places where there is oblique continental structure. Another seems to convince the reader that extended continental crust is everywhere underestimated, so oceanic crust is therefore overestimated. This leads to much of the manuscript reviewing

examples of passive margins to say that the extent of continental crust is greatly underestimated.
Response: Agreed. However, the overestimation of oceanic crust is a direct consequence of the fact that orogenic structures in various areas can be traced far at sea into previously assumed oceanic domain, e.g., at the Greenland–Iceland–Faroe Ridge (Koehl et al., 2024 Faroes) and in the Fram Strait (Koehl, 2020, 2024; Koehl et al., 2021; Koehl and Mottram, 2024). Thus, this cannot be considered a lack of focus.
This comment contrasts with the reviewer's comment 17 in that "the authors have not demonstrated that all TF must be dictated by continental orogenic trends". On the one hand it is suggested that the manuscript is not focused enough and includes a review of (too) many examples, and on the other hand it is suggested that the authors of the present manuscript did not include enough examples. Since this is the founding manuscript of a brand-new theory (Orogenic Bridge Theory), it is natural that a thorough review of key examples is made. The authors of the present manuscript tend to agree more with the reviewer's comment 17 in that it would be best to include more examples to further establish the theory and enable its testing by a broader community. The authors of the present manuscript also concede that an estimation of the overestimation of the extent of oceanic crust should be provided. See also response to comment 17.
Changes: Added an estimate of the overestimation of the extent of oceanic crust at each discussed margin. See response to comments 6, 12, 13, and 17.

Comment 4: Another is to convince the reader that fault and fold trends are continuous from one continent, across the OB, and into the conjugate continent.
Response: Partly agreed. This is only true at continuous orogenic bridges, e.g., the Greenland–Iceland–Faroe Ridge (Koehl et al., 2024), Davis Strait (Dalhoff et al., 2006; Dafoe et al., 2022) and possibly the Fram Strait (Koehl, 2020, 2024; Koehl et al., 2021). At other ruptured orogenic bridges, rifting has broken the crust up and oceanic crust is forming at the mid-ocean ridges.
Changes: Added an introduction paragraph to the "continuous Orogenic Bridge" section: "The concept of continuous orogenic bridge implies that continental crust continues across previously inferred oceanic domain. In such areas, the extent of oceanic crust is proposed to be overestimated by 100% (i.e., no oceanic crust yet). This implies the existence of sections of hybrid continental crust (see Figure 2a and b) capped by thick successions of volcanic rocks (e.g., lava flows) and extensively intruded by igneous rocks (e.g., Seaward-Dipping Reflectors). Sections of hybrid continental crust are locally believed to extend the width of previously assumed oceanic domains. Three potentially continuous orogenic bridge are discussed here, the Timanian orogenic bridge in the Fram Strait, the Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and the Greenland–Iceland–Faroe orogenic bridge ( Figure 4).".
Also split the fifth paragraph of the "Greenland–Iceland–Faroe orogenic bridge" sub-section into two and included the findings of Laxfordian thrust systems off the Faroe Islands and Iceland–Faroe Ridge by Koehl et al. (2024, 2025): "In northern Europe, a possible candidate to explain crustal thickening in the GIFR is the correlate of the Ammassalik Belt, the late Paleoproterozoic Laxfordian Orogen on the Rockall Plateau and northern Scotland. This orogen was thought to consists of WNW–ESE-striking, subvertical shear zones showing strike-slip kinematics ( Attfield, 1987; Coward & Park, 1987; Dickin, 1992). However, recent mapping on reprocessed seismic reflection data has revealed that the Laxfordian shear

zones onshore northern Scotland are part of much larger structures, namely tens of km thick, WNW–ESE-striking, dominantly NNE-dipping thrust systems around the Faroe Islands ( Koehl *et al.*, 2024). These were reworked into hundreds of km wide, NE–SW-striking open folds during the Caledonian Orogeny and extend beyond the Seaward-Dipping Reflectors and previously assumed continent–ocean boundary off the Faroe Islands ( Koehl *et al.*, 2024). Ongoing seismic mapping at the GIFR indicates that these late Paleoproterozoic structures extend to below southeastern Iceland and thus that the Iceland–Faroe segment of the GIFR is fully continental ( Koehl *et al.*, 2025). Of notable interest, the hundreds of km wide, NE–SW-striking open folds mapped along the entire length of the GIFR by Hjartarson *et al.* (2017) coincide with the Caledonian folds reworking late Paleoproterozoic structures off the Faroes Islands and at the Iceland–Faroe Ridge ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). This may explain the thickness variations of the GIFR along its length (i.e., in a WNW–ESE direction; Hjartason *et al.*, 2017 their figure 3c).
In eastern Europe, the WNW–ESE-striking Tornquist Zone, i.e., the Teisseyre–Tornquist Zone ( Krzywiec *et al.*, 2022; Mazur *et al.*, 2015) and its probable continuation the Sorgenfrei–Tornquist Zone ( Ponikowska *et al.*, 2024), extends from the Black Sea ( Mikolajczak *et al.*, 2019; Narkiewicz *et al.*, 2015) to the southern North Sea ( Kalani *et al.*, 2020 ; Phillips *et al.*, 2018) and is a natural potential continuation for some of the Laxfordian structures at the GIFR and off the Faroe Islands ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). Available seismic reflection data in the central and northern North Sea and west of the Faroe Islands suggest that the Sorgenfrei–Tornquist Zone may continue as far north as the Shetland Plateau (e.g., Bird *et al.*, 2016; Fossen & Hurich, 2005; Gabrielsen *et al.*, 2015; Koehl *et al.*, unpublished manuscript; Serck *et al.*, 2022). The Tornquist Zone accommodated significant contractional deformation and related crustal thickening as early as the Neoproterozoic during the closure of the Tornquist Ocean ( Torsvik & Rehnström, 2003). The Tornquist Zone possibly consists of top-northeast ( Abramovitz *et al.*, 1999; Krzywiec *et al.*, 2017; Lyngsie & Thybo, 2007; Mazur *et al.*, 2015; Mazur *et al.*, 2018) and top-SSW thrusts (Phillips *et al.*, 2018 their figures 2 and 11; Koehl *et al.*, unpublished manuscript).".

Comment 5: Further, an issue is the citation of references. The authors bury their arguments with the number of references. Rather than citing the best reference or two, they give many more. Some paragraphs are >50% references. Sometimes I need to read a paragraph several times to extract the meaning.
Response: Agreed. Such a task comes at a price, that of having to cite many previous studies. A comment cause of dissatisfaction is the non-inclusion of specific references viewed highly by specific reviewers. The present manuscript attempts to avoid this as much as possible and satisfy as many parties as possible. Another crucial reason as to why the authors of the present manuscript add this many references is because it is paramount to ascertain which study is the first source of specific arguments and/or hypotheses. An example is inexplicable metamorphosis of the De Geer Zone, a presumed hundreds of km long Cenozoic paleo-transform fault between Svalbard and Greenland, from a hypothesis based on the linear morphology of the bathymetry and coastline in western Svalbard and northern Greenland to a fact (De Geer, 1926; du Toit, 1937; Wegmann, 1948; Harland, 1961, 1967, 1969a; Horsfield and Maton, 1970; Faleide et al., 1993, 2008; Piepjohn et al., 2016) without any critical scientific argument ever being introduced to support the existence of such a fault. Koehl (2024) has demonstrated that late Neoproterozoic thrust systems in the Fram Strait continue past the presumed location of the De Geer Zone with no lateral offset

and that the specific fault segments inferred to be part of the De Geer Zone (e.g., Hornsund Fault Complex) are rift-related listric normal faults rather than strike-slip faults. In some cases, it is therefore crucial to include numerous references to previous work, thus notifying the reader that these previous works were reviewer carefully by the authors of the present manuscript and taken into account.
Changes: None.

Comment 6: I think that the discussion of oceanic vs. continental crust is overblown and biased. Everywhere the authors conclude that oceanic crust should be banished and replaced with continental crust. I think this comes from two things. I think the authors feel the need to have all OB be all continental crust all the way across the ocean (as portrayed in Figure 2). I don't see why this is necessary because major transform faults, once established during continental rifting, tend to stay in place unless there is a major plate motion reorganization. So the OB idea works as long as you are satisfied that there was structural grain in the continent that caused an offset of the rift when rifting began. Indeed, in most of the arguments made by the authors, this seems to be the case – i.e., the rift offset formed as the rift formed. One does not need a continuous bridge of continental crust across the entire ocean. This is difficult to prove.
Response: Agreed. The authors of the present manuscript do not argue that any of the potential orogenic bridges are continuous across the entire ocean, except in the case of the Greenland–Iceland–Faroe Ridge (Koehl et al., 2024, 2025), Davis Strait (Dafoe et al., 2022) and possibly the Fram Strait (Koehl, 2020, 2024). As mentioned in the response to the comments by Prof. Jolivet (reviewer 2), the current state of the art in the Fram Strait is that there is thus far no firm evidence of the presence of gabbroic–basaltic oceanic crust, only of thin layers of volcanics and exhumed mantle (Koehl, 2020; Koehl et al., 2021). The authors of the present manuscript neither argue that oceanic crust should be banished, nor that it should be replaced with continental crust everywhere, but only at very specific areas discussed in the present manuscript (e.g., Madagascar Ridge, Greenland–Iceland–Faroe Ridge, Mozambique Ridge, Walvis Ridge, Rio Grande Ridge, Laccadive Ridge, Gunnerus Ridge, Astrid Ridge, Mauritia). In many of these places, a continental origin of the crust at depth was already proposed by other studies, e.g., Mauritia (Torsvik et al., 2013), Greenland–Iceland–Faroe Ridge (Foulger et al., 2020), Gunnerus Ridge (Leitchenko et al., 2008), Rio Grande Ridge (Ventura Santos et al., 2019), Davis Strait (Dalhoff et al., 2006; Dafoe et al., 2022) to cite only a few. The unification of all these observations with regional work on new seismic reflection data at various margins worldwide into a global update of plate tectonics is thus a natural continuation of these previous works.
Regarding figure 2, it does include an inset with a typical passive margin with oceanic crust (a). However, the oceanic crust domain is not the central part of the present paper, but rather the newly identified inner and outer Seaward-Dipping Reflectors of Geoffroy et al. (2022b). The authors of the present manuscript concede that this could have been better outlined in the figure caption.
Regarding transform faults, the authors of the present manuscript agree with the reviewer in that once formed, transform faults may be reused during subsequent events. However, this is not the issue explored and discussed in the present manuscript, which targets the causes of formation of major transform faults in the first place. The global correlation of all major transform faults on Earth with rift-orthogonal or rift-oblique orogens on adjacent continental margins strongly suggests that there is a causal relationship there. This is

supported by preliminary and ongoing studies in the Fram Strait, Davis Strait, and at the Greenland–Iceland–Faroe Ridge, which show that major transform faults in these regions may have formed along preexisting, rift-orthogonal thrust systems (Peace et al., 2018; Foulger et al., 2020; Koehl et al., 2021, 2024, 2025).
The authors agree that continuous orogenic bridges are not required. However, they are likely in the Davis Strait and Greenland–Iceland–Faroe Ridge and possibly in the Fram Strait. This will be relatively easy to demonstrate in these areas in the near future since the character of major thrust systems on seismic reflection data is now well established (e.g., Koehl, 2020, 2024; Koehl et al., 2022, 2023a, 2023b, 2024; Koehl and Stokmo, 2024). My issues with the integrity of the arguments mostly stem from this attempt to conclude that there are areas of continuous continental crust. Below are some examples.
Changes: Added "The concept of continuous orogenic bridge implies that continental crust continues across previously inferred oceanic domain. In such areas, the extent of oceanic crust is proposed to be overestimated by 100% (i.e., no oceanic crust yet). This implies that sections of hybrid crust (see Figure 2a and b) capped by thick successions of volcanic rocks and intruded by extensive magmatic intrusions (e.g., lava flows and Seaward-Dipping Reflectors) as continental." as introduction to the "Continuous Orogenic Bridge" section and "In the examples discussed, the overestimation of the extent of oceanic crust is in the order of 20–60%." to the introduction to the "Disrupted Orogenic Bridge" section. Also specified in % the approximate overestimation of oceanic crust at the various potential orogenic bridges discussed. Added "Seismic reflection data nevertheless shows the occurrence of thin layers of volcanics and exhumed mantle along the Molloy fault zone (Koehl, 2020; Koehl et al., 2021)." to the "Timanian orogenic bridge" sub-section. See also response to comments 12 and 13.
Rewrote the caption of Figure 2a into "Typical rifted margin with thinned continental crust, SDRs, and oceanic crust (based on the new classification of SDRs and new margin architecture by Geoffroy *et al.*, 2022b). Note the occurrence of the continent–ocean boundary somewhat farther seaward than typically suggested".
Added "The present study explores the factors controlling the formation of major transform faults." in the second paragraph of the "Major issues with plate tectonics" section of the Introduction chapter.
Rewrote the first sentence of the third paragraph of the "New correlations" section into "It was possible to establish this correlation in great part due to major improvements in the quality of seismic imaging and partly to our ability to now identify major shear zones (e.g., Bird *et al.*, 2016; Fazlikhani *et al.*, 2017; Hedin *et al.*, 2016; Lenhart *et al.*, 2019; Phillips *et al.*, 2016; Ye *et al.*, 2020), major thrust systems, and related contractional structures on seismic reflection data, whose seismic facies is now well established (e.g., Koehl, 2020; Koehl, 2021; Koehl, 2024 awaiting peer review; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Koehl & Stokmo, 2024 Morley *et al.*, 2017).".

Comment 7: Cape-Falkland OB: The statement that the Falkland Plateau (FP) and Maurice Ewing Bank (MEB) are continental crust is not supported by cited references. Schimschal & Jokat (2018) interpret seismic data to show continental crust slightly offshore of Falklands islands but oceanic farther seaward (on the FP). Chamale et al. (2018) do indeed study zircons in continental rock cored by DSDP. This hole penetrated <10 m of continental rock. Even Chamale et al. sketch this rock as a cap on the MEB crust (but give no evidence to support the sketch). The authors interpret this evidence to indicate that the entire FP is

continental. This is an overinterpretation unsupported by data.
Response: Is the reviewer suggesting that if a wellbore would have recovered < 10 m of basalt and/or gabbro, an interpretation of the plateau as oceanic crust would have been an overinterpretation? Or is it simply an overinterpretation because the interpretation made by the authors of the present manuscript is not in agreement with some previous interpretation? The authors of the present manuscript argue that there is evidence both for an interpretation of the whole Falkland Plateau and Maurice Ewing Bank as fully continental or as oceanic with continental rafts/debris/mini-terranes/microcontinents. However, the interpretation requiring the least amount of tectonic movement and thus being simplest (Occam's Razor) is an interpretation as fully continental (+/- mafic intrusions), which is also in agreement with crustal thicknesses in the area. Should the Falkland Plateau and Maurine Ewing Bank not be fully continental, where would the boundary/ies be? The gravimetric data in Stanca et al. (2022) suggest a relatively thick crust both in the entire Falkland Plateau and at Maurice Ewing Bank (their figure 4a), and seismic sections confirm the orogenic character of the crust at depth, which can only mean one thing: the crust is continental (their figures 5, 8, 12, and 13 all of which show folded Paleozoic sedimentary successions of the Cape Fold Belt). Or is the reviewer suggesting that the Cape Fold Belt is underlain by oceanic crust?
The authors of the present manuscript understand the point the reviewer is skeptical about: the citing of specific publications with a reinterpretation of those publication's data. Here is another concrete example and why this must be done this way by the authors of the present manuscript (and hopefully by other authors in their own manuscript). Faehnrich et al. (2020) performed a geochronological study of WNW–ESE-striking shear zones in southern Svalbard and obtained a 538 ±21 Ma age. Faehnrich et al. (2020) chose to interpret this age as inherited from a ca. 640 Ma Torrelian/Timanian muscovite and interpreted the shear zone to have formed during the Caledonian Orogeny. After regional geophysical mapping in the region, Koehl et al. (2022a) correlated WNW–ESE-striking shear zones in Svalbard with Timanian thrust systems in northwestern Russia. It becomes clear that the WNW–ESE-striking shear zones in Svalbard had formed in the late Neoproterozoic and were later overprinted during the Caledonian Orogeny in Svalbard (Koehl et al., 2022). This is the process performed repeatedly in the present manuscript, including the Stanca et al. (2022) study. Should the reviewer suggest that such a process is not allowed or unethical, the authors of the present manuscript disagree with this. If scientific data is published, it is therefore made accessible to entire communities, thus empowering specialists around the world to critically analyze the data again and agree with the interpretations and conclusions of the authors of the study or not. Should members of the community disagree with the interpretations and conclusions of the study, these members are free to make it known and to formulate their own interpretations and conclusions. If the reviewer suggests that such process should not be allowed and that, instead, every member of the community should only interpret his own personally collected data, then the authors of the present manuscript argue that this would be a major infringement to the sharing of data to promote scientific progress and a huge waste of (generally public) funds. If the reviewer is suggesting that the authors of the present manuscript should publish one manuscript for each study the interpretation of which they disagree or only partly agree with, then again what the reviewer would be suggesting would be a huge waste of public funds (including but not limited to the salary of the academics contributing to writing such manuscripts, publication fees, administrative cost, etc.). The authors of the present manuscript feel that this huge

waste would significantly hinder scientific progress, something that mankind cannot afford. Regarding the study by Schimschal and Jokat (2018), it is based on seismic refraction data, which are known to be controversial. For example, Breivik et al. (2005) interpreted the location of the potential mid-Paleozoic Caledonian suture in the Barents Sea using seismic refraction data. Koehl et al. (2022) demonstrated that such a suture is not plausible in the Barents Sea since late Neoproterozoic Timanian thrust systems are continuous throughout the interpreted potential suture instead of being truncated and offset. Another example is the use of refraction data to interpret the nature of the crust as oceanic at the Greenland–Iceland–Faroe Ridge and off northeastern Greenland with the interpretation of two microcontinents there (Hovgård Ridge and East Greenland Ridge; e.g., Funck et al., 2017). At the Greenland–Iceland–Faroe Ridge, seismic reflection data show that late Paleoproterozoic thrust systems extend beyond the Seaward-Dipping Reflectors (i.e., past the presumed continent–ocean boundary) and, thus, that the crust within the Greenland–Iceland–Faroe Ridge may be continental. In northeastern Greenland, new magnetic data clearly show that the previously interpreted microcontinents are fully attached to Greenland's continental crust, i.e., that the interpretation of oceanic crust based on seismic refraction data was erroneous. Thus, seismic refraction data cannot be used as a stand-alone approach, and interpretations of the crust nature spawning from seismic-refraction-based datasets should be treated with care. In the present manuscript, the authors of the present manuscript therefore argue for an alternative interpretation to that by Schimschal and Jokat (2018), which, as it turns out, does not include sufficient evidence to argue for an oceanic nature of the crust under the Falkland Plateau and Maurice Ewing Bank.
The authors of the present manuscript, however, concede that the first mention of Schimschal and Jokat (2018) is confusing and agree to rewrite the sentence.
Changes: Added "( Chemale Jr. *et al.*, 2018; Stanca *et al.*, 2022)" midway through the sentence to stress that the "recent studies have provided robust evidence that the crust is continental" statement comes from other studies, and that only the thin character of the crust at Maurice Ewing Bank spawns from the Schimschal and Jokat (2018) study.

Comment 8: The authors show E-W late Paleozoic fault trends north of the Falklands Islands and on the northern Falklands plateau in Figure 4. These trends are cited as being from Stanca et al. (2022). I checked that paper and I could not find these lineaments. That paper analyzed seismic data and shows late Paleozoic folds in deep sediments, but I could not find any definition of lineaments. The survey also does not cover much of the area where the lines in Figure 4 are shown. The authors claim that Paleozoic faults at Falklands Plateau reconstruct parallel to those in Cape Fold Belt in South Africa. I cannot tell this from Figure 4, but if you move the former to the latter along the fracture zone, it does not look like this is true. The authors claim a connection between contractional belt of Southern South American cordillera and subsequent formation of transform faults. This is not shown in Figures 1 or 4 nor is it explained.
Response: Disagreed. For the lineament plotted in the present manuscript's figure 4, the reviewer is referred to figure 4a in Stanca et al. (2022), which shows E–W-striking lineament in gravimetric data north of the Falkland Islands, along the Agulhas–Falkland fault zone in the north and in the northern part of Maurice Ewing Bank, i.e., exactly where the E–W-striking lineaments are plotted in the present manuscript's figure 4 (see red arrows in lower inset).

Notably, the E–W-striking lineaments north of the Falkland Islands coincide with major folds and thrusts in Paleozoic sedimentary rocks in seismic reflection data (Stanca et al., 2022 their figure 5b). The probability for E–W-striking lineaments at Maurice Ewing Bank to correspond to Cape Fold Belt folds and thrusts is therefore relatively high considering the continental material recovered there (Chemale Jr. et al., 2018). This is compatible with the presence of extensive magmatic intrusions both in the Falkland Plateau and at Maurice Ewing Bank (e.g., Stanca et al., 2022 their figures 5a and 9a).
Regarding the potential parallelism between the structures of the Cape Fold Belt on the Falkland Plateau and Maurice Ewing Bank and in South Africa, the reviewer is referred to the structural maps in Paton et al. (2022 their figures 1a–b and 6a–b), which show that structures of the Cape Fold Belt onshore and offshore southeastern South Africa strike NE–SW, i.e., parallel to the Agulhas–Falkland fault zone there and parallel to the Cape Fold Belt structures on the Falkland Plateau. The authors of the present manuscript concede that this should be better illustrated in Figure 4. The authors of the present manuscript also concede that the potential formation of the Agulhas–Falkland fault zone along structures of the Cape Fold Belt should be better explained.
Changes: Added NE–SW-striking structures of the Cape Fold Belt onshore and offshore southeastern South Africa in Figure 5. Also added “Notably, the Agulhas–Falkland fault zone parallels thrusts of the Cape Fold Belt both onshore and offshore southern South Africa (Paton *et al.*, 2022) and on the Falkland Plateau and Maurice Ewing Bank (Stanca *et al.*, 2022 their figures 4a, 5b, 12b–c, and 13a–c), which strike respectively NE–SW and E–W (Figure 5). These late Paleozoic–earliest Mesozoic thrusts therefore likely controlled the strike and geometry of the Agulhas–Falkland fault zone.” to the second paragraph in the “Cape–Falkland orogenic bridge” section.

Comment 9: East African-Antarctic OB: To argue that the OB is mostly continental, the authors claim that the Mozambique, Madacascar, and Davies ridges (Africa) and Gunneris and Astrid ridges (Antarctica) are continental. At best, these ridges are partly continental, not entirely as implied. Klimke et al. (2018) studied Antarctic margin and connection to Africa for plate motion. They do not mention Mozambique Ridge, but instead say that the Gunneris Ridge is possibly continental. The Gunneris Ridge connects to Mozambique Ridge. Vorman & Jokat investigate Davies Ridge near Africa and they find that it has continental core part way from African margin towards Madagascar. Leithenkov et al (2008) says that marginal part of Astrid Ridge is continental, but they cannot tell about segment farther offshore. Roeser et al. (1996) interprets seismic data to show that the northern Astrid Ridge is oceanic. The authors also claim that Sato et al. (2022) show that the Del Cano Rise (oceanic rise between continents) is continental. Those authors said nothing of the sort. They only said that their data did not allow them to rule out that Del Cano is continental. In sum, the authors have taken some partial evidence of continental affinity and assumed that all of the ridges and Del Cano Rise are continental. This is misleading.
Response: The authors of the present manuscript do not blindly assume that the Mozambique Ridge is continental. They base their assumption on the thickness of the crust there, which is considerably thicker than typical oceanic crust. The reviewer may argue that this is probably related to plume magmatism (e.g., Jacques et al., 2019), to which the authors of the present manuscript would respond: plume magmatism of the same nature as at the Greenland–Iceland–Faroe Ridge into which late Paleoproterozoic thrust systems

were traced? While the authors of the present manuscript do not demy the possible existence of a plume and that it may very well be responsible for the extensive magmatic rocks capping the Mozambique and Madagascar ridges, it does not change the issue: the crust is too thick and should completely collapse on its own weight if fully oceanic. This is not the case. Once one has eliminated all that is impossible, the only solution that remains must then be the truth. The crust below the Mozambique Ridge and Madagascar Ridge is therefore most likely continental. This hypothesis will be further explored using state-of-the-art geophysical data, including but not limited to seismic reflection data.

Regarding the claim of the reviewer that "Roeser et al. (1996) interprets seismic data to show that the northern Astrid Ridge is oceanic", this is incorrect, and the authors of the present manuscript thank the reviewer for highlighting this interesting issue. Roeser et al. (1996) clearly state in their study (page 243, paragraph 1) that "Seismic data were not obtained on the Astrid Ridge.". Their conclusion that the northern segment of the Astrid Ridge is oceanic is based on the interpretation of E–W-striking magnetic anomalies (i.e., parallel to the mid-ocean ridge) in the northern part of the Astrid Ridge: "Figure 6 of Bergh (1987) displays strong magnetic anomalies over the northern part of the Astrid Ridge which strike mainly in an E-W direction. Except for their greater amplitude and irregularity, they resemble those in the Riiser-Larsen Sea" (page 253, paragraph 5). They were however not successful in correlating these anomalies along the margin: "However, it is not possible to correlate the most prominent peaks over all lines" (page 253, paragraph 5). They nevertheless went on to conclude that the northern Astrid Ridge was probably oceanic: "This is not unusual for submarine plateaus with thickened oceanic crust because they may consist of lava flows with large horizontal extensions which reduce the clarity of the magnetic lineations" (page 253, paragraph 5). Roeser et al. (1996) however stressed that the magnetic anomalies in the northern Astrid Ridge display a "greater amplitude and irregularity" than those in the adjacent oceanic domain (Riiser–Larsen Sea; page 253, paragraph 5). In the light of most recent studies of high-resolution seismic reflection data and magnetic data off various rifted margins suggesting that the outermost linear magnetic anomalies reflect mafic intrusions in continental crust (e.g., southeastern Greenland, Faroe Islands, Namibia; Geoffroy et al., 2021 their figure 1b, 3b–c, and 5; Geoffroy et al., 2022 their figures 2 and 3; Koehl et al., 2024 their figure 2e), the authors of the present manuscript disagree with the interpretation of Roeser et al. (1996) of an interpretation of the northern Astrid Ridge as oceanic. The authors of the present manuscript argue that it is much more likely that the observed E–W-striking anomalies reflect mafic intrusions in continental crust as suggested in Geoffroy et al. (2021, 2022). This reinterpretation is strongly suggested by the impossibility to correlate the magnetic anomalies in the northern Astrid Ridge with discrete anomalies in adjacent oceanic domains (Riiser–Larsen Sea) and by their more irregular character and different amplitude from regular ocean-floor anomalies, which is typical of Seaward-Dipping Reflectors according to Geoffroy et al. (2021): "Thick packages of inner seaward-dipping reflectors at volcanic passive margins create broad and irregular magnetic anomalies, generally of high amplitude" (page 6, paragraph 6 in Geoffroy et al., 2021). The authors of the present manuscript thank the reviewer for raising this issue and concede that it should be added to the present manuscript.

Regarding the Madagascar Ridge and Del Cano Rise, the authors of the present manuscript call the attention of the reviewer to paragraph 3 on page 4 in Sato et al. (2022) where the authors of the study indicate that "Although the Del Cano Rise has been recognized as having thick oceanic crust by various geophysical features, no rock samples have been

recovered, so the nature of this rise remains in question, similar to that of the southern Madagascar Ridge". Thus, to start with, the interpretation of the southern part of the Madagascar Ridge and of the Del Cano Rise as oceanic is speculative. The authors of the present manuscript concede that this should be mentioned in the present manuscript.
Regarding the claim that Sato et al (2022) did not say that "the Del Cano Rise [...] is continental", the authors of the present manuscript concede that Sato et al. (2022) wrote "We cannot exclude the possibility that the two rises are partly continental fragments rather than products of hotspot-induced excess volcanism" in the Plain language summary, which is unfortunate and definitely does not reflect the content of the article. Sato et al. (2022) also wrote in the last sentence of the abstract that "Like other aseismic ridges in the southern Indian Ocean, these two rises may possibly have been formed partly by continental fragments". The authors also added in the sentence just before that the crust at Del Cano Rise is "thicker-than-normal" and that "linear magnetic anomalies have not been observed across the main part of these rises, suggesting that magmatic activity controlled by seafloor spreading is unlikely." Again, since the crust is thicker than normal oceanic crust, it is highly likely that it is (at least partly if not completely) continental. The authors of the present manuscript concede that this should be better specified in the manuscript.
Regarding the Madagascar Ridge, Sato et al. (2022, page 4 paragraph 2) state that Schlich (1982) showed that "the transition zone [i.e., the zone between the thick continental-like northern part of the Madagascar Ridge and the oceanic-like southern part] has an intermediate structure between normal oceanic and continental crust", which suggests that there is (at least some) continental crust in the transition zone in addition to the continental crust in the northern part of the ridge. The most likely scenario for the transition zone is that is corresponds to thinned continental crust because it is adjacent to a rifted margin and the crust in the northern part of the Madagascar Ridge is still thicker than 26 km (Goslin et al., 1981). A possible scenario for the southern part of the Madagascar Ridge, which is still thicker than typical oceanic crust (c. 14 km; Goslin et al., 1981), is that it corresponds to hyperextended continental crust or rafted microcontinents (e.g., Péron-Pinvidic et al., 2015).
Finally, regarding both the Del Cano Rise and the Madagascar Ridge, Sato et al. (2022) write in the last paragraph of the discussion just before the conclusion that they "propose that the southern Madagascar Ridge and the Del Cano Rise may have been formed partly by continental fragments. These two rises have been recognized as oceanic LIPs; however, the observed magnetic anomalies and isochrons suggest that plume-induced excess volcanism controlled by seafloor spreading can be ruled out for their main origin. The magnetic anomalies can also be explained by sporadic magmatic activity similar to that of the Mozambique Ridge. The thicker-than-normal crust and low RMBAs [Residual Mantle Bouguer Anomaly] of these rises may be explained by continental fragments covered by volcanic activity, similar to the model for the Elan Bank and the southern Kerguelen Plateau."
The authors of the present manuscript thus argue that, although more work is needed to provide a definitive answer, there are far more evidence favoring a continental nature of the crust at the Madagascar Ridge, Mozambique Ridge, and Del Cano Rise. Nevertheless, this needs to be better explained in the present manuscript and the authors of the present manuscript thank the reviewer for his valuable comment.
Changes: Added "A relevant issue is the nature of the crust at the Astrid Ridge. Roeser et al. (1996) interpreted the northern part of the Astrid Ridge as oceanic. The authors of this work clearly state in their study (page 243, paragraph 1) that "seismic data were not obtained on

the Astrid Ridge" as part of their study and that they based their interpretation on existing magnetic data from Bergh (1987). The data show E–W-striking magnetic anomalies in the northern part of the Astrid Ridge, i.e., parallel to the mid-ocean ridge (Bergh, 1987 his figure 6). Roeser et al. (1996) argued that "except for their greater amplitude and irregularity, they (the E–W-striking magnetic anomalies in the northern Astrid Ridge) resemble those in the Riiser-Larsen Sea" (page 253, paragraph 5). However, they were unable to correlate these anomalies with anomalies in adjacent oceanic domains in the Riiser–Larsen Sea. Roeser et al. (1996) stressed that the magnetic anomalies in the northern Astrid Ridge display a "greater amplitude and irregularity" than those in the adjacent oceanic domain (Riiser–Larsen Sea; page 253, paragraph 5). In the light of recent studies of high-resolution seismic reflection data and magnetic data off various rifted margins showing that the outermost linear magnetic anomalies reflect mafic intrusions in continental crust (e.g., southeastern Greenland, Faroe Islands, Namibia; Geoffroy et al., 2021 their figure 1b, 3b–c, and 5; Geoffroy et al., 2022 their figures 2 and 3; Koehl et al., 2024 their figure 2e), it is argued that it is much more likely that the observed E–W-striking anomalies reflect mafic intrusions in continental crust. This reinterpretation is supported by the impossibility to correlate the magnetic anomalies in the northern Astrid Ridge with discrete anomalies in adjacent oceanic domains (Riiser–Larsen Sea) and by their more irregular character and different amplitude from regular ocean-floor anomalies. The more irregular and high-amplitude character of Seaward-Dipping-Reflector-related magnetic anomalies was specifically pointed out by Geoffroy et al. (2021)." after the second paragraph in the "East African–Antarctica orogenic bridge" section. Also added the location of the Riiser–Larsen Sea in Figure 5 and to Figure 5's caption and Bergh (1987) to the reference list.
Added "More specifically, continental material, namely c. 1 Ga granulite rocks, was dredged at the Mozambique Ridge, thus suggesting that at least the southern part of the ridge is continental (Hartnady et al., 1992 and references therein). More recent geophysical studies then revealed that the northern part of the Mozambique Ridge consists of thinned continental crust and the southern part of intermediate crust, i.e., probably hyperextended continental crust as suggested by the southwards increase in the degree of extension and thinning of the crust, overlain by magmatism rocks (Ryzhova et al., 2022)." after the first paragraph in the "East African–Antarctica orogenic bridge" section.
Added "At the Madagascar Ridge, the crust is thought to be continental in the northern part, where it consists of complex basement structure, and probably in the transition zone, where the crust is 26–22 km thick (Goslin et al., 1981) and most likely consists of a thinned version of the northern segment since located at a rifted margin. In the southern part of the ridge, the 14 km thickness of the crust led previous workers to postulate a thick oceanic crust (oceanic Large Igneous Province) despite the lack of bedrock samples in drilling attempts (Sato et al., 2022). Similarly at the Del Cano Rise, the 16 km crustal thickness was assumed to result from plume magmatism (oceanic Large Igneous Province; Sarto et al., 2022). However, the lack of linear magnetic anomalies and thicker-than-normal character of the crust both in the southern Madagascar Ridge and Del Cano Rise clearly indicate that seafloor-related processes can be ruled out and the irregular magnetic anomalies may be explained by more sporadic magmatic activity comparable to that which occurred at the continental Mozambique Ridge (Sato et al., 2022). Thus, the thicker-than-normal crust and low residual bouguer anomalies at the southern Madagascar Ridge and Del Cano Rise were interpreted to reflect continental crust capped by mafic volcanics (Sato et al., 2022), a scenario also suggested for other areas of thickened offshore crust in the Indian Ocean,

e.g., southern Kerguelen Plateau and Elan Bank (Jiang et al., 2021 their figure 4). A likely scenario, which should be further tested is that the southern Madagascar Ridge and Del Cano Rise consist of hyperextended (i.e., very thin) continental crust and/or rafted continental blocks (e.g., Péron-Pinvidic et al., 2015). This is suggested by the fact that they occur at rifted margins and by the similar gradual southwards thinning of the continental crust at the Mozambique Ridge in adjacent areas (Hartnady et al., 1992; Ryzhova et al., 2022).” after the first paragraph in the “East African–Antarctica orogenic bridge” section.
Also added reference to Jiang et al. (2021) to the reference list.
Also rewrote the first sentence of the third paragraph in the “East African–Antarctica orogenic bridge” section into “Thus it is possible that late Neoproterozoic shear zones observed onshore Dronning Maud Land in Antarctica may extend into the (at least partly) continental crust at Del Cano Rise ( Sato *et al.*, 2022; Figure 5).”.

Comment 10: The authors cite Chu and Gordon (1999) to delineate a diffuse plate boundary that intersects the Southwest Indian Ridge (SWIR) at a major offset. They claim that this shows that major transform faults are where such boundaries intersect the ridge. Chu and Gordon do not show where the boundary is. I followed other references, and this got complicated. Meyzen and SchwarzSchampera (2023) show two diffuse boundaries intersecting the SWIR, but incorrectly attribute their sketch. These two boundaries are used in the plate model of DeMets et al. (2010), but their attribution is also incorrect. The result is that I can’t find where the definition of these boundaries originated. I think one of the claims is probably correct, one correlates with the Andrew Bain FZ, but the other does not correlate to a major offset.
Response: Disagreed. The diffuse plate boundary indeed originates from Chu and Gordon (1999). The reviewer is referred to white lines and dashed light pink (almost grey) lines in figure 2 in Chu and Gordon (1999; attached below with red arrows pointing at the relevant features) and to the figure’s caption, which states that “North–south white line segments adjacent to the SWIR show the eastern and western confidence limits on the intersection of a hypothetical narrow Nubia-Somalia boundary with the SWIR. North–south pink line segments show the limits we assumed for our proposed diffuse Nubian–Somalian plate boundary along the SWIR”. To the knowledge of the authors of the present manuscript, Chu and Gordon (1999) is the first study mentioning the discussed diffuse plate boundary in this area. Meyzen and Schwarz-Schampera (2023) and possibly DeMets et al. (although the authors of the present manuscript do not know of a 2010 study, but of 2005, 2015, and 2020 studies; cf. Meyzen and Schwarz-Schampera, 2023), of whom R.G. Gordon (as in Chu and Gordon, 1999) is a co-author, also mention the diffuse plate boundary.
Figure
*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
Changes: None.

Comment 11: The authors say that these FZ are colder than normal oceanic faults. They cite Ligi et al. (2002) and imply that those authors said the wide, multifault FZ are similar to continental crust because they involve cold crust. They then extrapolate this idea to the fact that the rocks of these FZ are older than predicted by SFS. This is not what I would conclude from that reference and these observations. The authors claim these plate boundary-transform connections show that this area between Antarctica and Africa is an OB, but the

rationale is not made clear.
Response: Agreed. The rationale for an orogenic bridge between Africa and Antarctica should be stated more clearly. See response to comment 9. However, the authors of the present manuscript are uncertain as to how the reviewer would rather interpret the claim by Ligi et al. (2002) that the crust at megatransform faults is colder and that these megatransforms are similar to continental strike-slip faults if not that there may be some slivers of continental crust far offshore along these megatransforms, which were possible ripped off adjacent rifted continental margins. A probable cause for the presence of such continental ribbons, which are elongated parallel to the megatransform, is the existence of preexisting zones of weakness in the continental crust prior to rifting. These preexisting zones of weakness must have been parallel to the transform faults to facilitate disruption of the continental crust parallel to the megatransform. The authors of the present concede that this should be better explained and illustrated in the present manuscript.
Changes: See response to comment 9. Also added "In such a scenario, transform-parallel ribbons of continental crust become detached from adjacent continental margins and entrained along major transform faults due to the occurrence of transform-parallel, preexisting zones of the weakness in the continental crust, such as major (mylonitic) thrust systems. These preexisting structures would facilitate rupture and dislocation of the crust along an axis parallel to the proto-transform faults and allow the inclusion of such transform-parallel continental ribbons into oceanic crust during seafloor spreading (Figure 10)." At the end of the last paragraph in the "East African–Antarctica orogenic bridge" section and designed a new figure showing the difference between rift-parallel microcontinents (rafts; e.g., Péron-Pinvidic et al., 2015) and transform-parallel microcontinents described here.

Comment 12: Passive Margins: The authors claim that 20-100% of crust categorized as oceanic is in fact continental. They cite Geoffroy et al. (2022) in the Warren Hamilton GSA volume. This paper and this volume were intended to be provocative to honor Hamilton, an iconoclast. In the Geoffroy paper figure was meant to apply to the north Atlantic between Greenland and Europe, not everywhere as implied. The text suggests that similar uncertainty exists in the width of the Newfoundland margin. I checked both Shillington et al. (2006) and Lymer et al. (2019) and do not see that they said this. These authors discussed margin width and the uncertainty of whether transitional crust is continental. Their work may enlarge the defined margins slightly, but do not support the 20-100% number.
Response: First off, the authors of the present manuscript acknowledge that the sentence including the "20–100%" statement is confusing and, in its current state, does not reflect the opinion of the authors and of the cited previous studies. Notably, a 100% overestimation of the extent of oceanic crust applies to areas with continuous orogenic bridges such as the Davis Strait and Greenland–Iceland–Faroe Ridge, and, potentially, the Fram Strait.
Is the reviewer suggesting that because a paper honors an iconoclast and presents provocative results and conclusions, then its findings should be less trustworthy than that of other studies? Looking at the data used in the Geoffroy et al. (2021; at the Greenland–Iceland–Faroe Ridge) and the Geoffroy et al. (2022; off Namibia) studies, the data used and the conclusions presented are robust in the expert opinion of the main author of the present study in seismic interpretation. Not only is the interpretation of continental crust and Seaward-Dipping Reflectors farther at sea than previously thought be Geoffroy et al. (2021, 2022) is robust, but it is further confirmed by the mapping of late Paleoproterozoic

thrust systems beyond the Seaward-Dipping Reflectors at the Greenland–Iceland–Faroe Ridge (Koehl et al., 2024). The fact that the results and conclusions of Geoffroy et al. (2021, 2022) are provocative should play no role in their acceptance if the research community treats them with an unbiased, scientifically objective attitude. The reviewer is of course welcome to point out potential scientific biases or errors in the work of Geoffroy et al. (2021, 2022) should there be any. Furthermore, these results can easily be applied to other margins worldwide and this (i.e., the correlation of nearshore linear magnetic anomalies with magmatic intrusions within continental crust and the existence of both inner and outer Seaward-Dipping Reflectors and related Distal Crustal Bulges at some margins as suggested by Geoffroy et al., 2021, 2022) must be further tested as suggested by the present manuscript. A limitation at some margins will be the lack of high-resolution seismic reflection data like those presented in Geoffroy et al. (2022) off Namibia. Nevertheless, despite the relatively poor coverage of such data at the Greenland–Iceland–Faroe Ridge, Paleoproterozoic thrust systems are still possible to trace from the Faroe Islands to Iceland (Koehl et al., 2025 http://dx.doi.org/10.13140/RG.2.2.12234.58560).
The authors of the present manuscript did not refer to Shillington et al. (2006). Regarding the Lymer et al. (2019), the seismic reflection data in their figure 5a–d and 7b clearly shows the occurrence of contractional folds and thrusts (probably at least Variscan in age since adjacent to the Variscan geosyncline onshore Iberia; Franke, 2006; Pastor-Galan et al., 2020; Shaw et al., 2012) in the footwall of the rift-related detachments. Ongoing mapping of the seismic reflection data by the main author of the present manuscript and Dr. Gaël Lymer will further illustrate these structures and their relationship.
Changes: Rewrote the last sentence of the first paragraph in the “Passive margins” section into “As a result, the extent of oceanic crust has likely been overestimated in some areas along passive margins around the globe ( Geoffroy *et al.*, 2022a), e.g., off the coast of Namibia ( Geoffroy *et al.*, 2022b), the Newfoundland–Iberian margin ( Lymer *et al.*, 2019; Shillington *et al.*, 2006), and the Rockall Plateau north of Ireland ( Dickin, 1992; Roberts *et al.*, 1973)”. In addition, added “Given the c. 2800 km distance to the mid-ocean ridge in this area, this suggests an underestimation of the extent of continental crust of 3.5 to 10.7%.” in the second paragraph of the same section, “The concept of continuous orogenic bridge implies that continental crust continues across previously inferred oceanic domain. In such areas, the extent of oceanic crust is proposed to be overestimated by 100% (i.e., no oceanic crust yet). This implies that sections of hybrid crust (see Figure 2a and b) capped by thick successions of volcanic rocks and intruded by extensive magmatic intrusions (e.g., lava flows and Seaward-Dipping Reflectors) as continental.” before the first paragraph of the “Continuous orogenic bridges” section, added “Considering the c. 3250 km distance between the previous continent–ocean boundary proposed by Schimschal and Jokat (2018; see also figure 1 in Stanca et al. 2022) and the mid-ocean ridge and the c. 1900 km distance between the eastern tip of Maurice Ewing Bank (the continent–ocean boundary proposed in the present manuscript) and the mid-ocean ridge, the extent of oceanic crust on the South American side of this ruptured orogenic bridge is overestimated by c. 41.3%.” to the first paragraph in the “Cape–Falkland orogenic bridge” sub-section and split the paragraph in two, added “Thus, the extent of oceanic crust at the Madagascar Ridge is c. 43.5% using a c. 1150 km distance between the previously inferred continent–ocean boundary at the transition zone between the northern and southern parts of the Madagascar Ridge at 31°S and the mid-ocean ridge and a c. 650 km distance between the southern tip of the southern Madagascar Ridge (i.e., the presently proposed continent–ocean boundary).” in between

paragraphs 1 and 2 in the “East African–Antarctica orogenic bridge” section (at the end of the second newly added paragraph), added “As such, the extent of oceanic crust at the Mozambique Ridge is currently overestimated by c. 55.9 % using a distance of 3400 km between the northern tip of the Mozambique Ridge (i.e., previously proposed continent–ocean boundary) and the mid-ocean ridge and a c. 1500 km distance from the southern tip of the Mozambique Ridge to the mid-ocean ridge (i.e., new continent–ocean boundary).” at the end of the first newly added paragraph after paragraph 1 in the “East African–Antarctica orogenic bridge” section, added “At the Astrid Ridge, the extent of oceanic crust could thus be overestimated by up to 20.6% using a c. 1700 km distance between the previously assumed continent–ocean boundary between the southern and northern parts of the Astrid Ridge (Roeser et al., 1996) and a c. 1350 km distance from the northern tip of the Astrid Ridge (new continent–ocean boundary). At the Gunnerus Ridge and taking into account the Del Cano Rise, oceanic crust extent may be overestimated by as much as 25.0% using a c. 2800 km distance between the southern tip of the Gunnerus Ridge and the mid-ocean ridge and c. 2350 km from the northern tip of the Gunnerus Ridge (new continent–ocean boundary) and including a c. 250 km wide continental crustal domain at Del Cano Rise (Sato et al., 2022).” after the newly added paragraph between paragraphs 2 and 3 in the “East African–Antarctica orogenic bridge” section, and added “In the examples discussed, the overestimation of the extent of oceanic crust is in the order of 20–60%.” at the end of the first paragraph in the “Ruptured orogenic bridges” section.

Comment 13: Namibia-Brazil: Paragraph 2 of this section states that Walvis Ridge is continental affinity. This statement is incorrect. Fromm et al 2017a does not say this (the seismic line is over the volcanic ridge). Fromm et al. 2017b analyzes a seismic profile that starts on the continent. They do not say that Walvis is continental, but instead show the transition between continent and the oceanic ridge. The authors cite the paper by Ventura Santos et al. (2019) to say that Rio Grande Rise (conjugate to Walvis) is continental. Ventura Santos et al. indeed found continental rocks but these rocks are usually fresh and lack the Mn coating of rocks that have been lying on the seafloor for tens of millions of years (I know because I have seen them). The type of rock is highly variable (unexpected from a single dredge or ROV pick-up). These rocks are likely dropstones carried by icebergs from Antarctica. Navigational charts show that Rio Grande Rise is south of the northern limit for icebergs. In sum, there is no reliable information that suggests Walvis Ridge is continental. Once again, the authors have taken a biased view to conclude that continental crust is the foundation of this ridge. The author cites Fairhead and Wilson (2005) as evidence that there has been significant strike slip motion along Walvis Ridge. This paper is an outlier. It was a crude analysis of structural features, but provided no solid evidence of strike-slip faulting. It is true that Walvis Ridge is associated with transform faults. The Frio Ridge (eastern part) is aligned with and next to a FZ that probably had a large offset (few hundred km) and this fault may have offset the continent during the Cretaceous (see Eagles, GJI, 2007). Near the end of the Cretaceous, this fault broke up and reformed as other transforms farther south (Sager et al., G-cubed, 2021). So the idea that there is a throughgoing transform is incorrect.
Response: The authors of the present manuscript are uncertain as to what the reviewer means by “the idea that there is a throughgoing transform is incorrect”. If the reviewer means “a transform fault going through the mid-ocean ridge and through the Walvis Ridge”, this is not what the authors of the present manuscript have argued for.
Regarding the statement of the Walvis Ridge being continental, one must admit that the

coincidence of the Rio Grande Ridge and the Walvis Ridge with rift-orthogonal orogens, which were linked prior to the opening of the South Atlantic Ocean is at the very least suspicious. The authors of the present manuscript concede that Fromm et al. (2017a, 2017b) did not argue that the crust at Walvis Ridge is continental and concede that the sentence should be rephrased to better reflect this. They show that the crust at Walvis Ridge has a comparable thickness and seismic velocities as the Greenland–Iceland–Faroe Ridge, and Foulger et al. (2020) and Koehl et al. (2024) show that the crust at the Greenland–Iceland-Faroe Ridge is most likely continental.
Regarding the evidence presented by the Ventura dos Santos et al. (2019) study, the reviewer makes a compelling point, and the authors of the present manuscript agree that the reasonable doubts around the origin of the samples recovered by Ventura dos Santos should be mentioned in the present manuscript, although Ventura dos Santos et al. (2019) specifying that a thin manganese crust was present on the samples “as determined by scanning electron microscopy” (Ventura dos Santos et al., 2019 page 426 paragraph 1) . Nevertheless, since manganese encrustations/coating may grow as rapidly as 1–125 mm per 1000 years (e.g., Koschinsky and Hein, 2017), is the reviewer suggesting that any dropstone, e.g., 1000–10000 years old, which would likely present such a manganese coating/crust, would be treated as having a higher chance to originate from the bedrock than a non-coated sample actually coming from an exposed fault zone or recent slump exposing fresh bedrock? If so, then it is clear that it is currently not possible to differentiate dropstones from bedrock samples in areas that were once exposed to iceberg flows (i.e., nearly all oceans on Earth?). As such, any sample recovered from any dredge around the world should be disregarded and this practice abandoned. Regardless, considering the statement of the reviewer that “Navigational charts show that Rio Grande Rise is south of the northern limit for icebergs”, this is possibly correct, but judging from existing literature on the topic it is clear that the number of icebergs reaching the area of the Rio Grande Ridge is highly limited (e.g., Bornhold et al., 1983 their figure 1; England et al., 2020 their figures 1 and 4; Starr et al., 2021 their figure 1; Barkley et al., 2024 their figure 1; Bigg, 2024 his figures 2, 5, 6, and 7; van der Does et al., 2024 their figure 4 and EM4 member sourced from ice-rafted debris). Notably, figure 7 in Bigg (2024) clearly show that the northern limits of iceberg observations from recent studies (Romanov et al., 2017 and Orheim et al., 2023 their figures 1, 2, 6, and 7) are all located south of Rio Grande Ridge. The authors of the present manuscript would be curious to see the navigation charts the reviewer is referring to to evaluate the reach and frequency of icebergs at Rio Grande Ridge. If the reviewer could share such a document or direct the authors of the present manuscript to any relevant webpage, this would be highly appreciated. The dredged rocks at Rio Grande Ridge yielded ca. 2.2–2.1 Ga, ca. 1.4 Ga, ca. 1 Ga, ca. 540 Ma, and Ordovician ca. 480 Ma U–Pb zircon ages, all of which are found both in Antarctica (Groenewald et al., 1995; Grunow and Encarnacion, 2000; Liu et al., 2014; Gao et al., 2023; Percival et al., 2023), and Africa (which is a potential source of old detrital zircons for Rio Grande Ridge) and Brazil (even though dominantly but not exclusively as detrital zircons for the 1.4 and 1 Ga ages in Brazil; Basei et al., 2008; Ventura dos Santos et al., 2019). Unless the reviewer shares documents clearly showing large influxes of icebergs around Rio Grande Ridge, the authors of the present manuscript argue that a proximal provenance of the dredged rocks at Rio Grande Ridge is more probable (i.e., sourced from Brazil or Africa). The authors of the present manuscript agree that the discussion around a potential ice-rafted debris origin for the continental samples at Rio Grande Ridge should be added to the manuscript.

Regarding the work by Fairhead and Wilson (2005), the authors of the present manuscript do not argue for significant strike-slip movements along the northern edge of the Rio Grande and Walvis ridges, but relative movements possibly caused by a viscosity contrast between regular oceanic crust in the north and continental/hybrid crust in the Walvis and Rio Grande ridges. Such relative movement may be accommodated by either or both bending and strike-slip faulting and amounts to a few tens to a hundred km relative movements between the ridges and regular (Penrose-like) thickness oceanic crust (e.g., Moores and Jackson, 1974) in the north over 125–120 Myr (time of breakup), which would amount to an average of up to 1 mm per year displacement.
The reviewer is thanked for recommending relevant contributions to include to the present manuscript. Note that the interesting reconstruction of Rio Grande Ridge and Walvis Ridge in Sager et al. (2021) does not preclude that the abnormal width of the magnetic anomalies at Rio Grande Ridge and Walvis Ridge in fact corresponds to magmatic intrusions into continental crust. This is suggested by the irregular and high-amplitude character of the anomalies, which is typical for magmatic intrusions in continental crust (e.g., Seaward-Dipping Reflectors; Geoffroy et al., 2021, 2022). The issue at Walvis and Rio Grande Ridge is that the seismic reflection data in the area (shown in Sager et al., 2021) display poor reflectivity 1 second (TWT) into the bedrock and, thus, do not provide a definitive answer to the continental versus oceanic nature of the crust there.
Changes: Split into three paragraph and rewrote the second paragraph in the "Brazil–Namibia margin" section into "The crust below the Walvis Ridge shows a thickness and seismic velocities comparable to the crust below Iceland ( Fromm *et al.*, 2017a; Fromm *et al.*, 2017b), which is likely continental ( Foulger *et al.*, 2020; Koehl *et al.*, 2024). In addition, basalts at the Walvis Ridge locally show traces of contamination by continental crust, which is similar to igneous province on continental crust, e.g., Parana and Etendeka provinces (e.g., Eroshenko & Kharin, 2019)."
On the conjugate South American margin, Proterozoic granite, gneiss, granulite, and gabbro were recovered from dredges on the Rio Grande Ridge ( Ventura Santos *et al.*, 2019). The large variety of rock types in the dredged samples at Rio Grande Ridge and the lack of a thick manganese coating/encrustation, which is typical for rocks exposed to seawater for extended periods of time, calls for caution when interpreting the origin of these samples, as these features may suggest the influence of ice-rafted debris from Antarctica. However, the absence of manganese coating may also suggest an origin from recent slumps and/or fault scarps, where fresh bedrock may be exposed and not yet encrusted. This is probable for most of the dredged samples, which were taken near a major bathymetric escarpment (see figure 2 in Ventura dos Santos *et al.*, 2019). The ca. 2.2–2.1 Ga, 1.4 Ga, 1.1 Ga, 540 Ma, and 480 Ma U–Pb zircon obtained for the samples at Rio Grande Ridge are unfortunately typical for both Antarctica ( Groenewald *et al.*, 1995; Liu *et al.*, 2014) and western Africa (which is a potential source for detrital zircon at Rio Grande Ridge) and Brazil ( Basei et al., 2008; Ventura dos Santos *et al.*, 2019). Thus, the geochronological record does not allow to segregate the source area. Nevertheless, studies of the northern limit for icebergs and of circum-Antarctic currents in the South Atlantic Ocean suggest that only very few icebergs (if any) make it to the Rio Grande Ridge area (e.g., Bornhold *et al.*, 1983 their figure 1; Romanov *et al.*, 2017; England *et al.*, 2020 their figures 1 and 4; Starr *et al.*, 2021 their figure 1; Orheim *et al.*, 2023 their figures 1, 2, 6, and 7; Barkley *et al.*, 2024 their figure 1; Bigg, 2024 his figures 2, 5, 6, and 7; van der Does *et al.*, 2024 their figure 4). An origin as ice-rafted debris from Antarctica is therefore unlikely and the samples probably reflect continental

crust at Rio Grande Ridge.
These new results indicate that the Walvis–Rio Grande Ridge most likely consists of continental to hybrid crust and that the continent–ocean boundary is located 400–850 km farther oceanward on both margins. This suggests that large portions of the offshore areas are underpinned by continental crust. At Rio Grande Ridge, the extent of oceanic crust could be overestimated by as much c. 46.2% using a c. 2600 km distance from the previously proposed continent–ocean boundary at the western edge of the Rio Grande Ridge and the mid-ocean ridge and c. 1400 km distance from the eastern tip of the Rio Grande Ridge (new continent–ocean boundary). At Walvis Ridge, overestimation could be up to 34.7% using a 2450 km distance from the the continental shelf break east of Walvis Ridge to the mid-ocean ridge and a distance of 1600 km from the central Walvis Ridge (new continent–ocean boundary) to the mid-ocean ridge.
Rewrote the last paragraph in the "Brazil–Namibia margin" section into "This is further supported by the (respectively clockwise and anticlockwise) bending of the seafloor flowlines in map view at the Walvis Ridge and Rio Grande Ridge, which indicates right- and left-lateral relative movement along the northern flank of the ridges in the order of a few tens to a hundred km ( Fairhead & Wilson, 2005) since breakup at ca. 125–100 Ma ( Eagles, 2007; Scotchman *et al.*, 2010), i.e., up to 1 mm per year. Such relative movements may be accommodated by either or a combination of bending (in map view) and strike-slip faulting. A possible cause for these relative movements is viscosity contrast between the continental to hybrid crust within the Walvis Ridge and Rio Grande Ridge and regular, c. 10 km thick, Penrose-like oceanic crust in the north. A major limitation at Rio Grande Ridge and Walvis Ridge is that current seismic reflection data show poor reflectivity 1 second (TWT) into the bedrock (Sager et al., 2021) and, thus, cannot provide a definitive answer as to the nature of the crust there (oceanic versus continental/hybrid). Nevertheless, the irregular and high-amplitude character of the magnetic anomalies at those ridges (Sager et al., 2021 their figure 17) is typical for intrusions (e.g., Seaward-Dipping Reflectors) in continental crust (Geoffroy et al., 2021, 2022).".

Comment 14: RRR Triple junctions: The authors say that triple junctions must be related to OB because the latter control fracture zones. Not much rationale is provided. The RRR triple junctions (Bouvet and Rodrigues) probably started with the separation of continents in Gondwana. When three blocks pull apart, you get a triple junction and this is where those triple junctions likely started. It is plausible that orogens dictated where the continents split, so yes, continental faulting probably initiated the TJ.
Response: Agreed. Since RRR triple junctions are generally T-shaped, i.e., two segments parallel to one another and, thus, two discrete strikes of transform faults, and since Orogenic Bridge Theory suggests that all major transform faults form parallel to rift-orthogonal orogens, it follows that RRR triple junctions must form at the intersection of two oblique orogens. The reviewer assumes that breakup is coeval along all three arms at RRR triple junctions and that RRR triple junctions therefore form early on because three blocks pull apart. This is clearly not the case for some triple junctions. For example, breakup is thought to have occurred later in the South Atlantic Ocean (ca. 125–100 Ma; e.g., Eagles, 2007; Scotchman et al., 2010) than along the South-West Indian Ridge (at ca. 160 Ma; Seton et al., 2012; DeMets et al., 2021), two arms of the Bouvet Triple Junction.
Changes: Added "Breakup at the southern Mid-Atlantic mid-ocean ridge is thought to have occurred at ca. 125–100 Ma (e.g., Eagles, 2007; Scotchman et al., 2010), i.e., later than along

the South-West Indian Ridge at ca. 160 Ma (Seton et al., 2012; DeMets et al., 2021)" to the first paragraph of the "Bouvet Triple Junction" sub-section and relevant references to the reference list.

Comment 15: Bouvet Triple junction: The authors state that Agulhas-Falkland FZ is parallel to trends in the Cape Fold Belt near Cape Town. The authors say its strike is SW-NE. The Cape Fold belt trends are N-S and E-W, so this appears erroneous. Arguments about fracture zone trends matching is unconvincing because some of those are on the Scotia backarc (a microplate) and we are talking two separate ridge systems (South America-Antarctic & Africa-Antarctic). The author cites Figure 4 which does not seem to support these claims. Another claim is that FZ on the southern MAR and SA-ANT ridge are parallel. This is clearly shown to be incorrect by Figure 4.
Response: The authors of the present manuscript argue that structures of the Cape Fold Belt in southeastern South Africa strike parallel to the Agulhas–Falkland fault zone, i.e., NE–SW. See response to comment 8.
The fact that the transform faults on the Scotia Plate also parallel the folds and thrusts of the Cape Fold Belt in the Falkland Plateau and Maurice Ewing Bank and its time-equivalent onshore Patagonia is relevant to the present discussion and the fact that they are located on a separate plate has no impact on their origin and on the present discussion. From the geometry of the Scotia Plate and Bouvet Triple Junction, it is clear that the rift tried to incise the Cape Fold Belt orogenic bridge between the Falkland Island and Maurice Ewing Bank in the south but failed as suggested by the 137–93 Ma ages obtained for basalt at the West Scotia Ridge (Riley et al., 2019). The rift then stepped to the east and succeeded to break the crust up east of Maurice Ewing Bank along the South Atlantic Mid-Ocean Ridge and American–Antarctic Ridge. This is also suggested by the left-stepping geometry of the mid-ocean ridge across the Agulhas–Falkland fault zone. The authors of the present manuscript concede that this should be mentioned in the manuscript.
The claim that transform faults crosscutting the South Atlantic Mid-Ocean Ridge and America–Antarctica Ridge are not parallel is unfounded. While the authors of the present manuscript concede that this does not appear fully correct while glancing at Figure 5, the reviewer is reminded that he must account for the curvature of Earth's surface when looking at broad areas as that displayed in Figure 5. If zooming in the targeted areas close to the Bouvet Triple Junction, the transform faults that truncate the South Atlantic Mid-Ocean Ridge and those crosscutting the American–Antarctica Ridge are clearly parallel. The authors of the present manuscript concede that this should be specified in the figure caption and regret that this cannot be perfectly illustrated in the figure.
*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
Changes: Added "A potential hypothesis to be further tested for the West Scotia Ridge and Phoenix Ridge system in the west and the American–Antarctic Ridge in the east is a failed attempt of the West Scotia–Phoenix Ridge system to break the orogenically thickened continental crust between the Falkland Islands and Maurice Ewing Bank in the south and to merge with South Atlantic Mid-Ocean Ridge. Instead, seafloor spreading aborted there and the rift stepped to the west with seafloor spreading initiating at the American–Antarctica Ridge and succeeding in rupturing the orogenic bridge. This scenario is already supported by the left-lateral offset/step of the South Atlantic Mid-Ocean Ridge across the Agulhas–Falkland fault zone ( Figure 5a–b) and by 137–93 Ma Ar–Ar ages for basalts at the

northern tip of the West Scotia Ridge (Riley et al., 2019). The latter suggest that magmatism along the northern tip of the West Scotia Ridge died out at 93 Ma, i.e., at the onset or soon after the breakup in the South Atlantic Ocean at ca. 100 Ma ( Eagles, 2007).” at the end of the third paragraph in the “Bouvet Triple Junction” section.
Added a new Figure 5b centered over the Bouvet Triple Junction and “(b) better illustrate the parallelism between transform faults truncating the South Atlantic Mid-Ocean Ridge and those crosscutting the American–Antarctica Ridge, which is partly impeded in (a) due to the curvature of the Earth surface. The white double arrow in (b) shows that the eastern portions of the Agulhas–Falkland fault zone is parallel to the Conrad fault zone.” and “in (a)” and “(a–b)” in the figure caption. Also updated all references to Figure 5 in the text.

Comment 16: Plume model: Paragraph 5: The authors take anti-plume approach and argue that available data unambiguously support that thickened crust is continental and not from hotspot volcanism. I think this is overstatement because there is ambiguity about crustal type in many of the places mentioned. The authors cast doubt on the widely-accepted hotspot model for Walvis Ridge formation because the ridge does not parallel MAR fracture zones. They conflate plate-plate relative motion (the FZ) with plate-mantle (hotspot) motion. The two do not need to be the same. Paleomagnetic data shows that Africa has changed paleolatitude during Walvis Ridge formation, so the continent has had some N-S motion relative to the mantle and hotspots. Hotspots themselves may have moved relative to the mantle. I don’t know why one must argue against mantle plumes here. I don’t think that they invalidate the OB idea. This is another example of lack of focus.
Response: Agreed. This section as it is written as present does not reflect the opinion of the authors of the present manuscript. Mantle plume may very well exist and contribute to producing thick successions of volcanic rocks, e.g., at Walvis Ridge. However, they can hardly explain anomalously thick crust offshore and reconcile it with isostasy. The authors of the present manuscript also agree that mantle plumes and Orogenic Bridge Theory may work together, e.g., in areas like Walvis Ridge and Greenland–Iceland–Faroe Ridge.
Changes: Deleted “, e.g., the nature and origin of the Walvis and Rio Grande ridges in the South Atlantic, which have been attributed to the migration of the tectonic plates over the Tristan da Cunha hotspot over time (e.g., Hoyer *et al.*, 2022). Both ridges are oblique to the fracture zones and transform faults, which reflect the direction of seafloor spreading and, therefore, the movements of the tectonic plates in the area. Thus, seafloor spreading and hotspot magmatism are difficult to reconcile with the oblique strike of the ridges.”.
Added “Finally, ongoing seismic reflection mapping off the Faroe Islands and southeastern Greenland and within the GIFR suggest that basement-seated, late Paleoproterozoic thrust systems of the Laxfordian Orogen and Ammassalik Belt extend to Iceland (Koehl et al., 2024, 2025). This most recent work clearly suggests that the GIFR consists dominantly of continental crust and that breakup may not yet have occurred in Iceland despite the several km thick cap of lavas.” at the end of the third paragraph of the “The plume model” section and “and of the GIFR as thickened oceanic crust (e.g., White & McKenzie, 1995)” and “near the Mozambique Ridge” in the fourth paragraph. Rewrote the end of the second paragraph into “but previous studies could not explain the anomalously thick character of the crust there” and the fifth paragraph into “Geophysical evidence unambiguously suggests that, although mantle plumes may very well have produced thick lava flow caps, they are unlikely to have formed thickened oceanic crust at the GIFR, Mozambique and Madagascar ridges, and Del Cano Rise ( Foulger *et al.*, 2003; Foulger *et al.*, 2020a, Foulger *et al.*, 2020b; Geoffroy

*et al.*, 2022a; Ryzhova *et al.*, 2022; Sato *et al.*, 2022). A genetic link between igneous rocks at the Mozambique and Madagascar ridges and those of the Karoo–Vestfjella province is not precluded by our model since the (plume-related?) magma intruded continental crusts affected by the same orogenic events (e.g., East African–Antarctic Orogen; Figure 5). Nevertheless, certain issues need to be further studied, e.g., tracking old orogenic structures into these areas of anomalously thick offshore crust on seismic reflection data." and the last part of the sixth paragraph's last sentence into "areas where thickened oceanic crust was proposed".

Comment 17: Testing the Existence of tentative paleo transforms: The authors say that the OB theory can predict whether a paleo transform is valid or not. They are not clear how exactly, but apparently make the judgment whether or not the TF parallels orogenic trends. I don't disagree entirely, but the authors have not demonstrated that all TF must be dictated by continental orogenic trends. Comparison with plate reconstructions seems a fruitful method.
Response: After having himself been involved in a research group performing full plate reconstructions, the main authors of the present manuscript argue that most paleo-transform faults invoked in reconstructions are generally postulated on very weak grounds and mostly used to accommodate flaws in relative plate movements, which are not yet possible to explain yet (e.g., several paleo-transform faults between Laurentia, Baltica, and Gondwana at 500–430 Ma in Domeier, 2016). Plate reconstructions are therefore not a good place to start, not to forget that plate reconstructions are models partly based on data rather than data.
The authors of the present manuscript are uncertain as to what the reviewer means with "make the judgment whether or not the TF parallels orogenic trends". The authors of the present manuscript simply use the available information at the targeted paleo-transform faults, the De Geer Zone and Wegener Fault, which is that orogenic trends in the Fram Strait and Nares Strait strike oblique to the bathymetry of the straits. In the Fram Strait, the Timanian Orogen and related structures strike WNW–ESE whereas the main bathymetric escarpment and the De Geer Zone trend NNW–SSE (see Figure 4 in present manuscript). In the Nares Strait, Eurekan thrust systems strike ENE–WSW, whereas the Nares Strait and correlated Wegener Fault strike NNE–SSW. The main orogenic grain in these two regions is thus oblique to the postulated paleo-transform faults, both of which are now known to be erroneous (e.g., Oakey and Damaske, 2006; Rasmussen and Dawes, 2011; Koehl, 2024). The present manuscript simply elaborates on the fact that using Orogenic Bridge Theory as a framework (i.e., that transform faults form exclusively along inherited, rift-orthogonal orogens) in these two instances would have hinted at the low probability of a NNW–SSE-striking paleo-transform fault in the Fram Strait and NNE––SSW paleo-transform fault in the Nares Strait. The authors of the present manuscript concede that this could be better explained in the manuscript. Note that these two examples illustrate once again that topographic/bathymetric data cannot be used as standalone approaches when mapping fault zones.
Regarding the fact that the authors of the present manuscript have not yet demonstrated that every single transform faults formed along inherited, rift-orthogonal orogenic structures, this is simply not feasible and will require further work by many teams of scientists over the next few years or decade(s?). This is why the present work proposes a new theory rather than a new ground truth. Nevertheless, the authors of the manuscript

concede that they should also include additional examples in order to give a more convincing foundation for Orogenic Bridge Theory.
Changes: Added an additional paragraph at the end of the “De Geer Zone” sub-section: “The postulated De Geer Zone strikes NNW–SSE (du Toit, 1937; Faleide *et al.*, 1993; Faleide *et al.*, 2008; Harland, 1961; Harland, 1967; Harland, 1969; Horsfield & Maton, 1970; Piepjohn *et al.*, 2016; Wegmann, 1948), i.e., oblique to the WNW–ESE-striking Timanian Orogen and related thrust systems in Svalbard, the Barents Sea, and the Fram Strait (Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl, 2024 awaiting peer review; Koehl & Mottram, 2024). Regardless of the numerous arguments raised in Koehl (2024 awaiting peer review), based on Orogenic Bridge Theory’s global correlation of major transform faults with inherited rift-orthogonal orogens on adjacent margins, the De Geer Zone is unlikely to have accommodated transform movements.” and rewrote the last paragraph of the “Wegener Fault” sub-section into “Structural trends of the Eurekan Orogen (and, more speculatively, of the Ellesmerian Orogen) in Arctic Canada and northern Greenland strike ENE–WSW ( Piepjohn *et al.*, 2016; Saalmann *et al.*, 2005), i.e., oblique to the postulated Wegener Fault ( Taylor, 1910). The OrBiT suggests that since the Wegener Fault does not parallel any known rift-orthogonal orogens in nearby areas ( Figure 4), it is unlikely to have accommodated any transform movements. Noteworthy, the Wegener Fault does not parallel the other transform faults in the Labrador Sea and Baffin Bay either (e.g., Ungava Fault Zone; Figure 4). In addition, the absence of any offset of any kind of the bedrock units and magmatic intrusions across the Nares Strait ( Dawes, 2008; Hansen *et al.*, 2011; Oakey & Damaske, 2006; Oakey & Stephensen, 2008; Rasmussen & Dawes, 2011) suggests that the Wegener Fault does not exist and that the negative topography characterizing the Nares Strait may not have been created by a fault. The OrBiT can therefore be used to (1) predict the orientation of future transform and paleo-transform faults, and (2) test the plausibility of existing models and transform fault hypotheses.”. Also added “i.e., that the De Geer Zone can anyways not have accommodated more than 200 km displacement” in the second paragraph of the “De Geer Zone” sub-section.
Added a new paragraph about the East African Orogen and its relationship with the Aqaba–Dead-Sea–Levant transform fault zone and proto transform faults in the Red Sea at the end of the “East African–Antarctica orogenic bridge” sub-section: “In the northern part of the East African Orogen, the Red Sea rift presents some peculiar relationships with preexisting sutures and shear zones in the Arabian–Nubian Shield. There, N–S-striking Neoproterozoic shear zones, such as the Barka (–Adobha) and (Onib–) Hamisana shear zones ( Abdelsalam, 2010; Collins *et al.*, 2021; Johnson & Woldehaimanot, 2003; Stern & Kröner, 1993), coincide with zones of high seismicity and minor steps, bends/kinks, and narrowing of the Red Sea rift, which were interpreted as potential (proto) transform faults ( Bosworth *et al.*, 2005; Dixon *et al.*, 1987; Molnar *et al.*, 2020). N–S-striking, late Neoproterozoic shear zones also parallel the Aqaba–Dead-Sea–Levant fault zone (Molnar *et al.*, 2020), some of which were reactivated in the order of km to tens of km ( Bosworth *et al.*, 2005). Conversely, NW–SE-striking late Neoproterozoic shear zones, e.g., Rehba and Tabalah–Tarj shear zones ( Bosworth *et al.*, 2005; Johnson & Woldehaimanot, 2003) and Najd fault system ( Moore, 1979; Stern, 1985; Hamimi *et al.*, 2021), strike parallel to the segmented Rea Sea spreading center, thus suggesting opening of the rift along preexisting late Neoproterozoic zones of weakness in the crust (rift-parallel endmember of orogenic bridge theory).”.
Also added new sub-sections about the Charlie Gibbs fault zone and the controlling

Appalachian–Caledonian orogenic bridge and the Romanche fault zone and Sergipano–Central African orogenic bridge.

Comment 18: The authors make claims that this paper is a major revision of plate tectonics and that it confirms the old land bridge hypothesis for fauna crossing the oceans. By the way, after the introduction, the land bridge is hypothesis is not addressed again and certainly unsupported by the paper discussion. The OB idea is called a "theory" rather than a hypothesis, as if it is a major cornerstone for understanding plate tectonics. I think these claims are bombastic and set a poor tone for the manuscript. As stated above, the idea of major offsets being inherited from continents is not new. The idea that a rift will be deflected by a zone of thick crust with oblique fabric is not new. The idea that this paper forces a major rethinking of plate tectonics is over the top.
Response: Partly disagreed. The authors of the present manuscript do not claim that Land Bridge Theory is true and that the continents are fixed. Orogenic bridges, on the contrary, deform together with adjacent plate segments. This was not clearly explained in the manuscript.
The authors of the present manuscript concede to the reviewer that "the idea of major offsets being inherited from continents is not new" and that "the idea that a rift will be deflected by a zone of thick crust with oblique fabric is not new" as also clearly shown in Prof. Jolivet's comment 7 (reviewer 2). However, the present manuscript is the first attempt at attempting a global systematic correlation of all major transform faults with matching rift-orthogonal orogens on adjacent margins and at proposing for the first time a mechanism (orogenic bridges) reconciling the prolonged connection between some of the continents suggested by Land Bridge Theory and continent mobility suggested by Continent Drift Theory and plate tectonics and anomalously thick crust offshore. This is undeniably a major update of modern plate tectonics and will lead to major changes in the way the geoscience community understands plate and planetary tectonics.
Changes: Changed "the" into "part of an" in the abstract. Added "idea of prolonged connection between some of the continents suggested by" in the last paragraph of the "Major issues with plate tectonics" section. Also split the second paragraph in the "Orogenic bridge theory" section into three, adding one extra paragraph, and made significant changes to this section overall.

Comment 19: Some examples: p.5, paragraph 1: This relationship has received little attention despite the potential ground breaking implications that it may have.
Response: Indeed, after an extensive two-year literature search on the topic, the main author of the present manuscript has not yet found a manuscript identifying or discussing the intriguing, apparently global correlation of all major transform faults on Earth with matching rift-orthogonal orogens on adjacent continental margins. Should the reviewer be aware of any such studies, the authors of the present manuscript would gladly appreciate any input on the topic. The authors of the present manuscript nevertheless concede that more details could be added to the targeted paragraph as also suggested by Prof. Jolivet (reviewer 2).
Changes: See response to comment 18.

Comment 20: Minor points: p. 4, last paragraph. Major transform faults are defined as those having an offset of a few km or more. That is most transforms. I thought this must be a

typo, but the same appears elsewhere. Maybe >100 km
Response: Agreed. The authors of the present manuscript meant “a few tens of km”.
Changes: Added “tens of” in the first paragraph of the “Orogenic bridge theory section” and later on in the same section.

Comment 21: p.8, paragraph 7: “Other orogens worldwide show similar 90° bends (e.g., Verkhoyansk Orogen in northeastern Russia; Figure 1).” Significance of 90° bends is not explained.
Response: The significance of the 90° is not known for certain and is not the focus of the present manuscript. Thus far, it is not known why the Caledonian Orogen bends almost 90° in the southern Barents Sea. This bend coincides with the transition to the Timanian Orogen. Knowing that Timanian thrust systems in the Fram Strait are (or were until very recently) continuous between Svalbard and Greenland (Koehl, 2020, 2024; Koehl et al., 2021, 2022, 2023; Koehl and Mottram, 2024), a potential impact of the Timanian Orogen on Caledonian deformation must have been a local reorientation of Caledonian structures. Caledonian contraction did rework Timanian thrust systems into dome-shaped anticlines and synclines (Koehl et al., 2022, 2023), but the pronounced obliquity of the Timanian Orogen may have prevented the Caledonian Orogen to develop in a rectilinear fashion and to cut through thickened orogenic Timanian crust in the Barents Sea and Svalbard. As a result, the Caledonian structures in Svalbard and the Barents Sea may have developed obliquely to their counterparts in mid-Norway and the UK.
Changes: None.

Comment 22: p. 9, paragraph 6: “Hence, they strike perpendicular to the active (East Scotia Ridge, American–Antarctic Ridge, and South Atlantic mid-ocean ridge) and paleo-mid-ocean ridges in the area (West Scotia Ridge and Phoenix Ridge; Figure 1 and 4.” These figures do not demonstrate this relationship and one would not expect different plate boundaries to have the same orientation.
Response: Agreed, the sentence is confusing. Nevertheless, such a relationship is to be expected should the mantle plume model be true. Extension is still trying to thin and rupture the crust in the southern Atlantic/Antarctic region and has attempted so repeatedly and in various places as suggested by the extinct Phoenix and West Scotia ridges, and the ultra-slow American–Antarctic Ridge and the more recent East Scotia Ridge. While it is true that for example the overall trend of the American–Antarctic Ridge is NE–SW, it is mostly due to the repeated lateral offset by transform faults, and the mid-ocean ridge segments in between the transform faults actually dominantly strike N–S. Again, the reviewer is reminded that the basemap of the figure in from GoogleEarth, which includes the curvature of the Earth’s surface. Hence, orientations between some of the features described may vary a little on the figure but they are generally parallel (see also new Figure 5b). See also response to comment 15.
Changes: Replaced “they” by “transform faults there all” and added “transform faults” in the second paragraph in the “Cape–Falkland orogenic bridge” sub-section. See also response to comment 15.

Comment 23: p. 10, paragraph 1: “This contractional belt may therefore also have helped control the formation of major transform faults in the area, though its geometry may have been controlled by the preexisting late Paleozoic fold-and-thrust belts.” Connections

unclear.
Response: It is clear from the geological record and previous studies that the southern part of Patagonia has been through at least two major episodes of tectonic contraction, including the Sierra-de-la-Ventana fold-and-thrust belt in the Permian–earliest Triassic (Rapela et al., 2003; Castillo et al., 2017), and the Tierra del Fuego fold-and-thrust belt in the Cenozoic (Klepeis, 1994; Fuentes, 2023). It is probable that the former controlled the geometry of the latter. Thus, if one is to discuss whether the Cenozoic Tierra del Fuego belt controlled the formation of local transform faults, one cannot but suggest that the causal relationship is most likely to be traced to the older orogen, i.e., the Permian–earliest Triassic Cape Fold Belt. The authors of the present manuscript concede that this could have been better phrased.
Changes: Replaced "This contractional belt" by "The Tierra del Fuego fold-and-thrust belt" and rewrote the last sentence of the paragraph into "The Tierra del Fuego fold-and-thrust belt may therefore also have helped control the formation of major transform faults in the area. However, its geometry may have been controlled by the preexisting late Paleozoic fold-and-thrust belt (Cape Fold Belt) in the first place, so although Cenozoic structures may very well have controlled the formation of the local transform faults, the cause of this inherited E–W strike is more likely to be found in the late Paleozoic Cape Fold Belt".

Comment 24: p. 11, last paragraph: This paragraph writes about these ill-defined plate boundaries (Lwandle plate from DeMets et al. 2010) and uses this to infer an OB? The rationale is not explained.
Response: Agreed. Also the authors of the present manuscript concede that the term "Lwandle plate" should at least be mentioned in the present manuscript. See also response to comment 9.
Changes: Added "Notably, the analysis of seismic reflection data in Klimke *et al.* (2018) clearly shows low-angle thrusts in the westernmost part of the Davie Ridge (the area labelled "compressed sediments" in their figure 6). These contractional structures may very well represent the offshore continuation of thrust systems of the East African–Antarctica Orogen between Madagascar and eastern Africa." in the previous paragraph. Also added "and possibly the Lwandle plate (DeMets *et al.*, 2010)" in the targeted paragraph and reference to DeMets et al. (2010) to the reference list. See also response to comment 9 for additional changes.

Comment 25: p. 11, paragraph 2: The authors write about large offset transforms having "oscillatory spreading", which I think means that the transform can jump from one side to another of a block within the transform domain. The conclusion is then that these must be continental. Why? No rationale is given.
Response: Agreed. See also response to comment 11.
Changes: Added "In such a scenario, transform-parallel ribbons of continental crust become detached from adjacent continental margins and are entrained along major transform faults due to the occurrence of transform-parallel, preexisting zones of the weakness in the continental crust, such as major (mylonitic) thrust systems. These preexisting structures would facilitate rupture and dislocation of the crust along an axis parallel to the proto-transform faults and allow the inclusion and entrainment of such transform-parallel continental ribbons into oceanic crust during seafloor spreading." at the end of the paragraph and designed in a new figure to illustrate the entrainment of transform-parallel

ribbons of continental crust along transform faults and the oscillatory behavior of related transform faults. See also response to comment 11.

Comment 26: p. 13, paragraph 3: “Given the control of rift orthogonal orogens on the formation of major transform faults, a relationship between at least two orogens and mid-ocean-ridge-related triple junctions is unavoidable.” Rationale is not given. “unavoidable” is probably hyperbole.
Response: Disagreed. It is simple logic. If RRR triple junctions are crosscut by two trends of transform faults (T-like RRR triple junctions), the formation of which was controlled by two discrete orogens, then it is only logical that RRR-triple junctions form at the intersection of two oblique orogens. While the authors of the present manuscript have only touched upon the Bouvet and Rodrigues triple junctions in the present manuscript, this principle may be applied to (1) all the other present-day RRR triple junctions, (2) paleo RRR triple junctions, and (3) failed RRR triple junctions.
(1) The Pacific–Nazca–Antarctica triple junction’s mid-ocean ridge segments are crosscut by transform faults that parallel the Sierra de la Ventana Fold-and-Thrust Belt and Cape Fold Belt in South America (von Gosen et al., 1990; Limarino et al., 1999; Rapela et al., 2003; Lopez-Gamundi, 2006; Castillo et al., 2017; Stanca et al., 2022; Grillo Vidal et al., 2024) and the late Paleozoic (Variscan?) fold belt of Indonesia and the Antarctic Peninsula (Graham Land) in Antarctica (Page, 1976; Brown et al., 1979; Davies, 1980; Pigram and Davies, 1987; Hill and Raza, 1999; Harahap, 2012). In this present instance, the mid-ocean ridge segments of the triple junction are crosscut by only one trend of transform faults, but the triple junction occurs near the intersection of the Permian Sierra de la Ventana Fold-and-Thrust Belt (von Gosen et al., 1990; Limarino et al., 1999; Rapela et al., 2003; Lopez-Gamundi, 2006; Castillo et al., 2017) and the Cambrian–Ordovician Pampean and Famatinian orogens (Rapela et al., 1998a, 1998b, 2001; Verdecchia et al., 2011; Ramos, 2018; Oriolo et al., 2021). This RRR triple junction therefore does not escape the proposed controlling relationship.
At the Galapagos triple junction, the transform faults crosscutting the E–W-striking mid-ocean ridge segment of the Galapagos are parallel to the Famatinian Orogen in Colombia and Ecuador (Garcia-Ramirez et al., 2017; Zuluaga et al., 2017; Ramos, 2018). The three major E–W-striking transform faults truncating the southern mid-ocean ridge are parallel to the bend in the late Cambrian–Ordovician Famatinian Orogen in Peru (Ramos, 2018). In the north, the E–W-striking transform faults are parallel to the Motagua Suture Zone in Honduras, Guatemala, and Mexico. The Motagua Suture Zone is a 400 km wide zone of contractional deformation including rocks metamorphosed up to blueschist and eclogite facies (Burke et al., 1988; Martens et al., 2007). Metamorphism occurred in the Cretaceous (starting in the earliest Cretaceous), but up to Grenvillian ages (ca. 1.1–1.0 Ga) were obtained, including early–mid Paleozoic metamorphic ages for E–W-striking igneous rock complexes (e.g., Chuacus complex) and shear zones, thus suggesting they may have been part of the Taconic–Acadian orogen (Martens et al., 2007; Brueckner et al., 2009; Ratschbacher et al., 2009).
(2) Regarding paleo RRR triple junctions, a key example is the junction of the present-day Reykjanes Ridge, Mid-Atlantic Ridge, and paleo Labrador Ridge at the Charlie Gibbs Fault Zone. There, the E–W-striking Appalachian–Caledonian Orogen between Newfoundland and Great Britain (Chew and Stillman, 2009; van Stall et al., 2009; Yang and Welford, 2023) intersects the N–S-striking Variscan Orogen between Newfoundland and Morroco–Iberia (Lefort et al., 1993; Franke, 2006; Pastor-Galan et al., 2020).

(3) Examples of failed RRR triple junctions are the Hammerfest and Bjørnøya basins in the southwestern Barents Sea and the North Sea rift. The Hammerfest and Bjørnøya basins are located at the intersection of the NE–SW-striking Caledonian and WNW–ESE-striking Timanian orogens (Olovyanishnikov et al., 2000; Roberts, 2003). Both basins parallel NE–SW-striking structures of the northernmost tip of the Caledonian Orogen, which partly consists of reworked Timanian thrust systems locally folded into a NE–SW direction (Koehl and Stokmo, 2024).
*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
*Caption: Bouguer anomaly map in the Barents Sea. Modified after figure 5a in Koehl et al. (2022). The map show the interaction of NE–SW- to N–S-striking Caledonian (dashed black) and Timanian (dashed yellow) structural trends in the Barents Sea. The Hammerfest Basin (HB) and Bjørnøya Basin (BB) in the west may represent failed attempts of the rift to propagate along preexisting Caledonian structures, which both basins parallel.*
The North Sea rift developed at the intersection of the locally N–S- to NNE–SSW-striking Caledonian Orogen and WNW–ESE-striking Laxfordian–Svecofennian Orogen. There are ample evidence from numerous onshore–offshore studies that the NNE–SSW-striking northern arm of the North Sea rift formed along reactivated Caledonian shear zones (e.g., Osmundsen and Andresen, 1994; Fazlikhani et al., 2017; Fossen et al., 2016, 2024). The two WNW–ESE-striking arms of the North Sea rift likely formed along the Laxfordian–Svecofennian Orogen, which includes WNW–ESE-striking Laxfordian shear zones onshore northern Scotland (Coward and Park., 1987) and thrust systems around the Faroe Islands and in the Iceland–Faroe Ridge (Koehl et al., 2024), and Svecofennian shear zones onshore southern Sweden (Saintot et al., 2011) and possibly the Sorgenfrei–Tornquist Zone (STZ; Ponikowska et al., 2024). There is notable evidence that rift-related basins in the North Sea formed along reactivated segments of the Sorgenfrei–Tornquist Zone (e.g., Farsund Basin; Phillips et al., 2018) and that these are related to WNW–ESE-striking late Paleoproterozoic thrust systems off the Faroe Islands and onshore northern Scotland.
*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
*Caption: Geological map of the North Sea rift from (Koehl et al., 2024) showing that the rift developed at the intersection of the NE–SW-striking Caledonian Orogen (orange lines) and WNW–ESE-striking Laxfordian–Svecofennian Orogen, which includes the Sorgenfrei–Tornquist Zone (STZ; light green WNW–ESE-striking lines) and similarly striking thrust systems around the Faroe Islands and northern Scotland (dark green lines).*
The authors of the present manuscript concede that at least some of these items need to be included to the present manuscript to add weight to the newly presented theory.
Changes: Rewrote the first paragraph of the “Implications for RRR triple junctions” section into “On restoration prior to breakup, all triple junctions linking three mid-ocean ridge segments (RRR), including paleo and failed triple junctions, appear to originate at the intersection of at least two major orogens that are oblique to one another. Most if not all RRR (may they be active, paleo, or failed) triple junctions display a T-like geometry, that is two mid-ocean ridge segments parallel to one another and a third segment oblique to the other two. As such, of the three mid-ocean ridge segments involved at RRR triple junctions, two are crosscut by transform faults with the same strike. Given the control of rift-orthogonal orogens on the formation of major transform faults, a relationship between at least two orogens and RRR triple junctions is logical. OrBiT therefore predicts that RRR triple

junctions form at the intersection of two preexisting orogens oblique to one another. To illustrate this, we explore the situation at the four currently active RRR triple junctions, the Bouvet, Rodrigues, Galapagos, and Pacific–Nazca–Antarctica triple junctions, as well as at a paleo RRR triple junction (Labrador–Reykjanes–Mid-Atlantic) and two failed RRR triple junctions (western Barents Sea and North Sea rift; Figure 1, Figure 5a–b, and Figure 5).".
Also added five new sub-sections as follows: "

***Galapagos triple junction***

At the Galapagos triple junction, the transform faults crosscutting the E–W-striking Cocos–Nazca Rift (i.e., Galapagos spreading center) are parallel to the Famatinian Orogen in Colombia and Ecuador (Garcia-Ramirez et al., 2017; Zuluaga et al., 2017; Ramos, 2018). The three major E–W-striking transform faults truncating the southern mid-ocean ridge segment are parallel to the bend in the late Cambrian–Ordovician Famatinian Orogen in Peru (Ramos, 2018). In the north, the E–W-striking transform faults crosscutting the East Pacific Rise are parallel to E–W-striking thrusts and shear zones and ophiolites (El Tambor Complex) of the Motagua Suture Zone in Honduras, Guatemala, and Mexico, a c. 400 km wide zone of contractional deformation including rocks metamorphosed up to blueschist and eclogite facies (Burke et al., 1988; Tsujimori et al., 2006; Martens et al., 2007; Ratschbacher et al., 2009; Brueckner et al., 2009). Metamorphism started in the earliest Cretaceous, but up to Grenvillian ages (ca. 1.1–1.0 Ga) were obtained. These include early–mid Paleozoic metamorphic ages for E–W-striking igneous complexes (e.g., Chuacus complex) and shear zones suggesting that the Motagua Suture Zone was part of the Taconic–Acadian orogen (Martens et al., 2007; Brueckner et al., 2009; Ratschbacher et al., 2009). Thus, upon reconstruction prior to seafloor spreading at the Cocos–Nazca Rift and in the Caribbean Plate, it is possible that the Galapagos triple junction initiated at the intersection of early–mid Paleozoic (Taconic–Acadian and Famatinian) or older (latest Mesoproterozoic–earliest Neoproterozoic Grenvillian and Famatinian) orogens.

***Pacific–Nazca–Antarctica triple junction***

The mid-ocean ridge segments merging at the Pacific–Nazca–Antarctica triple junction are crosscut by transform faults that parallel the Cape Fold Belt and Sierra de la Ventana Fold-and-Thrust Belt in South America (von Gosen et al., 1990; Limarino et al., 1999; Rapela et al., 2003; Lopez-Gamundi, 2006; Castillo et al., 2017) and the late Paleozoic (Variscan?) fold belt of Indonesia and the Antarctic Peninsula (Graham Land) in Antarctica (Page, 1976; Brown et al., 1979; Davies, 1980; Pigram and Davies, 1987; Hill and Raza, 1999; Harahap, 2012). In Papua (Indonesia) and Papua New Guinea, Silurian–Devonian rocks of the Omung Group were tightly folded and metamorphosed to greenschist facies prior to the deposition of late Paleozoic–Mesozoic sedimentary rocks and intrusion by Mesozoic igneous rocks (Page, 1976; Brown et al., 1979; Davies, 1980; Pigram and Davies, 1987; Hill and Raza, 1999). In this present instance, the mid-ocean ridge segments of the triple junction are crosscut by only one trend of transform faults. Nevertheless, the triple junction occurs near the intersection of the E–W-striking, Permian Sierra de la Ventana Fold-and-Thrust Belt (von Gosen et al., 1990; Limarino et al., 1999; Rapela et al., 2003; Lopez-Gamundi, 2006; Castillo et al., 2017; Stanca et al., 2022; Grillo Vidal et al., 2024) and the N–S-striking, Cambrian–Ordovician Pampean and Famatinian orogens (Rapela et al., 1998a, 1998b, 2001; Verdecchia et al., 2011; Ramos, 2018; Oriolo et al., 2021). This RRR triple junction thus does not make exception to the proposed controlling relationship and may have initiated at the intersection of Permian and Cambrian–Ordovician orogens.

***Labrador–Reykjanes–Mid-Atlantic paleo triple junction***

The present-day Reykjanes Ridge, Mid-Atlantic Ridge, and paleo Labrador Ridge join at the Charlie Gibbs Fault Zone ( Figure 1). There, the E–W-striking Appalachian–Caledonian Orogen between Newfoundland and Great Britain (Chew and Stillman, 2009; van Stall et al., 2009; Yang and Welford, 2023) intersects the N–S-striking Variscan Orogen between Newfoundland and Morroco–Iberia (Lefort et al., 1993; Franke, 2006; Pastor-Galan et al., 2020).

A possible scenario to be further explored for this paleo triple junction is that upon meeting the thickened orogenic crust of the WNW–ESE-striking, late Paleoproterozoic Laxfordian–Ammassalik Orogen towards Iceland, the rift tried to incise the continental crust along the Charlie Gibbs fault zone and then proceeded to open the Labrador Sea. There, the orogen incised through the NE–SW-striking, late Paleoproterozoic Makkovikian–Ketilidian Orogen (Garde et al., 2002; Hinchey, 2021) separating the North Atlantic Craton in western Greenland from the Nain Province in northeastern Canada. In the Davis Strait, rifting met yet another barrier of orogenically thickened crust, the N–S- to E–W-striking Nagssugtoqidian–Torngat orogen (van Gool et al., 2002a, 2002b, 2005; Figure 4), and stepped into Baffin Bay along the Ungava Fault Zone (e.g., Oakey and Chalmers, 2012; Dafoe et al., 2022). Eventually, rifting died out in the Labrador Sea and Baffin Bay and rifting proceeded into the northeastern Atlantic along the Reykjanes Ridge ( Figure 4).

***Western Barents Sea failed triple junctions***

Examples of failed RRR triple junctions include the Hammerfest and Bjørnøya basins in the southwestern Barents Sea ( Figure 13). These basins are located at the intersection of the NE–SW-striking Caledonian and WNW–ESE-striking Timanian orogens (Olovyanishnikov et al., 2000; Roberts, 2003; Figure 13). Both basins and respective boundary faults, e.g., Troms–Finnmark Fault Complex and Bjørnøyrenna Fault Complex, formed along Timanian thrusts and folds reworked into NE–SW-striking structures during the Caledonian Orogeny (Gudlaugsson et al., 1998; Gernigon et al., 2014; Koehl et al., 2018; Koehl et al., 2023a; Koehl and Stokmo, 2024). This suggests that rifting attempted at thinning the crust along preexisting Caledonian (or reoriented Timanian) thrusts (Gernigon et al., 2014; Koehl et al., 2018; Koehl and Stokmo, 2024), but eventually failed and merged with the Gakkel Ridge in the Arctic Ocean through delayed rifting in the Fram Strait (Koehl, 2020; Koehl and Mottram, 2024; Figure 4).

*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*

Figure 13. Bouguer anomaly map in the Barents Sea.

The map shows the interaction of NE–SW- to N–S-striking Caledonian (dashed black) and Timanian (dashed yellow) structural trends in the Barents Sea. Notice how the Hammerfest Basin (HB) and Bjørnøya Basin (BB) in the west parallel preexisting Caledonian grain. Modified after Koehl et al. (2022a).

***North Sea failed triple junction***

The North Sea rift displays a triple-junction-like geometry in that it consists of three failed rift arms, including two WNW–ESE-striking arms extending from Moray Firth onshore the northern UK to Denmark and including the Sorgenfrei–Tornquist Zone and a third N–S to NNE–SSW-striking arm between the Shetland Islands and southern Norway ( Figure 4). The N–S- to NNE–SSW-striking arm clearly developed along inherited Caledonian structures as supported by numerous onshore field and offshore seismic reflection studies (e.g., Fazlikhani et al., 2017; Fossen et al., 2016; Fossen et al., 2024; Osmundsen and Andresen, 1994; Serck et al., 2022; Figure 4).

In contrast, the two WNW–ESE-striking arms of the North Sea rift formed along the WNW–ESE-striking Laxfordian–Svecofennian Orogen. The latter includes WNW–ESE-striking Laxfordian shear zones onshore northern Scotland (Coward and Park., 1987) and thrust systems around the Faroe Islands and in the Iceland–Faroe Ridge (Koehl et al., 2024), and Svecofennian shear zones onshore southern Sweden (Saintot et al., 2011) and possibly the Sorgenfrei–Tornquist Zone (STZ; Ponikowska et al., 2024). There is notable evidence that rift-related basins in the North Sea formed along reactivated segments of the Sorgenfrei–Tornquist Zone (e.g., Farsund Basin; Phillips et al., 2018) and that these are related to WNW–ESE-striking late Paleoproterozoic thrust systems off the Faroe Islands and onshore northern Scotland (Koehl et al., 2024). Thus, the North Sea rift seems to have been completely controlled by preexisting orogens."

Comment 27: p. 13 paragraph 3: "…the OrBiT predicts at least two discrete strikes of transform faults at any RRR triple junction." I don't know why. Rationale not given.
Response: See response to comment 26.
Changes: See response to comment 26.

Comment 28: p. 13, paragraph 6: "East of the Bouvet Triple Junction, the Atlantic–Indian Ridge is truncated by NE–SW-to N–S-striking transform faults, which include the Andrew Bain Fault Zone (e.g., Peyve et al., 2007; Sclater et al., 2005) and other minor faults such as the Du Toit, Moshes, and Bouvet fault zones (Figure 5; Ligi et al., 1999)." According to the provided figure (and a check with Google Earth), none of these faults is oriented N-S.
Response: Fair enough. They strike NE–SW to somewhere between NNE–SSW and N–S.
Changes: Changed "N–S" into "NNE–SSW".

Comment 29: p. 13, paragraph 7: "Major transform faults offsetting the southern segment of the Atlantic midocean ridge and the American–Antarctic Ridge strike parallel to one another, and both groups of transform faults parallel the late Paleozoic, E–W-striking Sierra de la Ventana Fold-and-Thrust Belt…" I believe this refers to the southern Mid-Atlantic Ridge (Atlantic mid-ocean ridge). These transforms do not appear parallel in the figure 4 and the figure does not clearly show this fold belt. The transforms on different plate boundaries should not be parallel.
Response: Disagreed. See response to comments 15 and 22.
Changes: See response to comments 15 and 22.

Comment 30: p. 15, paragraph 5: "typical 10-km thick oceanic crust". Oceanic crust is typically much thinner. Christensen, Rev. Geophys., 2019 gives an average of slightly more than 6 km.
Response: Agreed. The authors of the present manuscript thank the reviewer for the relevant reference and information.
Changes: Rewrote the third sentence of the targeted paragraph into "First, the thickness of the crust varies between 25 and 40 km ( Darbyshire *et al.*, 1998; Foulger *et al.*, 2003), which is much thicker than typical 6-km-thick oceanic crust ( Christeson *et al.*, 2019)." and added Christeson et al. (2019) to the reference list.

Comment 31: p. 15, paragraph 5: The authors repeat a statement by Foulger in her 2020 paper about the Greenland-Iceland-Faroe Ridge to say that polarity reversal magnetic

anomalies do not occur in the ridge and therefore it is continental in nature. I think that is an overstatement. The anomalies are distorted, but can be traced through; although, it is true that because of this distortion, analysts trace magnetic anomalies from the sides and connect them over the GIFR.
Response: Partly disagreed. The reviewer concedes that the anomalies are distorted. The authors of the present manuscript however argue that sub-linear magnetic anomalies within the Greenland–Iceland–Faroe Ridge do not conform to the typical character of seafloor-spreading-related (see first figure below). They rather resemble pseudo-linear outer anomalies, which were demonstrated by Geoffroy et al., 2022a, 2022b) to correspond to linear intrusions in thinned continental crust (see second figure below). In addition, their locally anastomosing and stepping character (third figure below) suggests that recent rift-related intrusions are only a component of the magnetic fabrics at the Greenland–Iceland–Faroe Ridge and that other magnetic bodies (e.g., magnetic metasedimentary beds and/or older intrusions in continental crust) exist. The authors of the present manuscript concede that this should be better phrased in the manuscript.

*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
*Caption: Uninterpreted (up) and interpreted (down) magnetic anomaly map in the northeastern Atlantic. The data shows that the magnetic anomalies at the Greenland–Iceland–Faroe Ridge curve, and are disrupted (i.e., poor continuity) and broad (dashed white lines), which contrasts with typical seafloor-spreading anomalies that are continuous for hundreds to thousands km. Data from Gaina et al. (2017).*
*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
*Caption: Magnetic data off the coast of Namibia showing the new continent–ocean boundary (dashed black line) based on high-resolution deep seismic reflection data and the occurrence of pseudo-linear magnetic anomalies in continental crust (white arrows in the right hand-side inset). From Geoffroy et al. (2022b).*

*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248221.17238_Jean-Baptiste_Koehl_to_William.pdf*
*Caption: Uninterpreted (up) and interpreted (down) zoom in magnetic data showing the broader, locally anastomosing and/or stepping character of magnetic anomalies at the Greenland–Iceland–Faroe Ridge (white lines; not dashed). Data from Gaina et al. (2017).*
Changes: Rewrote the fourth argument in the targeted paragraph into “Fourth, magnetic anomalies in the GIFR do not conform to the typical character of seafloor-spreading-related ( Foulger *et al.*, 2020a; Gaina *et al.*, 2017). Instead of showing narrow, continuous, linear anomalies, the GIFR consists of broader, distorted, curving and disrupted, anomalies ( Foulger *et al.*, 2020a; Gaina *et al.*, 2017), which rather resemble pseudo-linear disrupted anomalies correlated with intrusions in thinned continental crust off southeastern Greenland, the UK and the Faroe Islands, and Namibia ( Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b; Figure 14). Moreover, their locally anastomosing character, branching off and splaying into two or more anomalies (Figure 14), suggests that the magnetic fabrics at the GIFR are not only the product of Cenozoic rift-related intrusions, and that these may interact

with older magnetic fabrics (older intrusions and/or folded magnetic metasedimentary beds?; e.g., Koehl & Stokmo, 2024 their figures 11–14).". Also added a new figure showing the anastomosing and splaying character of magnetic anomalies at the Greenland–Iceland–Faroe Ridge.

Comment 32: p. 15, paragraph 6: "Geophysical evidence unambiguously suggests that mantle plumes are unlikely to have formed the thickened oceanic crust at the GIFR, Mozambique and Madagascar ridges, and Del Cano Rise." Foulger (2020) argues that the entire GIFR is continental. Although that paper is well-crafted and thought provoking, I don't think the case is unequivocal. The others are certainly not unequivocal as claimed.
Response: Partly agreed. The sentence should be rephrased.
Changes: Rewrote the targeted sentence into "Geophysical evidence unambiguously suggests that, although mantle plumes may very well have produced thick lava flow caps, they are unlikely to have formed thickened oceanic crust at the GIFR, Mozambique and Madagascar ridges, and Del Cano Rise ( Foulger *et al.*, 2003; Foulger *et al.*, 2020a, Foulger *et al.*, 2020b; Geoffroy *et al.*, 2022a; Ryzhova *et al.*, 2022; Sato *et al.*, 2022; Koehl *et al.*, 2024; Koehl *et al.*, 2025).".

Comment 33: p. 17, paragraph 2: "The OrBiT explains the variations in earthquake focal mechanisms in the area." Perhaps it does, but this is not explained.
Response: Agreed, the sentence needs further clarification.
Changes: Rewrote the targeted sentence into "OrBiT explains the variations in earthquake focal mechanisms in the area – normal in the Laptev Sea and N–S-striking segment of the Verkhoyansk Orogen where E–W extension occur along N–S-striking faults, and strike-slip at the E–W segment of the orogen, which is oriented parallel to the extension direction and, thus, can only accommodate strike-slip movements ( Cook *et al.*, 1986; Imaeva *et al.*, 2018; Imaeva *et al.*, 2019; Figure 15b).".

Comment 34: p. 19, paragraph 2: "...suggests that the dynamism of seafloor spreading at mid-ocean ridges and the extent of hybrid continental crust should be reexamined." What does dynamism mean? BTW, the next sentence is basically the same statement (repetitious).
Response: Disagreed. The first sentence states that the amount and extent of oceanic crust was overestimated, whereas the second sentence states that seafloor spreading was overestimated. Nonetheless, the authors of the present manuscript concede that the paragraph should be rewritten in a more comprehensive way.
Changes: The paragraph was rewritten into "The overestimation of the extent of oceanic crust on Earth, especially at orogenic bridges (e.g., Foulger *et al.*, 2003; Foulger *et al.*, 2020a; Foulger *et al.*, 2020b; Geoffroy *et al.*, 2022a) and magmatic passive margins (e.g., Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b; Koopmann *et al.*, 2014; Reeve *et al.*, 2021), suggests that the intensity and speed of seafloor spreading at mid-ocean ridges may have been overestimated in many paleogeographic reconstructions. Future reconstructions should therefore address this issue by including updated (extended) domains of continental (including hybrid) crust.".

Comment 35: p. 19, conclusions, point 6: "The orogenic bridge theory suggests less dynamism in paleo-plate tectonics than current models show." I have no idea what this means – and besides, this point was discussed in one sentence. This seems an odd

conclusion.
Response: Agreed.
Changes: Rewrote the sentence into “Orogenic bridge theory suggests that the extent of oceanic crust was overestimated and, thus, that the intensity, amount, and speed of seafloor spreading should be toned down in future paleogeographic reconstructions

***Competing Interests:*** No competing interests were disclosed.

Reviewer Report 14 September 2024

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**Samuel Rybar**
Comenius University, Bratislava, Slovakia

I read the paper by Jean-Baptiste P. Koehl and his co-authors with great interest, as it focuses on plate tectonics, one of the most important, if not the most important, foundational theories in Geology.
The author raises some intriguing points, but it's important to note that the idea that pre-existing geological structures (pre-existing anisotropy) influence or constrain the formation of younger structures is not novel. This concept has been recognized for some time.
Furthermore, the claim that plate tectonics as a theory requires a review is bold – thus extraordinary claims demand equally extraordinary evidence. While the "orogenic bridge" theory is well described in the paper, particularly in map view, it would require additional support, such as a new plate reconstruction numerical model, to provide more compelling evidence.
The author themselves frequently mentions issues with current plate reconstructions (e.g., in the Passive Margins and Rockall Plateau chapters). While these criticisms may be valid, presenting an improved reconstruction model would be essential to substantiate such claims.
One particular statement stood out to me: “Geophysical data may also be limited in extent and/or quality, especially in areas where seismic data are more challenging to acquire (e.g., onshore central Europe).” This is simply not accurate. There is a wealth of high-quality seismic data available in Central Europe, including many ultra-deep 2D lines and highly detailed 3D grids. Several examples come to mind, such as: Ref: 1,2,3,4.

The review is well-written, but it occasionally becomes dense with regional nomenclature, listing numerous place names and structure names. While I understand the need to support the theory, condensing and generalizing these references might help focus more on the key elements and mechanisms of the theory, this could improve readability.
Overall, before I can recommend the paper for indexing, I strongly encourage the authors to develop a new plate reconstruction numerical model.

You don't need to start from scratch; you can utilize existing platforms (e.g. GPleats, https://www.gplates.org/ - or any other). I understand there may not be enough time to do this on a global scale, but I suggest focusing on a region that best exemplifies your orogenic bridge theory. Even just a few well constrained time snapshots of such a model would be sufficient to illustrate the mechanisms behind your theory.
Wishing the authors, the best of luck.

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**Is the work clearly and accurately presented and does it cite the current literature?**
Partly

**Is the study design appropriate and does the work have academic merit?**
Yes

**Are sufficient details of methods and analysis provided to allow replication by others?**
Yes

**If applicable, is the statistical analysis and its interpretation appropriate?**
Not applicable

**Are all the source data underlying the results available to ensure full reproducibility?**
Yes

**Are the conclusions drawn adequately supported by the results?**
Yes

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Geologist

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

Author Response 20 Feb 2025

**Jean-Baptiste Koehl**

Dear Dr. Rybar, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

**Comments by the reviewer**
**Comment 1: The author raises some intriguing points, but it's important to note that the idea that pre-existing geological structures (pre-existing anisotropy) influence or constrain the formation of younger structures is not novel. This concept has been recognized for some time.**
Response: Agreed. Prof. Jolivet (reviewer 2) and Prof. Sager (reviewer 4) also raised this issue and brought to the attention of the authors of the present manuscript previous studies that should be cited in the present manuscript (e.g., Dunbar and Sawyer, 1989; Buiter and Torsvik, 2014).
Changes: Added “This relationship was previously noted by Buiter & Torsvik (2014) who suggested that the Agulhas–Falkland fault zone formed along an inherited suture zone between the Falkland Plateau and South Africa” in the third paragraph in the “The Cape–Falkland orogenic bridge” sub-section and replaced “This relationship” by “This relationship was remarked and investigated locally at a few margins only by a few studies ( Buiter & Torsvik, 2014; Peace *et al.*, 2018). However, the global pattern defined by transform faults and rift-orthogonal orogens” in the second paragraph of the “Orogenic bridge theory” section. Added a new paragraph at the end of the “Previous work” section: “Another relevant study is the modelling of the influence of preexisting zones of weakness in the crust and mantle on rifting ( Dunbar & Sawyer, 1989). While mantle weaknesses were suggested to explain the formation of “wet” rift with intense magmatism and narrow passive configurations, crustal weaknesses were associated to the formation of “dry” rifts and broad passive margins. Like Lundin & Doré (2005), this study attempted at relating zones of intense magmatism with preexisting structural fabrics.”. Also added a new paragraph at the end of the “Issues with mantle plumes” sub-section: “The wet” versus “dry” rift classification by Dunbar & Sawyer (1989) related the intensity of magmatism and width of the resulting rift with the existence of preexisting weaknesses in the crust and/or mantle. For example, preexisting mantle weaknesses would tend to form narrow “wet” rifts with intense magmatism (e.g., Iceland), whereas crustal weaknesses lead to the development of broad “dry” rifts (e.g., Iberia–Newfoundland). This work assumes that breakup has occurred at the Greenland–Iceland–Faroe Ridge, which is not (yet) the case ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, if the magma-rich Greenland–Iceland–Faroe Ridge is a through-going orogenic bridge where breakup has not yet occurred whereas breakup has occurred at magma-poor margins, e.g., in the Arctic Ocean (ultra-slow-spreading Gakkel Ridge), then it follows that intense magmatism and preexisting mantle weaknesses or plumes have no or little effect on breakup. Other factors, e.g., rift-parallel and rift-orthogonal orogens, must therefore come into play.”.

**Comment 2: Furthermore, the claim that plate tectonics as a theory requires a review is bold – thus extraordinary claims demand equally extraordinary evidence. While the**

**"orogenic bridge" theory is well described in the paper, particularly in map view, it would require additional support, such as a new plate reconstruction numerical model, to provide more compelling evidence. The author themselves frequently mentions issues with current plate reconstructions (e.g., in the Passive Margins and Rockall Plateau chapters). While these criticisms may be valid, presenting an improved reconstruction model would be essential to substantiate such claims.**
Response: Disagreed. Plate modelling simply cannot be considered as evidence supporting plate tectonics or Orogenic Bridge Theory since it only serves to illustrate potential relationships and builds on the actual geological and geophysical data. In other words, and to quote an experienced and established plate modeler the main author of the present manuscript has worked with, “plate modelling is like a video game” and models may be changed to accommodate future findings, including the ones presented in the present manuscript. In addition, such new reconstructions would be (at least for the last half Wilson Cycle) equal in most points to existing plate reconstructions (save minor corrections addressing the erroneous Wegener Fault and De Geer Zone; see discussion in the present manuscript). The authors of the present manuscript do, like most geoscientists, believe that the continents have moved away from one another in the past 300 Myr. What the authors of the present manuscript question is the nature of the crust in some critical areas, which they claim is continental, e.g., at the Greenland–Iceland–Faroe Ridge and various areas with anomalously thick crust offshore (e.g., Madagascar Ridge, Walvis Ridge, and Rio Grande Ridge; see new Figure 1). New reconstructions would therefore have a relatively limited impact (some continents located somewhat farther away from one another when Pangea was formed) but consume a large amount of time. A preliminary reconstruction for the Fram Strait was attached in a new figure illustrating the main claim of the manuscript, i.e., that some areas of thickened orogenic crust with rift-oblique structures may be further stretched while breakup has already occurred at adjacent segments with rift-parallel orogenic structures.
Changes: Added the extent of anomalously thick offshore crust in Figure 1. Also added a new figure illustrating the evolution of the Fram Strait in the Cenozoic.

**Comment 3: One particular statement stood out to me: “Geophysical data may also be limited in extent and/or quality, especially in areas where seismic data are more challenging to acquire (e.g., onshore central Europe).” This is simply not accurate. There is a wealth of high-quality seismic data available in Central Europe, including many ultra-deep 2D lines and highly detailed 3D grids. Several examples come to mind, such as: Ref: 1,2,3,4.**
Response: Agreed, the sentence is confusing and poorly written. First, the authors of the present manuscript meant “onshore western Europe”. Second, the quality of onshore seismic reflection may be in some cases better than that of offshore data. Third, the authors of the present manuscript meant to write that seismic reflection data have tighter coverage offshore (including numerous 3D volumes; e.g., North Sea and various rifted margins worldwide; e.g., www.TGS.com, www.sodir.no/en/diskos/) than onshore because of exploration campaigns for natural resources. In addition, moving the acquisition equipment is more challenging onshore than offshore.
Changes: Rewrote the sentence into “Geophysical data may also be limited in extent, especially in areas where seismic data is more challenging to acquire, e.g., in mountainous onshore regions, whereas decades of exploration for natural resources in offshore areas

like the North Sea have produced a wealth of seismic reflection datasets.”.

**Comment 4: The review is well-written, but it occasionally becomes dense with regional nomenclature, listing numerous place names and structure names. While I understand the need to support the theory, condensing and generalizing these references might help focus more on the key elements and mechanisms of the theory, this could improve readability.**
Response: The opposite was suggested by reviewer 4 (Prof. William Sager) in his comment 17, in which he suggested that the authors of the present manuscript have not demonstrated that every major transform fault formed parallel to a rift-orthogonal orogen. The authors of the present manuscript tend to agree with Prof. Sager in that more arguments and examples are needed to further facilitate future testing of the newly presented theory.
Changes: See response to reviewer 4’s comment 17 (Prof. William Sager).

**Comment 5: Overall, before I can recommend the paper for indexing, I strongly encourage the authors to develop a new plate reconstruction numerical model. You don't need to start from scratch; you can utilize existing platforms (e.g. GPleats, https://www.gplates.org/ - or any other). I understand there may not be enough time to do this on a global scale, but I suggest focusing on a region that best exemplifies your orogenic bridge theory. Even just a few well constrained time snapshots of such a model would be sufficient to illustrate the mechanisms behind your theory.**
Response: See response to comment 2.
Changes: See response to comment 2.

***Competing Interests:*** No competing interests were disclosed.

Reviewer Report 12 September 2024

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**Laurent Jolivet**
Institut des Sciences de la Terre de Paris, UMR CNRS, INSU,, Sorbonne Universite, Paris, Île-de-France, France

This paper proposes a new theory adding a component of the old continental bridges theory to the current plate tectonics model. It is based upon observations of the geometrical relations between rifts and earlier orogens, the latter influencing the propagation of intracontinental rifts. The heritage of an earlier orogen will facilitate the formation of a parallel rift, as was proposed already in some old and recent papers. Orogens striking perpendicular to rift will, on the opposite, prevent or modify the propagation, forcing the rift to step aside, thus inducing the formation of

transform faults. Another consequence of this theory is that the surface covered by oceanic crust would be much smaller than classically thought and plate tectonics less dynamic. Large parts of oceans, where these continental bridges supposedly are, would be made of extremely thinned continental crust. Also, RRR triple junctions would form where two or more orogens intersect.

1. The paper is meant as a worldwide synthesis of these interactions with several regional examples and some general conclusions are drawn to propose this new theory. Although a discussion of the interactions between orogens and rifts could be worth publishing, I was not convinced at all by this new manuscript. The figures provided are very general with patches of color to indicate orogens and their epoch of formation and no detail, or only very few, on the internal geometry and kinematics, even less thermal evolution, of these orogens. It seems that authors have selected a small number of orogens, leaving some prominent ones out of the scope of the paper. For instance, the Variscan orogen of Western Europe and Northwest Africa is not mentioned although it had a very strong impact of the thermal and rheological evolution of the lithosphere in that region. My impression is that early orogens were dissected by the dispersion of continents by plate tectonics at different periods and that all sorts of geometrical relations can be found.

2. The idea that some orogens favor the later formation of a rift, with the famous example of the Caledonian orogeny and the Northern Atlantic Ocean dates back to Emile Argand and it has been reconsidered several times, until the recent paper of Buiter and Torsvik who studied again the influence of heritage in the formation of rifts and oceans. The new idea here is that orogens perpendicular to rifts would be reworked as large transform faults and several examples in the central and southern Atlantic are shown. But nothing, or very little, is said about the structure of these orogens, except for the area they cover shown by color patches, and how they could have influenced the geometry of rifting. There are, besides, some more orogens in the same region that are not considered at all. Why choosing only those perpendicular to the rift instead of discussing the others which are oblique on the rift? A general synthesis would probably show a great diversity of geometrical relations that would suggests a more random organization. I have not done this sort of study, but it seems to me unavoidable before proposing any general ideas such as the orogenic bridge theory.

3. It found some non-logical statements in several parts of the paper. For instance, the fact that the traces of hot spots in the Atlantic are not parallel to transform faults is presented as an argument in favor of a complete misunderstanding of the dynamics of plate motion. But transform faults shows the direction of the relative motion between plates, as shown originally by Morgan, while hot spot traces show the direction of absolute motion of the same plates. I do not see where the problem is supposed to be.

4. The paper does not say clearly which are the kinematic implications of the new theory. How much of the supposed oceanic crust would be in fact continental? No detailed reconstructions are given to show the progressive evolution of the rifts and their evolution into oceans. Only quite vague statements ...

5. I can accept the idea that some margins are highly extended to such an extent that it become difficult to differenciate between continental and oceanic crust, that above a plume the continent crust becomes so weak that it can be stretched on considerable distances, that some pieces of highly stretched continental crust may exist in the middle of oceans, but I do not see how this would change significantly the past kinematics that is based upon magnetic anomalies and paleomagnetism. Without detailed reconstructions it is difficult to accept the authors conclusions.

Especially when space geodesy has fully confirmed the geologically-based present-day plate kinematics.

6. Nothing is said about mantle plumes, or only briefly to deny their existence. A wealth of seismic tomographic models has been published showing the distribution and geometry of these mantle anomalies, and their evolution has been modeled numerically with some success. In this paper it seems like the mantle has no influence at all on the dynamics of the lithosphere. **Conclusions:** Before going to some more detailed remarks, which my conclusions are based on, I conclude that this paper is not at all ready for indexation. Beside a text really difficult to read and too simple figures showing very little in terms of geometry, structure, rheology and kinematics of orogens, the manuscript lacks cross-sections, detailed reconstructions, and above all an exhaustive synthesis of the geometry of orogens worldwide and their relations to rifts. The paper, as it stands, is totally unconvincing to me and I cannot support its indexing.

Detailed remarks:

- Page 3 it is said " *since the orogens are consistently older than the rifts and transform with which they correlate they are therefore proposed to have played a central role in controlling the formation of the transform faults and in forcing the rift to step sideways…*". I do not see any logical inference here ("*therefore*"). You suppose some mechanical effects of the presence of an orogen but you never say how this would work.

- Figure 1: why selecting only such a small number of orogens? There are many more around the globe and they might also have had some influence on rifting dynamics, aren't they?

- Page 4, first paragraph: here, I am lost. Different types of structures and considerations are mixed up, I do not see what is new here and what you mean.

- Page 4, major issues about plate tectonics: you make a confusion between relative (transforms) and absolute (Walvis and Rio Grande ridges) motion. This cannot be taken as an argument against plate tectonics!

- Page 4: the OrBiT… "*every major transform fault on Earth strikes parallel to an orogen…*". Until you have considered all orogens instead of selecting only a few of them, you cannot convince me here. They seem to strike in all directions. You avoid some major orogens, such as the Variscan in western Europe and north Africa, for instance.

- Page 5: "*preexisting orogenic belts striking parallel to a propagating rift will facilitate the opening and propagation of the rift and control the strike and geometry of structures formed during rifting*." Probably yes, this has been proposed already but we need to know why in mechanical terms, thus the importance of the detailed internal structures of orogens, there thermomechanical state when rifting starts etc…

- Page 5: you should show a figure taken from old papers showing the location of continental bridges. I also want to remind you here that this theory was disproved very early based on simple isostatic considerations…

- Page 5: the Corinth Rift, which is the most active intracontinental rift, goes across the Hellenides without major problems, and coeval large strike-slip faults (transforms) form

outside the orogen (North Anatolian Fault and Kephalonia Fault). The teaching of active structures is useful in general when dealing with the deformation of the continental crust and lithosphere.

- Page 5 "*much of the submarine area around the globe*…": how much is the question, this is much too vague.

- Page 5: "*Land bridges were once proposed by knowledgeable scientists in the early 20$^{th}$ century. It is therefore not surprising that it may hold some truth after all*". What is surprising here is that the fact these scientists were famous is presented as a scientific argument in favor of your theory! Many famous scientists have made mistakes in the past! And it is probably the same nowadays.

- Page 5 "*the amount of … lateral movements… over the history of the Earth are currently overestimated*". In the absence of alternative quantitative estimates and proposition of an alternative quantitative model, I do not understand how you can dismiss the figures given by magnetic anomalies and transform faults. Even more so when we know that space geodesy agrees at more than 99% with classical plate kinematics.

- Page 8 and following: I miss a detailed reconstruction of the evolution of the Fram strait and surrounding regions following your theory here. I am not even sure you think that the Atlantic ocean ever opened … This remark is true for all the examples you discuss in the next sections. The text and figures are much too unprecise to convince anyone.

- Page 13 and following: I need figures showing the evolution of RRR triple junctions in your model…

- Page 15: about Iceland. How is the presence of a thick crust incompatible with a plume underneath? A plume leads to more oceanic crust production and thus a thicker crust. Also " *no seismic evidence of anomalously high temperature or melts in Iceland's subsurface*"… is the intense volcanic activity not enough as an evidence? And seismic tomography shows the anomaly quite well.

- Pages 15-16: again a confusion between absolute and relative motions…

- The discussion about far East Asia seems totally speculative.

- Page 19: implications for plate tectonics and modeling. These two paragraphs are really difficult to follow, I did not get the message.

Laurent Jolivet

**Is the work clearly and accurately presented and does it cite the current literature?**
No

**Is the study design appropriate and does the work have academic merit?**

No

**Are sufficient details of methods and analysis provided to allow replication by others?**
No

**If applicable, is the statistical analysis and its interpretation appropriate?**
No

**Are all the source data underlying the results available to ensure full reproducibility?**
No

**Are the conclusions drawn adequately supported by the results?**
No

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Geodynamics, tectonics

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.**

Author Response 10 Mar 2025

**Jean-Baptiste Koehl**

Dear Prof. Jolivet, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

**Comments by the reviewer**
Comment 1: This paper proposes a new theory adding a component of the old continental bridges theory to the current plate tectonics model. It is based upon observations of the geometrical relations between rifts and earlier orogens, the latter influencing the propagation of intracontinental rifts. The heritage of an earlier orogen will facilitate the formation of a parallel rift, as was proposed already in some old and recent papers. Orogens striking perpendicular to rift will, on the opposite, prevent or modify the propagation, forcing the rift to step aside, thus inducing the formation of transform faults.

Response: Agreed.
Changes: None required.

Comment 2: Another consequence of this theory is that the surface covered by oceanic crust would be much smaller than classically thought and plate tectonics less dynamic.

Response: Agreed, though the authors of the present manuscript concede that this should

be better expressed in the present manuscript.

Changes: Added a new paragraph to the “Implications for plate tectonics and modeling” section: “Less magmatism at (both present-day and paleo) mid-ocean ridges does not necessarily imply less tectonic extension since orogenic bridges contract and extend together with adjacent oceanic domains ( Figure 3). However, the pinning of Baltica and Laurentia for the past 1.8 Gyr via continuous late Paleoproterozoic orogenic bridge at GIFR implies significantly less dynamic relative and absolute paleo plate movements. Notably, the Iapetus Ocean was probably much narrower than the previously suggested 5000 km (Torsvik & Trench, 1991; Fortey & Cocks, 2003) and a $\leq$ 1000 km width similar to that of the present-day North Atlantic Ocean is more plausible because it would not have resulted in rupture of the Timanian and Greenland–Iceland–Faroe orogenic bridges. For example, if the late Paleoproterozoic Greenland–Iceland–Faroe orogenic bridge would have ruptured, it would include traces of intense Caledonian deformation with possible suture zones, tight folds, and segments of oceanic crust. This is neither in line with current crustal thickness estimates across the GIFR, which indicate continental crust in Iceland’s lower crust (Darbyshire *et al.*, 1998; Foulger *et al.*, 2003; Foulger *et al.*, 2020), nor with the open/gentle character of the Caledonian folds reworking the late Paleoproterozoic thrust systems at the GIFR, which indicate mild Caledonian deformation (Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, models like that of the rotation of Baltica in the Cambrian–Ordovician (e.g., Torsvik & Rehnström, 2001; Trench & Torsvik, 1992) are no longer viable alternatives.”. Also split the second paragraph of the same section and rewrote it into “The overestimation of the extent of oceanic crust on Earth, especially at orogenic bridges (e.g., Foulger *et al.*, 2003; Foulger *et al.*, 2020a; Foulger *et al.*, 2020b; Geoffroy *et al.*, 2022a) and magmatic passive margins (e.g., Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b; Koopmann *et al.*, 2014; Reeve *et al.*, 2021), suggests that the intensity, amount, and speed of seafloor spreading at mid-ocean ridges may have been overestimated in many paleogeographic reconstructions. Future reconstructions should therefore address this issue by including updated (extended) domains of continental (including hybrid) crust.”. Also rewrote point six of the conclusion into “Orogenic bridge theory suggests that the extent of oceanic crust was overestimated and, thus, that the intensity, amount, and speed of seafloor spreading should be toned down in future paleogeographic reconstructions.”.

Comment 3: Large parts of oceans, where these continental bridges supposedly are, would be made of extremely thinned continental crust.

Response: Disagreed. The offshore is not necessarily extremely thin. In Iceland, the lower crust believed to be continental is c. 20–25 km thick, which is extended, but not hyperextended (Darbyshire et al., 1998; Foulger et al., 2003, 2020b). At the Walvi Ridge, the crust is still 20–30 km (Fromm et al., 2018a, 2018b). The authors of the present manuscript concede that crustal thickness should be specified where relevant.

Changes: Specified the crustal thickness of the studied areas with anomalously thick offshore crust, c. 16 km at the Del Cano Rise and 22–26 km at the Madagascar Ridge: “At the Madagascar Ridge, the crust is thought to be continental in the northern part, where it consists of complex basement structure, and probably in the transition zone, where the crust is 26–22 km thick (Goslin *et al.*, 1981) and most likely consists of a thinned version of

the northern segment since located at a rifted margin. In the southern part of the ridge, the 14 km thickness of the crust led previous workers to postulate a thick oceanic crust (oceanic Large Igneous Province) despite the lack of bedrock samples in drilling attempts (Sato *et al.*, 2022). Similarly at the Del Cano Rise, the 16 km crustal thickness was assumed to result from plume magmatism (oceanic Large Igneous Province; Sarto *et al.*, 2022). However, the lack of linear magnetic anomalies and thicker-than-normal character of the crust both in the southern Madagascar Ridge and Del Cano Rise clearly indicate that seafloor-related processes can be ruled out and the irregular magnetic anomalies may be explained by more sporadic magmatic activity comparable to that which occurred at the continental Mozambique Ridge (Sato *et al.*, 2022). Thus, the thicker-than-normal crust and low residual bouguer anomalies at the southern Madagascar Ridge and Del Cano Rise were interpreted to reflect continental crust capped by mafic volcanics (Sato *et al.*, 2022), a scenario also suggested for other areas of thickened offshore crust in the Indian Ocean, e.g., southern Kerguelen Plateau and Elan Bank (Jiang *et al.*, 2021 their figure 4). A likely scenario, which should be further tested is that the southern Madagascar Ridge and Del Cano Rise consist of hyperextended (i.e., very thin) continental crust and/or rafted continental blocks (e.g., Péron-Pinvidic *et al.*, 2015). This is suggested by the fact that they occur at rifted margins and by the similar gradual southwards thinning of the continental crust at the Mozambique Ridge in adjacent areas (Hartnady *et al.*, 1992; Ryzhova *et al.*, 2022). Thus, the extent of oceanic crust at the Madagascar Ridge is c. 43.5% using a c. 1150 km distance between the previously inferred continent–ocean boundary at the transition zone between the northern and southern parts of the Madagascar Ridge at 31°S and the mid-ocean ridge and a c. 650 km distance between the southern tip of the southern Madagascar Ridge (i.e., the presently proposed continent–ocean boundary).". Also added "Seismic reflection data nevertheless shows the occurrence of thin layers of volcanics and possibly mantle exhumed along extensional detachments, e.g., core complex parallel to the Molloy fault zone ( Koehl, 2020; Koehl et al., 2021). This together with the dramatically thin character of the continental crust on the northeastern Greenland margin indicate that the crust is hyperextended and is generally thinner than 12 km except at the Hovgård Ridge and East Greenland Ridge where it is about 12 km ( Dumais *et al.*, 2020; Døssing *et al.*, 2008; Ritzmann *et al.*, 2004)." to the first paragraph of the "Timanian orogenic bridge" sub-section.

Comment 4: Also, RRR triple junctions would form where two or more orogens intersect

Response: Agreed.
Changes: None required

Comment 5: 1. The paper is meant as a worldwide synthesis of these interactions with several regional examples and some general conclusions are drawn to propose this new theory. Although a discussion of the interactions between orogens and rifts could be worth publishing, I was not convinced at all by this new manuscript. The figures provided are very general with patches of color to indicate orogens and their epoch of formation and no detail, or only very few, on the internal geometry and kinematics, even less thermal evolution, of these orogens. It seems that authors have selected a small number of orogens, leaving some prominent ones out of the scope of the paper. For instance, the Variscan orogen of Western Europe and Northwest Africa is not mentioned although it had a very strong impact of the thermal and rheological evolution of the lithosphere in that

region.

Response: Partly agreed. Although the authors of the present manuscript concede that the Variscan Orogeny "had a very strong impact of the thermal and rheological evolution of the lithosphere" in "Western Europe and Northwest Africa", it simply is not relevant to the present manuscript. The main author of the present manuscript is involved in ongoing work about the impact of Variscan thrusts on rifting in western Europe–eastern Canada, but this work is too detailed and is building on the present manuscript. In addition, the work concerning the Variscan Orogeny is linked to the rift-parallel endmember of Orogenic Bridge Theory (orogenic structures striking parallel to active rifts facilitating rifting and crustal thinning) and, thus, is not the focus of the present manuscript because more studied and accepted than the rift-orthogonal endmember. Indeed, the authors of the present manuscript have selected only the orogens relevant to the present manuscript. The present manuscript is not a global review of all orogens on Earth, but only of rift-orthogonal orogens, which may have controlled the formation of major transform faults. If the reviewer is referring again to the Variscan Orogen, it has not yet become of relevance to the presented theory, which must first be presented in a general (first-order) fashion to avoid confusing the readers/community. As the reviewers may have noticed, it was challenging to put this new theory into words. Regarding the amount of detail about each orogen discussed, the present manuscript is a global review of rift-orthogonal orogens, which may have controlled the formation of major transform faults. The authors of the present manuscript concede that some more details may help support the proposed theory. However, it is not possible to dwell on every geometric and kinematic variation in each orogens. For such details, the reader and reviewer are referred to the articles cited in the present manuscript, which provide reasonable amounts of detail.

Changes: Added internal structures to the Cape Fold Belt in South Africa and on the Falkland Plateau and Maurice Ewing Bank (Figure 5). Added "While the Svalbard margin thins rapidly and is relatively narrow (< 200 km), the Greenland margin is much broader (up to 600 km at the East Greenland Ridge; Figure 4), which is possibly related to the dominant top-east vergence of Caledonian thrusts (rift-parallel endmember of OrBiT; e.g., Ohta *et al.*, 1986; Ohta *et al.*, 1995; Koehl, 2024 awaiting peer review)." to the first paragraph of the "Timanian orogenic bridge" sub-section. Also added an extra paragraph at the end of the same sub-section: "Noteworthy, the proposed late Neoproterozoic (650–550 Ma) age of the rift-orthogonal orogen in the Fram Strait, which is supported by various geochronological studies throughout Svalbard ( Manecki *et al.*, 1998; Majka *et al.*, 2008, 2012; Koglin *et al.*, 2022; Koehl & Mottram, 2024) is a conservative estimate. It is possible that the orogen in the Fram Strait and the Barents Sea may as well be part of the late Paleoproterozoic Svecofennian Orogen, which crops out in western Troms in northern Norway and displays the same structural trend (WNW–ESE) and dominant thrust vergence (top-SSW) as the Timanian Orogen ( Bergh *et al.*, 2010; Bergh *et al.*, 2022). Noteworthy, the Svecofennian Orogen is a time-equivalent to the Laxfordian and Nagssugtoqidian orogens, which if traces of late Paleoproterozoic orogenesis were to be found in Svalbard and the Barents Sea would suggest a first-order impact of this ca. 1.9–1.8 Ga orogenic event on the Orogenic Bridge Theory and resulting plate tectonics.". Split the fifth paragraph in the "Greenland–Iceland–Faroe orogenic bridge" sub-section and rewrote the first part into "In northern Europe, a possible candidate to explain crustal thickening in the GIFR is the

correlate of the Ammassalik Belt, the late Paleoproterozoic Laxfordian Orogen on the Rockall Plateau and northern Scotland. This orogen was thought to consists of WNW–ESE-striking, subvertical shear zones showing strike-slip kinematics ( Attfield, 1987; Coward & Park, 1987; Dickin, 1992). However, recent mapping on reprocessed seismic reflection data has revealed that the Laxfordian shear zones onshore northern Scotland are part of much larger structures, namely tens of km thick, WNW–ESE-striking, dominantly NNE-dipping thrust systems around the Faroe Islands ( Koehl *et al.*, 2024). These were reworked into hundreds of km wide, NE–SW-striking open folds during the Caledonian Orogeny and extend beyond the Seaward-Dipping Reflectors and previously assumed continent–ocean boundary off the Faroe Islands ( Koehl *et al.*, 2024). Ongoing seismic mapping at the GIFR indicates that these late Paleoproterozoic structures extend to below southeastern Iceland and thus that the Iceland–Faroe segment of the GIFR is largely continental ( Koehl *et al.*, 2025). Of notable interest, the hundreds of km wide, NE–SW-striking open folds mapped along the entire length of the GIFR by Hjartarson *et al.* (2017) coincide with the Caledonian folds reworking late Paleoproterozoic structures off the Faroes Islands and at the Iceland–Faroe Ridge ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). This may explain the thickness variations of the GIFR along its length (i.e., in a WNW–ESE direction; Hjartason *et al.*, 2017 their figure 3c). This also suggests that the ca. 1.8 Ga U–Pb age obtained for zircons from basalts in southeastern Iceland ( Schaltegger *et al.*, 2002), where Laxfordian thrust systems occur at shallow crustal level (c. a few km; Koehl *et al.*, 2025), may be genuine. Further efforts should therefore concentrate on dating zircons from lavas in southeastern Iceland." and the first sentence of the second part into "In eastern Europe, the WNW–ESE-striking Tornquist Zone, i.e., the Teisseyre–Tornquist Zone ( Krzywiec *et al.*, 2022; Mazur *et al.*, 2015) and its probable continuation the Sorgenfrei–Tornquist Zone ( Ponikowska *et al.*, 2024), extends from the Black Sea ( Mikolajczak *et al.*, 2019; Narkiewicz *et al.*, 2015) to the southern North Sea ( Kalani *et al.*, 2020; Phillips *et al.*, 2018) and is a natural potential continuation for some of the Laxfordian structures at the GIFR and off the Faroe Islands ( Koehl *et al.*, 2024; Koehl *et al.*, 2025).". Added a new paragraph at the end of the "Greenland–Iceland–Faroe orogenic bridge" sub-section: "Previous studies have suggested that the continental crust in Iceland is connected to the Jan Mayen Microcontinent Complex ( Torsvik *et al.*, 2015). Northeast of Jan Mayen, the West and East Jan Mayen fault zones are parallel to late Paleoproterozoic orogenic structures in northern and southern Scandinavia (Svecofennian–Svecokarelian Orogen; Bergh *et al.*, 2010; Johansson *et al.*, 2015; Saintot *et al.*, 2011) and at the Greenland–Iceland–Faroe Ridge and northern Scotland (Coward and Park, 1987; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Figure 4). In addition, these transform faults as depicted in Blischke *et al.* (2022 their figure 5a) dip very gently at depth and display a geometry more typical of thrust faults. This and the occurrence of wiggly seismic reflections along the entire length of the Jan Mayen Microcontinent Complex probably representing contractional asymmetric folds (e.g., ) strongly suggest that deep rift-orthogonal orogenic structures controlled the formation of the Jan Mayen fault zones. Like in northern Scotland, northern Norway, and elsewhere, these late Paleoproterozoic orogenic structures were mildly reworked during the Caledonian Orogeny (e.g., Koehl *et al.*, 2024; Koehl *et al.*, 2025). Knowing that the Baltica craton was already formed in the late Paleoproterozoic, it is logical that late Paleoproterozoic structures analogous to those found at the surface in northwestern Norway (West Troms Basement Complex; Bergh *et al.*, 2010; Bergh *et al.*, 2015) and southern Sweden (Johansson *et al.*, 2015; Saintot *et al.*, 2011) continue at depth below Caledonian nappes to the northwest where they were reworked by Caledonian

contraction, their original geochronological signal most likely completely overprinted in some (most?) places. Thus, late Paleoproterozoic rift-orthogonal orogenic structures should be expected at depth along the entire length of the Norwegian continental shelf in the northwest, including adjacent to the Jan Mayen Microcontinent Complex and Jan Mayen fault zones. The presence of such structures should be possible to test using the dense coverage of 2D–3D seismic reflection data in Norway. Noteworthy, the Jan Mayen Microcontinent Complex represents a ruptured segment of the discussed late Paleoproterozoic orogenic bridge between Greenland and Europe and was rifted in the Cenozoic from Europe by seafloor spreading at the extinct Ægir Ridge and from Greenland by ongoing oceanic crust formation at the Kolbeinsey Ridge ( Figure 4).". Added "Notably, the Agulhas–Falkland fault zone parallels thrusts of the Cape Fold Belt both onshore and offshore southern South Africa (Paton *et al.*, 2022) and on the Falkland Plateau and Maurice Ewing Bank (Stanca *et al.*, 2022 their figures 4a, 5b, 12b–c, and 13a–c), which strike respectively NE–SW and E–W (Figure 5a). These late Paleozoic–earliest Mesozoic thrusts therefore likely controlled the strike and geometry of the Agulhas–Falkland fault zone. This relationship was previously noted by Buiter & Torsvik (2014) who suggested that the Agulhas–Falkland fault zone formed along an inherited suture zone between the Falkland Plateau and South Africa." to the third paragraph of the "Cape–Falkland orogenic bridge" sub-section. Added "Notably, the analysis of seismic reflection data in Klimke *et al.* (2018) clearly shows low-angle thrusts in the westernmost part of the Davie Ridge (the area labelled "compressed sediments" in their figure 6). These contractional structures may very well represent the offshore continuation of thrust systems of the East African–Antarctica Orogen between Madagascar and eastern Africa.", "The case of the Mozambique and Somali basins illustrate well the impact of orogenic bridges on rifting. Both basins host extinct, ENE–WSW-striking spreading centers and magnetic anomalies (e.g., Coffin & Rabinowitz, 1987; Davis *et al.*, 2016; Norton & Sclater, 1979; Sauter *et al.*, 2018; Simpson *et al.*, 1979; Figure 6) and a tectonic evolution somewhat similar to that proposed by Seton *et al.* (2012 their figure 15) and Vormann & Jokat (2021 their figure 3) is considered likely. In such as model, the Indian rift attempted at cutting through the East African–Antarctica Orogen at suitably oriented zones of weakness in the (Late Jurassic?–) Early Cretaceous. An area with suitably oriented structures is the Lurio Belt in northeastern Mozambique ( Bingen *et al.*, 2009; Viola *et al.*, 2008; Sacchi *et al.*, 2000) and its counterpart in western India and Sri Lanka (Kuunga Orogen; Brandt *et al.*, 2014; Dharmapriya *et al.*, 2015; Ghosh *et al.*, 2004; He *et al.*, 2018; Hirayama *et al.*, 2020; Srinivasan & Rajeshdurai, 2010), both of which consist of ENE–WSW-striking structures ( Figure 1 and Figure 6). These structures were oriented perpendicular to the c. N–S extension direction and were thus suitable to efficiently thin the thickened orogenic crust of the East African–Antarctica Orogen. However, upon meeting unsuitably oriented, major orogenic structure of the East African–Antarctica Orogen, e.g., N–S-striking contractional structures at the Davie Ridge (Klimke et al., 2018 their figures 2–6) and its southern prolongation, the Madagascar Ridge, the rift may have been forced to step laterally, i.e., in the northern Mozambique Basin, where suitably oriented structures of the E–W-striking Kuunga Orogen occur in adjacent areas onshore southern Madagascar ( Armistead, 2019; Collins *et al.*, 2003; Collins *et al.*, 2012). Nevertheless, upon meeting yet another unsuitably oriented N–S-striking structure at the Mozambique Ridge (e.g., Matsinhe et al., 2021 their figures 2, 4, and 6), the Indian rift eventually stepped farther south into its present-day location at the South West Indian Ridge ( Seton *et al.*, 2012; Figure 1 and Figure 6).", and "In the northern part of the East African Orogen, the Red Sea rift presents some

peculiar relationships with preexisting sutures and shear zones in the Arabian–Nubian Shield. There, N–S-striking Neoproterozoic shear zones, such as the Barka (–Adobha) and (Onib–) Hamisana shear zones ( Collins *et al.*, 2021; Johnson & Woldehaimanot, 2003; Stern & Kröner, 1993), coincide with zones of high seismicity and minor steps, bends/kinks, and narrowing of the Red Sea rift, which were interpreted as potential (proto) transform faults ( Bosworth *et al.*, 2005; Dixon *et al.*, 1987; Molnar *et al.*, 2020). N–S-striking, late Neoproterozoic shear zones also parallel the Aqaba–Dead-Sea–Levant fault zone (Molnar *et al.*, 2020), some of which were reactivated in the order of km to tens of km ( Bosworth *et al.*, 2005). Conversely, NW–SE-striking late Neoproterozoic shear zones, e.g., Rehba and Tabalah–Tarj shear zones ( Bosworth *et al.*, 2005; Johnson & Woldehaimanot, 2003) and Najd fault system ( Moore, 1979; Stern, 1985; Hamimi & Fowler, 2021), strike parallel to the segmented Rea Sea spreading center, thus suggesting opening of the rift along preexisting late Neoproterozoic zones of weakness in the crust (rift-parallel endmember of orogenic bridge theory).” to the “East African–Antarctica orogenic bridge” sub-section. Also added two new sub-sections about the Appalachian–Caledonian and Sergipano–Central African orogenic bridges.

Comment 6: My impression is that early orogens were dissected by the dispersion of continents by plate tectonics at different periods and that all sorts of geometrical relations can be found.

Response: Partly agreed. Indeed, some early orogens were dissected by rifting and breakup. However, the presently proposed new theory suggests that this was not the case everywhere. The present manuscript presents compelling examples showing that late Paleoproterozoic (Ammassalik–Laxfordian) and late Neoproterozoic (Timanian) orogens in the North Atlantic–Arctic region were not dissected at the GIFR and in the Davis Strait and Fram Strait. The present manuscript is attempting to bring order where there seemed to be chaos.

Changes: None.

Comment 7: 2. The idea that some orogens favor the later formation of a rift, with the famous example of the Caledonian orogeny and the Northern Atlantic Ocean dates back to Emile Argand and it has been reconsidered several times, until the recent paper of Buiter and Torsvik who studied again the influence of heritage in the formation of rifts and oceans. The new idea here is that orogens perpendicular to rifts would be reworked as large transform faults and several examples in the central and southern Atlantic are shown. But nothing, or very little, is said about the structure of these orogens, except for the area they cover shown by color patches, and how they could have influenced the geometry of rifting. There are, besides, some more orogens in the same region that are not considered at all. Why choosing only those perpendicular to the rift instead of discussing the others which are oblique on the rift? A general synthesis would probably show a great diversity of geometrical relations that would suggests a more random organization. I have not done this sort of study, but it seems to me unavoidable before proposing any general ideas such as the orogenic bridge theory.

Response: The authors of the present manuscript do not have access to the work by Emile

Argand and can, thus, not cite it. Nevertheless, his work was picked up by others later on (e.g., Wilson, 1966). The authors of the present manuscript concede that reference to such work is missing. The authors of the present manuscript also concede that the Buiter and Torsvik (2014) study is a great addition to the present manuscript. Again, the present manuscript is not a global review of all orogens on Earth. Only the orogens that are perpendicular to active rifts and mid-ocean ridges are relevant to discuss. Else the manuscript would be unnecessarily lengthened and confuse the reader. The authors of the present manuscript do not dispute that other orogens exist in the areas discussed, but these are irrelevant to discuss. The aim of the present manuscript is not to bring more chaos to a complex debate, but to bring order where there previously was chaos. The manuscript presents a clear correlation between major transform faults and rift-orthogonal orogens. May orogens striking oblique to active rifts and mid-ocean ridges also potentially correlate with major transform faults, the reviewer is welcome to provide specific examples. The authors of the present manuscript would be grateful for such an addition as it would only strengthen the presented correlation and the new theory. See also response to comment 5. Should the reviewer still be referring to the Variscan Orogen, e.g., off Iberia and Newfoundland, this belongs to rift-parallel endmember of Orogenic Bridge Theory in that, there, the orogen facilitated rifting and breakup. This endmember is more studied and accepted than the rift-orthogonal endmember and is therefore not the focus of the present manuscript. However, it may be brought up in a summary of the theory once the theory becomes more established.

Changes: Added reference to the work by Wilson (1966) to the first paragraph of the “Major issues with plate tectonics” section. Added “This relationship was previously noted by Buiter & Torsvik (2014) who suggested that the Agulhas–Falkland fault zone formed along an inherited suture zone between the Falkland Plateau and South Africa” in the third paragraph in the “The Cape–Falkland orogenic bridge” sub-section and replaced “This relationship” by “This relationship was remarked and investigated locally at a few margins only by a few studies ( Buiter & Torsvik, 2014; Peace *et al.*, 2018). However, the global pattern defined by transform faults and rift-orthogonal orogens” in the second paragraph of the “Orogenic bridge theory” section. See also response to comment 5 for additional changes.

Comment 8: 3. It found some non-logical statements in several parts of the paper. For instance, the fact that the traces of hot spots in the Atlantic are not parallel to transform faults is presented as an argument in favor of a complete misunderstanding of the dynamics of plate motion. But transform faults shows the direction of the relative motion between plates, as shown originally by Morgan, while hot spot traces show the direction of absolute motion of the same plates. I do not see where the problem is supposed to be.

Response: Agreed.

Changes: Deleted “In addition, offshore thickened slices of crust, e.g., the Walvis and Rio Grande ridges, commonly strike oblique to nearby major transform faults. Since transform faults are direct indicators of the direction of spreading at mid-ocean ridges and therefore of plate movements, should anomalously thick crustal ridges comprise deep mafic igneous rocks built by static magma reservoirs, they would be expected to lie parallel to the transform faults. This is rarely the case.” page 4 and “, e.g., the nature and origin of the

Walvis and Rio Grande ridges in the South Atlantic, which have been attributed to the migration of the tectonic plates over the Tristan da Cunha hotspot over time (e.g., Hoyer *et al.*, 2022). Both ridges are oblique to the fracture zones and transform faults, which reflect the direction of seafloor spreading and, therefore, the movements of the tectonic plates in the area. Thus, seafloor spreading and hotspot magmatism are difficult to reconcile with the oblique strike of the ridges" page 15–16.

Comment 9: 4. The paper does not say clearly which are the kinematic implications of the new theory. How much of the supposed oceanic crust would be in fact continental? No detailed reconstructions are given to show the progressive evolution of the rifts and their evolution into oceans. Only quite vague statements ...

Response: Agreed, the present manuscript is not specific enough. However, reconstructions would only serve to test the newly proposed theory and cannot be taken as direct arguments of its validity, which would be circular reasoning. Plate reconstructions build on geological data to test whether specific movements are realistic. Thus, plate reconstruction are out of the scope of the present manuscript.

Changes: Added areas with anomalously thick crust offshore to Figure 1. Also added a new figure detailing the formation of orogenic bridges. Added estimates (in %) for the proposed overestimation of oceanic crust at the discussed margins. E.g., added an introduction paragraph to the "continuous Orogenic Bridge" section: "The concept of continuous orogenic bridge implies that continental crust continues across previously inferred oceanic domain. In such areas, the extent of oceanic crust is proposed to be overestimated by 100% (i.e., no oceanic crust yet). This implies the existence of sections of hybrid continental crust (see Figure 2a and b) capped by thick successions of volcanic rocks (e.g., lava flows) and extensively intruded by igneous rocks (e.g., Seaward-Dipping Reflectors). Sections of hybrid continental crust are locally believed to extend the width of previously assumed oceanic domains. Three potentially continuous orogenic bridge are discussed here, the Timanian orogenic bridge in the Fram Strait, the Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and the Greenland–Iceland–Faroe orogenic bridge ( Figure 4)." and "In the examples discussed, the overestimation of the extent of oceanic crust is in the order of 20–60%." to the introduction to the "Disrupted Orogenic Bridge" section. Also added "Given the c. 2800 km distance to the mid-ocean ridge in this area, this suggests an underestimation of the extent of continental crust of 3.5 to 10.7%." in the second paragraph of the "Passive margins" section, "Considering the c. 3250 km distance between the previous continent–ocean boundary proposed by Schimschal and Jokat (2018; see also figure 1 in Stanca et al. 2022) and the mid-ocean ridge and the c. 1900 km distance between the eastern tip of Maurice Ewing Bank (the continent–ocean boundary proposed in the present manuscript) and the mid-ocean ridge, the extent of oceanic crust on the South American side of this ruptured orogenic bridge is overestimated by c. 41.3%." to the first paragraph in the "Cape–Falkland orogenic bridge" sub-section and split the paragraph in two, "Thus, the extent of oceanic crust at the Madagascar Ridge is c. 43.5% using a c. 1150 km distance between the previously inferred continent–ocean boundary at the transition zone between the northern and southern parts of the Madagascar Ridge at 31°S and the mid-ocean ridge and a c. 650 km distance between the southern tip of the southern Madagascar Ridge (i.e., the presently proposed continent–ocean boundary)." in between paragraphs 1 and 2 in the

"East African–Antarctica orogenic bridge" section (at the end of the second newly added paragraph), "As such, the extent of oceanic crust at the Mozambique Ridge is currently overestimated by c. 55.9 % using a distance of 3400 km between the northern tip of the Mozambique Ridge (i.e., previously proposed continent–ocean boundary) and the mid-ocean ridge and a c. 1500 km distance from the southern tip of the Mozambique Ridge to the mid-ocean ridge (i.e., new continent–ocean boundary)." at the end of the first newly added paragraph after paragraph 1 in the "East African–Antarctica orogenic bridge" section, and "At the Astrid Ridge, the extent of oceanic crust could thus be overestimated by up to 20.6% using a c. 1700 km distance between the previously assumed continent–ocean boundary between the southern and northern parts of the Astrid Ridge (Roeser et al., 1996) and a c. 1350 km distance from the northern tip of the Astrid Ridge (new continent–ocean boundary). At the Gunnerus Ridge and taking into account the Del Cano Rise, oceanic crust extent may be overestimated by as much as 25.0% using a c. 2800 km distance between the southern tip of the Gunnerus Ridge and the mid-ocean ridge and c. 2350 km from the northern tip of the Gunnerus Ridge (new continent–ocean boundary) and including a c. 250 km wide continental crustal domain at Del Cano Rise (Sato et al., 2022)." after the newly added paragraph between paragraphs 2 and 3 in the "East African–Antarctica orogenic bridge" section. Also rewrote the first paragraph of the "Implications for plate tectonics and modeling" section into "We propose the existence of long-lived, continuous orogenic bridges, e.g., the late Neoproterozoic Timanian orogenic bridge in the Fram Strait, late Paleoproterozoic Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and late Paleoproterozoic Nagssugtoqidian–Laxfordian Greenland–Iceland–Faroe orogenic bridge at the GIFR ( Foulger *et al.*, 2020a; Koehl & Mottram, 2024; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Peace *et al.* 2018; Figure 3a–d and Figure 4). The theory suggests that past plate tectonics was less dynamic than typically suggested by current plate models. Models involving the repeated opening of through-going Phanerozoic oceans, which unzipped continental blocks and/or continents now known to be still connected by continuous (or recently ruptured) Precambrian orogenic bridges are no longer viable solutions to geological observations and geophysical datasets. For example, the Iapetus Ocean and northeastern Atlantic Ocean both opened between Norway and Greenland as suggested by the occurrence of Cambrian ophiolites and Caledonian metamorphism and thrusting in mid-Norway (e.g., Furnes *et al.*, 1988; Slagstad *et al.*, 2020). However, despite the occurrence of blueschist-facies metamorphism of Caledonian age suggesting rapid subduction of mafic rocks to great depth in western Svalbard ( Horsfield, 1970; Kosminska *et al.*, 2014), it is unlikely that these two oceans fully opened between Svalbard and Greenland because this would require rupture of a possibly still continuous late Neoproterozoic orogenic bridge (e.g., Timanian orogenic bridge between Svalbard and northern Greenland; Figure 4). This is supported by the mapping of late Neoproterozoic Timanian thrust systems without any offset or truncation ( Koehl, 2020; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl & Mottram, 2024; Koehl, 2024 awaiting peer review) across the previously assumed Caledonian/Iapetus sutures in the Barents Sea and western Svalbard ( Breivik *et al.*, 2005; Horsfield, 1970; Kosminska *et al.*, 2014). It is also supported by the delayed opening of the Fram Strait at ca. 24 Ma ( Engen *et al.*, 2008) or possibly still yet to happen (present study and Koehl *et al.*, 2021), i.e., much later than the opening of the Mohns Ridge between Greenland and Norway and Arctic Ocean at ca. 56 Ma ( Faleide *et al.*, 1993; Faleide *et al.* 2008; Gaina *et al.*, 2002; Srivastana, 1985). If the late Neoproterozoic Timanian orogenic bridge had already been ruptured by the opening of Iapetus, breakup in the Fram Strait would not have taken

more time (or at least not much longer) to achieve than between Norway and Greenland and in the Arctic Ocean. This also applies to the Iapetus Ocean and northeastern Atlantic Ocean at GIFR. Furthermore, if breakup had already occurred at the GIFR, transform faulting at the Tjörnes fault zone accommodating sliding of late Paleoproterozoic (or older) continental crust in the southwest against Cenozoic oceanic crust in the northeast would not have been required. Thus, although Iapetus did open and close in some places (e.g., between Norway and Greenland), it clearly did not in others (GIFR and Fram Strait)." and added to new paragraphs after that: "Less magmatism at (both present-day and paleo) mid-ocean ridges does not necessarily imply less tectonic extension since orogenic bridges contract and extend together with adjacent oceanic domains ( Figure 3). However, the pinning of Baltica and Laurentia for the past 1.8 Gyr via continuous late Paleoproterozoic orogenic bridge at GIFR implies significantly less dynamic relative and absolute paleo plate movements. Notably, the Iapetus Ocean was probably much narrower than the previously suggested 5000 km (Torsvik & Trench, 1991; Fortey & Cocks, 2003) and a $\leq$ 1000 km width similar to that of the present-day North Atlantic Ocean is more plausible because it would not have resulted in rupture of the Timanian and Greenland–Iceland–Faroe orogenic bridges. For example, if the late Paleoproterozoic Greenland–Iceland–Faroe orogenic bridge would have ruptured, it would include traces of intense Caledonian deformation with possible suture zones, tight folds, and segments of oceanic crust. This is neither in line with current crustal thickness estimates across the GIFR, which indicate continental crust in Iceland's lower crust (Darbyshire *et al.*, 1998; Foulger *et al.*, 2003; Foulger *et al.*, 2020a), nor with the open/gentle character of the Caledonian folds reworking the late Paleoproterozoic thrust systems at the GIFR, which indicate mild Caledonian deformation (Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, models like that of the rotation of Baltica in the Cambrian–Ordovician (e.g., Torsvik & Rehnström, 2001; Trench & Torsvik, 1992) are no longer viable alternatives. This has implications for ophiolites and eclogite- and blueschist-facies metamorphism as it may indicate that some presumed ophiolites, e.g., km-wide blueschist units in western Svalbard ( Agard *et al.*, 2005; Horsfield, 1970; Kosminska *et al.*, 2014), may simply correspond to lava flows and/or igneous rocks intruded into continental crust, which were later imbricated during subsequent (Caledonian) orogenesis. This may suggest that some presently assumed ophiolites may not necessarily reflect the closure of paleo-oceans (sutures). If these presumed ophiolites have indeed been deposited onto or intruded into and imbricated together with continental crust, they would have been relatively difficult to quickly subduct to great depth ($\geq$ 50–70 km) due to the relative buoyancy of continental crust. Thus far, rapid subduction to great 50– 70 km depth was generally considered necessary to explain the occurrence of blueschist metamorphism (e.g., Agard *et al.*, 2005; Agard *et al.*, 2009). Hence, alternative models may therefore need to be further explored for the formation of some high-pressure metamorphic rocks ( Jamtveit *et al.*, 2018; Luisier *et al.*, 2019; Moulas *et al.*, 2013; Yamato & Brun, 2016), and the interpretation of some rock units as ophiolites may need to be reexamined.".

Comment 10: 5. I can accept the idea that some margins are highly extended to such an extent that it become difficult to differenciate between continental and oceanic crust, that above a plume the continent crust becomes so weak that it can be stretched on considerable distances, that some pieces of highly stretched continental crust may exist in the middle of oceans, but I do not see how this would change significantly the past kinematics that is based upon magnetic anomalies and paleomagnetism. Without detailed

reconstructions it is difficult to accept the authors conclusions. Especially when space geodesy has fully confirmed the geologically-based present-day plate kinematics.

Response: The authors of the present manuscript do not debate evidence from geodesy for present-day plate kinematics. However, the authors of the present manuscript insist on the fact that the interpretation of magnetic anomalies is currently being righteously disputed in several areas in the world, especially areas targeted by the present manuscript. For example, Geoffroy et al. (2021) clearly show that outer magnetic anomalies reflect magmatic intrusions in continental crust. Dumais et al. (2020) show that there are no magnetic anomalies in between Greenland and presumed microcontinents in the Fram Strait (East Greenland Ridge and Hovgård Ridge) and, thus, that the extent and amount of oceanic crust there was greatly overestimated. Furthermore, Foulger et al. (2020) show that magnetic anomalies at the Reykjanes Ridge segment of the Northeastern Atlantic do not extend evenly into the GIFR and, thus, that the interpretation of the nature of the crust at the GIFR as oceanic is doubtful, especially considering the significantly thicker character of the crust there (25–40 km; Darbyshire et al., 1998; Foulger et al., 2003) than typical oceanic crust. Finally, paleomagnetic data cannot resolve the position of paleocontinents with resolution smaller than 550 km (Butler, 1992), which is about twice less the size of the GIFR and is less than the distance of Iceland to the presumed continent–ocean boundary off the Faroe Islands and off southeastern Greenland. Thus, paleomagnetism does not have the necessary resolution to investigate recent movements on either sides of the presumed mid-ocean ridge onshore Iceland. The new description on seismic reflection data of the geometry of major old thrust systems, which characterize continental crust, by Koehl et al. (2022, 2023, 2024) now allows the segregate confidently continental from oceanic crust in the subsurface. Koehl et al. (2024b) clearly shows that NW–SE-striking late Paleoproterozoic thrust systems off the Faroes extend beyond the presently assumed continent–ocean boundary. Ongoing seismic reflection mapping using Koehl et al. (2022, 2023, 2024)'s description suggests that these thrust systems extend until Iceland and, thus, that the entire GIFR consists of continental crust below the several km thick cover of Cenozoic lavas. See response to comment 9 about plate reconstructions. Regarding the occurrence of microcontinents within oceanic crustal domains, it has been discussed in various previous studies, e.g., rafts (Péron-Pinvidic et al., 2015) and transform-parallel continental slivers along major transform faults (e.g., Figure 10). In addition, recent results show that continental fragments may be trapped in Rifted Oceanic Magmatic Plateaus and possibly be entrained into oceanic crustal domain during seafloor spreading (e.g., Rime et al., 2024). Major changes to past plate tectonics are introduced with the concept of orogenic bridges, especially those that are still continuous, e.g., late Paleoproterozoic Greenland–Iceland–Faroe orogenic bridge, which pins Baltica and Laurentia together for the past 1.8 Gyr and, thus, (1) greatly restricts the possible range of movements of these two cratons on Earth surface without colliding with other continental blocks (absolute movements) and (2) limits the relative movements of these two cratons, which must have mostly moved together and remained more or less close to one another (similar to present-day configuration or closer) in the past 1.8 Gyr.

Changes: Added a new figure detailing the formation of rift-parallel (rafts; Péron-Pinvidic et al., 2015) and rift-orthogonal microcontinents (slivers; present manuscript). Also added reference to Péron-Pinvidic et al. (2015) and Rime et al. (2024) in the new third paragraph of

the “East African–Antarctica orogenic bridge” sub-section. Added a new paragraph to the “Implications for plate tectonics and modeling” section: “Less magmatism at (both present-day and paleo) mid-ocean ridges does not necessarily imply less tectonic extension since orogenic bridges contract and extend together with adjacent oceanic domains ( Figure 3). However, the pinning of Baltica and Laurentia for the past 1.8 Gyr via continuous late Paleoproterozoic orogenic bridge at GIFR implies significantly less dynamic relative and absolute paleo plate movements. Notably, the Iapetus Ocean was probably much narrower than the previously suggested 5000 km (Torsvik & Trench, 1991; Fortey & Cocks, 2003) and a $\leq$ 1000 km width similar to that of the present-day North Atlantic Ocean is more plausible because it would not have resulted in rupture of the Timanian and Greenland–Iceland–Faroe orogenic bridges. For example, if the late Paleoproterozoic Greenland–Iceland–Faroe orogenic bridge would have ruptured, it would include traces of intense Caledonian deformation with possible suture zones, tight folds, and segments of oceanic crust. This is neither in line with current crustal thickness estimates across the GIFR, which indicate continental crust in Iceland’s lower crust (Darbyshire *et al.*, 1998; Foulger *et al.*, 2003; Foulger *et al.*, 2020), nor with the open/gentle character of the Caledonian folds reworking the late Paleoproterozoic thrust systems at the GIFR, which indicate mild Caledonian deformation (Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, models like that of the rotation of Baltica in the Cambrian–Ordovician (e.g., Torsvik & Rehnström, 2001; Trench & Torsvik, 1992) are no longer viable alternatives.”. Rewrote the last point of the conclusion into “Orogenic bridge theory suggests that the extent of oceanic crust was overestimated and, thus, that the intensity, amount, and speed of seafloor spreading should be toned down in future paleogeographic reconstructions.”.

Comment 11: 6. Nothing is said about mantle plumes, or only briefly to deny their existence. A wealth of seismic tomographic models has been published showing the distribution and geometry of these mantle anomalies, and their evolution has been modeled numerically with some success. In this paper it seems like the mantle has no influence at all on the dynamics of the lithosphere.

Response: Agreed. The authors of the present manuscript concede that this section should be partly rewritten to better reflect the authors’ opinion, which is that Orogenic Bridge Theory may very well work with or without plumes, i.e., plumes may be handy to explain anomalously high amount of magmatism but cannot account for issues such as anomalously thick crust offshore (e.g., at the GIFR).

Changes: Completely rewrote the abstract to mention the potential control exerted by mantle plumes on plate tectonics: “Plate tectonics is a centerpiece of Earth’s geodynamics and is of primary importance in making our planet habitable, securing natural resources, mitigating geohazards and climate change, and investigating the evolution of life. Understanding plate tectonics is increasingly important due to the ongoing energy transition. At the core of plate tectonics, the supercontinent cycle suggests that continental landmasses repeatedly accrete into supercontinents and then break up during rifting. Thus far, rifting was thought to gradually unzip continents from one another and to be mostly controlled by geodynamic processes (e.g. subduction, mantle plumes). Orogenic Bridge Theory (OrBiT) suggests another first-order controlling factor and states that preexisting orogens perpendicular to active rifts hinder breakup, forcing rifts to jump, and localizing

major transform faults. Such orogens require more time to break due to the thickened character of orogenic crust and obliquity of related structures. Thus, while seafloor spreads on either side of rift-orthogonal orogens, extension continues to stretch the orogenic crust until breakup occurs there later. These regions of stretched continental crust flanked by oceanic crust are called “orogenic bridges”. OrBiT implies that the extent of continental crust may be underestimated and, thus, that our understanding of plate tectonics is incomplete. OrBiT may help predict future plate tectonics, e.g. localization of future rifts and transform faults, which typically host natural resources and cause geohazards. This new theory is based on a new global correlation of major transform faults with rift-orthogonal orogens and ongoing work at various potential orogenic bridges and continental margins, which are hereby further discussed in the hope that the new theory gets further tested.”. Rewrote the first sentence of the fifth paragraph of the “Mantle plume model” section into “Geophysical evidence unambiguously suggests that, although mantle plumes may very well have produced thick lava flow caps, they are unlikely to have formed thickened oceanic crust at the GIFR, Mozambique and Madagascar ridges, and Del Cano Rise ( Foulger *et al.*, 2003; Foulger *et al.*, 2020a, Foulger *et al.*, 2020b; Geoffroy *et al.*, 2022a; Ryzhova *et al.*, 2022; Sato *et al.*, 2022; Koehl *et al.*, 2024; Koehl *et al.*, 2025).” and added “(plume-related?)” to the second sentence of the same paragraph. Also added a new paragraph at the end of the “Mantle plume model” section: “The wet” versus “dry” rift classification by Dunbar & Sawyer (1989) related the intensity of magmatism and width of the resulting rift with the existence of preexisting weaknesses in the crust and/or mantle. For example, preexisting mantle weaknesses would tend to form narrow “wet” rifts with intense magmatism (e.g., Iceland), whereas crustal weaknesses lead to the development of broad “dry” rifts (e.g., Iberia–Newfoundland). This work assumes that breakup has occurred at the Greenland–Iceland–Faroe Ridge, which is not (yet) the case ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, if the magma-rich Greenland–Iceland–Faroe Ridge is a through-going orogenic bridge where breakup has not yet occurred whereas breakup has occurred at magma-poor margins, e.g., in the Arctic Ocean (ultra-slow-spreading Gakkel Ridge), then it follows that intense magmatism and preexisting mantle weaknesses or plumes have less effect on breakup than previously assumed. Other factors, e.g., rift-parallel and rift-orthogonal orogens, must therefore come into play.”.

Comment 12: Conclusions: Before going to some more detailed remarks, which my conclusions are based on, I conclude that this paper is not at all ready for indexation. Beside a text really difficult to read and too simple figures showing very little in terms of geometry, structure, rheology and kinematics of orogens, the manuscript lacks cross-sections, detailed reconstructions, and above all an exhaustive synthesis of the geometry of orogens worldwide and their relations to rifts. The paper, as it stands, is totally unconvincing to me and I cannot support its indexing.

Response: The manuscript is already indexed, and a DOI was assigned. The manuscript cannot be rejected and will remain published and, eventually, if successful, will pass peer review after having been revised at least once. The peer-review format of Open Research Europe prevents articles from being rejected and, thus, empowers authors (especially early-career scientists) to share new ideas and theories more easily and with a broader community. See also response to comment 5 regarding adding mention of all existing orogens. The authors of the present agree that some figures are too simple, e.g., Figure 1.

See response to comment 9 about plate reconstructions. See response to comment 5 regarding the amount of detail on the discussed orogens. Adding cross sections for each orogens, though potentially useful, would result in significantly lengthening the manuscript and would require a level of detail totally unnecessary to the present manuscript and rather confuse the reader and/or dream him/her with too many local names.

Changes: Added extent of offshore areas with anomalously thick crust as dashed yellow line in Figure 1. Also modified Figures 4 and 5 to include further details. See response to comment 9 about plate reconstructions. See response to comment 5 regarding the amount of details on the discussed orogens.

Comment 13: Detailed remarks: Page 3 it is said " since the orogens are consistently older than the rifts and transform with which they correlate they are therefore proposed to have played a central role in controlling the formation of the transform faults and in forcing the rift to step sideways...". I do not see any logical inference here ("therefore"). You suppose some mechanical effects of the presence of an orogen but you never say how this would work.

Response: Agreed. This is not sufficiently described in the manuscript. The current understanding of the theory of plate tectonics is that the continents were accreted into a supercontinent (Pangea) and then oceans like the Atlantic and Indian oceans opened. This means that the old pre-rift orogens mapped by previous workers on either sides of these oceans were once connected, forming a whole. Since these orogens predate rifting, they must have impacted it, whereas the present-day episode of rifting and ocean opening cannot have had any impact on the initial geometry of these orogens. Rifting is currently modifying the geometry of these old orogens, e.g., by dramatically thinning them and, in places, truncating them, thus leading to breakup. Should rifting have tried to incise through thickened orogenic crust with structures perpendicular to the rift axis, it would necessarily have resulted in rifting and breakup being hindered. First, rift-orthogonal thrust systems are unsuitably oriented to facilitate significant thinning of the crust necessary to achieve breakup because they parallel the extension direction. Second, these thrusts are unsuitable to accommodate transform movements necessary to achieve breakup due to their low angle geometry. Thus, breakup is necessarily delayed at rift-orthogonal orogens. It is only after a tedious process of incising through rift-orthogonal orogens that rifting and breakup may proceed. A textbook example is the Fram Strait. There, WNW–ESE-striking Timanian thrusts strike sub-orthogonal to the rift axis and were later reworked into N–S-striking folds and thrusts during the Caledonian Orogeny, i.e., sub-perpendicular to the Timanian structural trend. It is only by incising repeatedly along the Caledonian and Timanian structural trends that rifting succeeded in breaking the crust up in the Fram Strait, which is only barely achieved at present if at all, whereas it was achieved much earlier (ca. 56 Ma; Faleide et al., 1993, 2008; Gaina et al., 2002; Srivastana, 1985) at the Mohns Ridge segment of the northeastern Atlantic and in the Arctic (see Figure 4 in present manuscript).

Changes: Added a new figure detailing the formation of orogenic bridges and described their formation in more detail. For example, rewrote the fifth paragraph of the "Orogenic bridge theory" section into "Conversely, orogens striking highly oblique to perpendicular to a propagating rift ("rift-orthogonal endmember") will act as barriers and significantly hinder

rift propagation, i.e., significantly delaying breakup or preventing the rift from opening in a linear fashion or from propagating. This endmember has thus far been little studied (Molnar *et al.*, 2020). The term "orogenic bridge" refers to the orogenically thickened crust of a rift-orthogonal orogen, which was (hyper-) extended during rifting ( Figure 2b and c) and is applied to areas of continental crust that extend further into the oceanic realm than normal passive margins. The term "bridge" is used in reference to the land bridges (also called Isthmian Links) inferred by the Land Bridge Theory to explain similar fauna and flora on separate continents, while rifting had already initiated (e.g., Gregory, 1929; Schuchert, 1932; von Ihering, 1931; Willis, 1932). All the previously proposed land bridge sites match the location of hereby proposed orogenic bridges, thus suggesting that parts of Land Bridge Theory may hold the key to unlocking a more advanced understanding of plate tectonics ( Figure 1).", and added two new paragraphs to the same section: "Despite the apparent correlation of the location of some of the proposed orogenic bridges with that of so-called land bridges, orogenic bridges are clearly different from land bridges. While land bridges imply continent fixity, orogenic bridges work in symbiosis with plate tectonics and extend and contract together with adjacent plate segments undergoing seafloor spreading. This is due to the fact that preexisting thrust systems at orogenic bridges strike dominantly oblique to orthogonal to the active rift ( Figure 3a–b). As such, these structures are unsuitable to accommodate crustal thinning ( Figure 3c). In addition, the low-angle character of thrust faults makes them unsuitable to accommodate transform movements. However, their rift-orthogonal orientation is suitable to control the formation of new subvertical transform faults. Thus, rift-orthogonal thrust systems hinder rifting, forcing the rift to jump or bypass certain areas (e.g., Greenland–Iceland–Faroe Ridge; Figure 3d). While oceanic crust forms on either side of orogenic bridges, the continental crust at orogenic bridges continues to stretch until break up occurs there too. Should there be any speed difference between seafloor spreading at mid-ocean ridges and stretching within the thinning orogenic bridge, these may be accommodated by transform faults at the continent–ocean boundary. Clear evidence of the reworking of orogenic bridges during orogenesis and rifting are shown in Koehl *et al.*, (2024, 2025). Notably at the GIFR, WNW–ESE-striking late Paleoproterozoic thrust systems of the Laxfordian–Nagssugtoqidian Orogen interpreted within the GIFR and adjacent continental margins of the Faroe Islands and southeastern Greenland ( Figure 3a) were reworked as 100–200 km wide open anticlines during the Caledonian Orogeny (i.e., shortened orogenic bridge; Figure 3b) and were later inverted during post-Caledonian extension, thus contributing to thinning the crust (extending orogenic bridge; Koehl *et al.*, 2024 their figure 2e; Koehl *et al.*, 2025; Figure 3c).". A possible mechanism was suggested in Koehl et al. (2021, 2025 submitted doi.org/10.12688/openreseurope.19399.1) for the formation of transform-parallel core complexes.

Comment 14: Figure 1: why selecting only such a small number of orogens? There are many more around the globe and they might also have had some influence on rifting dynamics, aren't they?

Response: Disagreed. The orogens selected are those that are relevant to the present manuscript. Including irrelevant features and structures to the present manuscript would only lengthen it and confuse the reader. Again, the present manuscript is not a global review of all orogens on Earth. See also response to comment 7.

Changes: See response to comment 7.

Comment 15: Page 4, first paragraph: here, I am lost. Different types of structures and considerations are mixed up, I do not see what is new here and what you mean.

Response: The targeted paragraph sets the stage for some of the most valuable pieces of evidence obtained from seismic reflection data in the past few years. The paragraph mentions a crucial breakthrough in interpreting specific orogenic structures on seismic reflection data, which can then be used to determine the nature of the crust offshore.

Changes: Rewrote the first sentence of the paragraph into "It was possible to establish this correlation in great part due to major improvements in the quality of seismic reflection imaging and partly to our ability to now identify major shear zones (e.g., Bird *et al.*, 2016; Fazlikhani *et al.*, 2017; Hedin *et al.*, 2016; Lenhart *et al.*, 2019; Phillips *et al.*, 2016; Ye *et al.*, 2020), major thrust systems and related contractional structures, whose seismic facies is now well established (e.g., Koehl, 2020; Koehl, 2021; Koehl, 2024 awaiting peer review; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Koehl & Stokmo, 2024 Morley *et al.*, 2017).".

Comment 16: Page 4, major issues about plate tectonics: you make a confusion between relative (transforms) and absolute (Walvis and Rio Grande ridges) motion. This cannot be taken as an argument against plate tectonics!

Response: Agreed. See also response to comment 8.

Changes: See response to comment 8.

Comment 17: Page 4: the OrBiT... "every major transform fault on Earth strikes parallel to an orogen...". Until you have considered all orogens instead of selecting only a few of them, you cannot convince me here. They seem to strike in all directions. You avoid some major orogens, such as the Variscan in western Europe and north Africa, for instance.

Response: The authors of the present manuscript fail to understand how irrelevant orogens may help convince the reviewer. The authors of the present manuscript concede that the Variscan Orogen in western Europe may have facilitated the opening of the Central Atlantic. The main author of the present manuscript is indeed involved in seismic mapping of Variscan thrusts off Iberia on seismic data. There, Variscan thrusts strike parallel to the active rift and appear to have controlled the formation of normal faults and low-angle detachments. However, this endmember of OrBiT (parallel endmember) is relatively well studied and accepted. Thus, it is not the focus of the present manuscript. The authors of the present manuscript concede that the Variscan Orogen and its potential control in the formation of the Bay of Biscay is an outstanding opportunity to further develop OrBiT and the influence of preexisting orogens on rifting and breakup. However, this is one order of magnitude below the features discussed in the present manuscript. Such issues will be discussed in subsequent manuscripts, e.g., in conjunction with the influence of Caledonian orogenic syncline and anticlines within the Greenland–Iceland–Faroe Ridge in controlling

magma rise through the crust and its extrusion as thick lava flows from magmatic centers such as the Faroes and other structural highs, and possible loading effect on the crust induced by extensive lava flowing preferentially towards and accumulating into (+/- eroded) Caledonian synclines (i.e., orogenic synclines may thus be breakup focal points). The authors of the present manuscript strongly encourage the reviewer to reach out to them after the peer-review process related to the present manuscript is concluded should he be interested in collaborating on such issues and resulting manuscripts. The authors of the present manuscript are very much open to new collaborations.

Changes: None.

Comment 18: Page 5: “preexisting orogenic belts striking parallel to a propagating rift will facilitate the opening and propagation of the rift and control the strike and geometry of structures formed during rifting.” Probably yes, this has been proposed already but we need to know why in mechanical terms, thus the importance of the detailed internal structures of orogens, there thermomechanical state when rifting starts etc…

Response: Preexisting orogens and related structures represent inherited scars/zones of weakness presenting lateral discontinuities (e.g., rheological contrasts), which are typically preferentially reused during subsequent deformation. This is well accepted and demonstrated by a wealth of previous studies (e.g., Lundin and Doré, 2005; Buiter and Torsvik, 2014; Le Pourhiet et al., 2017; Koehl, 2020; Lundin et al., 2022; Koehl et al., 2022, 2023; Koehl and Stokmo, 2024). However, the way preexisting structures are reused varies according to the tectonic setting. See also response to comments 5 and 13.

Changes: Added two new paragraphs to the “Previous work” section: “Another relevant study is the modeling of the influence of preexisting zones of weakness in the crust and mantle on rifting ( Dunbar & Sawyer, 1989). While mantle weaknesses were suggested to explain the formation of “wet” rift with intense magmatism and narrow passive configurations, crustal weaknesses were associated to the formation of “dry” rifts and broad passive margins. Like Lundin & Doré (2005), this study attempted at relating zones of intense magmatism with preexisting structural fabrics. Other studies investigated the impact of oblique preexisting discontinuities on rift segmentation and obliquity (e.g., Brune *et al.*, 2017; Brune *et al.*, 2018; Molnar *et al.*, 2017; Zwaan *et al.*, 2021). However, they did not address the formation of transform faults and the specific influence of preexisting orogens, which the present study attempts to theorize for the first time.”. See response to comments 5 and 13.

Comment 19: Page 5: you should show a figure taken from old papers showing the location of continental bridges. I also want to remind you here that this theory was disproved very early based on simple isostatic considerations…

Response: Agreed. The authors of the present manuscript do not intend to revive the old Land Bridge Theory. They agree that the continents have moved and are moving. The only thing they concede to the Land Bridge Theory is the existence of long-lived connections between the continents, though not through so-called “Land Bridges”, which are fixed, but through orogenic bridges, which are dynamic features extending and contracting together

with neighboring oceanic crust along-strike mid-ocean ridges. The authors of the present manuscript concede entirely that this is not made crystal clear in the present manuscript and intend to correct this major shortcoming.

**Attached is a new figure which will be included in the present manuscript to detail the evolution of orogenic bridges through at least two phases of orogenesis and subsequent rifting. See also response to comments 9, 10, and 13.**

**Please refer to this link to view figure attached -** https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248186.Image.pdf

Changes: See also response to comments 9, 10, and 13.

Comment 20: Page 5: the Corinth Rift, which is the most active intracontinental rift, goes across the Hellenides without major problems, and coeval large strike-slip faults (transforms) form outside the orogen (North Anatolian Fault and Kephalonia Fault). The teaching of active structures is useful in general when dealing with the deformation of the continental crust and lithosphere.

Response: Regarding the North Anatolian Fault, it actually parallels mid-Paleozoic (Caledonian?) E–W-striking folds in Upper Silurian rocks (Ketin, 1959; Kozur and Göncüoglu, 1998; Sen, 2022), the E–W-striking Variscan belt in northeastern Turkey (Ketin, 1959; Karsli et al., 2020; Salacinska et al., 2022; Rezeau et al., 2023), the E–W-striking Triassic Eo-Cimmerian Orogen in northern Iran (Zanchi et al., 2009; Hässig et al., 2013), and the Late Cretaceous–early Cenozoic, E–W-striking Pontides and Tauride fold-and-thrust belts (Koc et al., 2017; McPhee et al., 2018; Rezeau et al., 2023). The North Anatolian Fault is therefore not in shortage of preexisting orogenic structures that may have controlled its formation. Potential future studies should focus on demonstrating the detailed interaction of the North Anatolian Fault with preexisting orogenic fabrics and structures. Regarding the Gulf of Corinth, it appears to connect the North Anatolian Fault in the east and the Kephalonia Transform Fault west of the Gulf of Corinth. The explanation is quite simple. The western tip of the North Anatolian Fault bends into a NE–SW strike, i.e., following the attitude of nearby contractional belts, e.g., Circum Rhodope Belt and northern Tethyan ophiolitic belts related to the Hellenides and Pontides (e.g., Meinhold and Kostopoulos, 2013; Papanikolaou, 2021 his figure 2.3; Kilias, 2024). At its westernmost tip, the NE–SW-striking western segment of the North Anatolian Fault becomes orthogonal to the dominant Alpine (Hellenides) fabrics and structures, which rapidly swing from a NE–SW strike in western Turkey to a NW–SW strike in Greece (e.g., Papanikolaou, 2021). Thus, the North Anatolian Fault possibly steps across the Hellenides, e.g., to the Achaia-Elia fault or, more probably, to the Kephalonian Transform Fault both of which show an NE–SW strike and dextral strike-slip kinematics matching that of the North Anatolian Fault in the Aegean Sea (e.g., Özbakir et al., 2020). The North Anatolian Fault is linked to the Achaia-Elia fault and Kephalonian Transform Fault by a series of E–W- to WNW–ESE-striking rifts, which include the Gulf of Corinth (Corinth Rift/graben) and the North Gulf of Evia (Sperchios–Atalanti graben; e.g., Goldsworthy et al., 2002; Sakellariou, et al. 2007; Tsodoulos et al., 2008; Özbakir et al., 2020 their figure 9). These rift basins are parallel to the Central Hellenic Shear Zone and form a relay zone between the North Anatolian Fault and Kephalonian Transform Fault (Goldsworthy et al.,

2002 their figure 20; Papanikolaou and Royden, 2007; Özbakir et al., 2020; Tsampouraki-Kraounaki et al., 2021). Crustal thickness is partly controlled by the Central Hellenic Shear Zone (e.g., Zelt et al., 2005; Papanikolaou and Royden, 2007) and, thus, it is not unconceivable that the Corinth Rift too formed along inherited orogenic structures. This is suggested by Pan African and Variscan contraction preserved in E–W-striking orogenic belts in Creta (Finger et al., 2002; Romano et al., 2004). Regardless, even though further work is required to determine whether the Central Hellenic Shear Zone formed along preexisting orogenic structures, it is anyway irrelevant to the present study, which focuses on the controlling relationship of rift-orthogonal orogens onto major transform faults. The proposed relationship also applies to the North Anatolian Fault. While it is tempting to include the case of the North Anatolian Fault in the present manuscript after uncovering a possible controlling relationship of preexisting orogens on this this fault too, it is unclear whether this would fit in the ruptured or continuous type of orogenic bridges.

Changes: None.

Comment 21: Page 5 “much of the submarine area around the globe…”: how much is the question, this is much too vague.

Response: Agreed. See response to comments 2 and 9.

Changes: See response to comments 2 and 9.

Comment 22: Page 5: “Land bridges were once proposed by knowledgeable scientists in the early 20th century. It is therefore not surprising that it may hold some truth after all”. What is surprising here is that the fact these scientists were famous is presented as a scientific argument in favor of your theory! Many famous scientists have made mistakes in the past! And it is probably the same nowadays.

Response: Disagreed. This fact is not used as an argument to support our theory, but to call out the reader’s attention to the fact that these scientists (e.g., H. von Ihering, C. Schuchert, J. Gregory) were not just complete idiots who got it completely wrong. As discussed in our response to comment 19, the present manuscript shows that the long-lived connections between some continents proposed by these scientists existed and still exist, though not in the form these scientists proposed them, and can be reconciled with Wegener’s Drift Theory and modern plate tectonics. See response to comments 13 and 19.

Changes: See response to comments 13 and 19.

Comment 23: Page 5 “the amount of … lateral movements… over the history of the Earth are currently overestimated”. In the absence of alternative quantitative estimates and proposition of an alternative quantitative model, I do not understand how you can dismiss the figures given by magnetic anomalies and transform faults. Even more so when we know that space geodesy agrees at more than 99% with classical plate kinematics.

Response: Again, the authors of the present manuscript do not dispute the fact that the continents are moving. However, it can be agreed that magnetic data are overinterpreted

and that rift-parallel linear magnetic anomalies do not necessarily reflect oceanic crust but may in some cases reflect linear intrusions in continental crust (e.g., Nasuti et al., 2015; Geoffroy et al., 2021, 2022; Koehl and Stokmo, 2024). The authors of the present manuscript concede that they should further specify their claims. Notably, the pinning of Baltica and Laurentia since the late Paleoproterozoic should be insisted upon. See response to comments 2, 9, and 10.

Changes: See response to comments 2, 9, and 10.

Comment 24: Page 8 and following: I miss a detailed reconstruction of the evolution of the Fram strait and surrounding regions following your theory here. I am not even sure you think that the Atlantic ocean ever opened ... This remark is true for all the examples you discuss in the next sections. The text and figures are much too unprecise to convince anyone.

Response: See response to comment 9 about plate reconstructions (which are out of the scope of the present manuscript). The remark of the reviewer is correct, there is no proof that there is oceanic crust in between the two transform faults in the Fram Strait. The authors of the present manuscript, however, do agree with the evidence suggesting that the Atlantic Ocean has opened at the Mohns and Knipovich segments and that the Arctic Ocean has opened too (and that the Iapetus Ocean probably opened between Greenland and Norway). Again, the only questionable oceanic domains (the authors of the present manuscript are not questioning entire oceans) is the Iapetus Ocean between Svalbard and Greenland and, possibly, the Atlantic–Arctic ocean between the two transform faults in the Fram Strait. The current state of the art there is that the mantle was exhumed along low-angle core-complex detachments and sediments deposited (Koehl et al., 2021). In addition, there is evidence of thin (hundreds of meters) volcanics along the Molloy fault zone (Koehl, in prep.). However, there is no evidence for gabbroic–basaltic oceanic crust thus far. The authors of the present manuscript concede that the specific oceanic domains they question should be better specified in the manuscript. See also response to comments 2, 9, 10, and 23.

Changes: Added outlines of the offshore areas with anomalously thick crust suggested to be continental instead of oceanic in Figure 1. See also response to comments 2, 9, 10, and 23 for all other changes.

Comment 25: Page 13 and following: I need figures showing the evolution of RRR triple junctions in your model...

Response: Disagreed. There is no need for plate reconstructions yet. See response to comment 9.

Changes: See response to comment 9.

Comment 26: Page 15: about Iceland. How is the presence of a thick crust incompatible with a plume underneath? A plume leads to more oceanic crust production and thus a thicker crust. Also “no seismic evidence of anomalously high temperature or melts in Iceland’s

subsurface"... is the intense volcanic activity not enough as an evidence? And seismic tomography shows the anomaly quite well.

Response: Disagreed. A plume would certainly leads to increased amounts of magmatism, but not to a thicker oceanic crust. This is not in line with the principle of isostasy. As it turns out, no, intense volcanism is not enough to determine the nature of the crust at depth. Counterexamples include Traps (e.g., Deccan and Siberian) and Rifted Oceanic Magmatic Plateau (e.g., Rime et al., 2024), which are episodes of intense magmatism occurring onto continental crust. The same appears to be true at the Greenland–Iceland–Faroe Ridge, where major late Paleoproterozoic thrust systems in continental crust can be traced below and past SDRs (Koehl et al., 2024b), which were previously thought to represent the continent–ocean boundary, and all the way to Iceland (Koehl et al., 2025) In southeastern Iceland notably, they reach up to relatively shallow crustal levels (c. 3–5 km). In addition, despite seismic tomography showing an anomaly, the anomaly is nowhere near what it should be to support the entirety of the Icelandic crust being oceanic. The model by Zhang et al. (2024 their figure 12) shows two narrow, cylindrical zones of upwelling below Iceland, which may represent magma ascending from the plume through the crust. The rest of the crust, especially the lower crust, is more likely to be continental. See response to comment 11.

Changes: See response to comment 11.

Comment 27: Pages 15-16: again a confusion between absolute and relative motions...

Response: Agreed. See response to comment 8.

Changes: See response to comment 8.

Comment 28: The discussion about far East Asia seems totally speculative.

Response: Disagreed. The earthquake record in northeastern Russia (Cook et al., 1986; Fujita et al., 1997; Imaeva et al., 2018; Imaeva et al., 2019) clearly indicates (1) that the Arctic rift and Gakkel Ridge are propagating towards the rift-parallel arm of the Verkhoyansk Orogen, and (2) that strike-slip movements already occur along the arm of Verkhoyansk Orogen orthogonal to the Gakkel Ridge. It is therefore probable that this rift-orthogonal orogen will be the locus of a new transform fault should the Gakkel Ridge propagate all the way to mainland Russia. Furthermore, present-day rifting is already known from the Baikal region. It is only natural to wonder and discuss whether the two rifts could potentially merge sometime in the future. Should the reviewer have specific comments about this discussion, he is welcome to submit them in his evaluation of the revised version of the manuscript. The authors of the present manuscript however concede that mention of the late Paleoproterozoic orogens in Siberia, which could facilitates propagation of the Baikal and Arctic rifts should be included in the present manuscript.

Changes: Modified Figure 7 to include the outline of the Siberian craton and of relevant late Paleoproterozoic orogens. Also rewrote the caption of Figure 1a into: "Location map of the Gakkel Ridge, its termination in the Arctic Ocean, and its possible future propagation

(dotted yellow line) on the edge of the Siberian craton. The possible future propagation could form along the N–S-striking segment of the Verkhoyansk Orogen in northern Russia, stepping sideways along a major future/proto transform fault (e.g., Ulakhan fault system) to form parallel to the E–W-striking segment of the orogen. Southward, the Gakkel Ridge may merge with the Baikal Rift either by stepping to the west along preexisting orogenic fabrics of the late Paleoproterozoic Akitkan Orogen (1) or along the southern continuation of the Verkhoyansk Orogen, i.e., following preexisting late Paleoproterozoic fabrics such as that of the Ulkan Orogen/Suture (2), and via another major step across another transform fault (South Tukuringra fault). The outline of the Siberian craton and related orogens is from Donskaya (2020). Abbreviations: AO: Akitkan Orogen; STF: South Tukuringra fault; UFS: Ulakhan fault system; UO: Ulkan Orogen/Suture.". Also added "and late Paleoproterozoic Akitkan Orogen (Donskaya, 2020; Sears & Price, 2000)", "where it may follow preexisting late Paleoproterozoic structures of the Ulkan Orogen/Suture (Didenko *et al.*, 2015; Donskaya, 2020; Sears & Price, 2000)", and ", which runs parallel to the E–W-striking Cis–Stanovoy Orogen (Donskaya, 2020). Thus, both proto transform faults in the area (Ulakhan fault system and Tukuringra fault) also follow preexisting orogenic structures and fabrics ( Figure 7a)." to the last two paragraphs of the "Propagation of the Gakkel Ridge towards northern Russia along the Verkhoyansk Orogen" sub-section.

Comment 29: Page 19: implications for plate tectonics and modeling. These two paragraphs are really difficult to follow, I did not get the message.

Response: Agreed. The authors of the present manuscript concede that this section needs reworking.

Changes: Rewrote the section nearly entirely and included three new paragraphs: "We propose the existence of long-lived, continuous orogenic bridges, e.g., the late Neoproterozoic Timanian orogenic bridge in the Fram Strait, late Paleoproterozoic Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and late Paleoproterozoic Nagssugtoqidian–Laxfordian Greenland–Iceland–Faroe orogenic bridge at the GIFR ( Foulger *et al.*, 2020a; Koehl & Mottram, 2024; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Peace *et al.* 2018; Figure 3a–d and Figure 4). The theory suggests that past plate tectonics was less dynamic than typically suggested by current plate models. Models involving the repeated opening of through-going Phanerozoic oceans, which unzipped continental blocks and/or continents now known to be still connected by continuous (or recently ruptured) Precambrian orogenic bridges are no longer viable solutions to geological observations and geophysical datasets. For example, the Iapetus Ocean and northeastern Atlantic Ocean both opened between Norway and Greenland as suggested by the occurrence of Cambrian ophiolites and Caledonian metamorphism and thrusting in mid-Norway (e.g., Furnes *et al.*, 1988; Slagstad *et al.*, 2020). However, despite the occurrence of blueschist-facies metamorphism of Caledonian age suggesting rapid subduction of mafic rocks to great depth in western Svalbard ( Horsfield, 1970; Kosminska *et al.*, 2014), it is unlikely that these two oceans fully opened between Svalbard and Greenland because this would require rupture of a possibly still continuous late Neoproterozoic orogenic bridge (e.g., Timanian orogenic bridge between Svalbard and northern Greenland; Figure 4). This is supported by the mapping of late Neoproterozoic Timanian thrust systems without any offset or truncation ( Koehl, 2020; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl & Mottram, 2024;

Koehl, 2024 awaiting peer review) across the previously assumed Caledonian/Iapetus sutures in the Barents Sea and western Svalbard ( Breivik *et al.*, 2005; Horsfield, 1970; Kosminska *et al.*, 2014). It is also supported by the delayed opening of the Fram Strait at ca. 24 Ma ( Engen *et al.*, 2008) or possibly still yet to happen (present study and Koehl *et al.*, 2021), i.e., much later than the opening of the Mohns Ridge between Greenland and Norway and Arctic Ocean at ca. 56 Ma ( Faleide *et al.*, 1993; Faleide *et al.*, 2008; Gaina *et al.*, 2002; Srivastana, 1985). If the late Neoproterozoic Timanian orogenic bridge had already been ruptured by the opening of Iapetus, breakup in the Fram Strait would not have taken more time (or at least not much longer) to achieve than between Norway and Greenland and in the Arctic Ocean. This also applies to the Iapetus Ocean and northeastern Atlantic Ocean at GIFR. Furthermore, if breakup had already occurred at the GIFR, transform faulting at the Tjörnes fault zone accommodating sliding of late Paleoproterozoic (or older) continental crust in the southwest against Cenozoic oceanic crust in the northeast would not have been required. Thus, although Iapetus did open and close in some places (e.g., between Norway and Greenland), it clearly did not in others (GIFR and Fram Strait). Less magmatism at (both present-day and paleo) mid-ocean ridges does not necessarily imply less tectonic extension since orogenic bridges contract and extend together with adjacent oceanic domains ( Figure 3). However, the pinning of long-lived continental blocks together, e.g., Baltica and Laurentia for the past 1.8 Gyr via a continuous late Paleoproterozoic orogenic bridge at GIFR, greatly restricts the amount of relative and absolute paleo plate movements of these two cratons, i.e., suggesting significantly less dynamic plate tectonics. Notably, the Iapetus Ocean was probably much narrower than the previously suggested 5000 km (Torsvik & Trench, 1991; Fortey & Cocks, 2003) and a $\leq$ 1000 km width similar to that of the present-day Northeastern Atlantic Ocean is more plausible because it would not have resulted in rupture of the Timanian and Greenland–Iceland–Faroe orogenic bridges. For example, if the late Paleoproterozoic Greenland–Iceland–Faroe orogenic bridge had ruptured, it would include traces of intense Caledonian deformation with possible suture zones, tight folds, and segments of oceanic crust. This is neither in line with current crustal thickness estimates across the GIFR (25–40 km), which indicate continental crust in Iceland's lower crust (Darbyshire *et al.*, 1998; Foulger *et al.*, 2003; Foulger *et al.*, 2020a), nor with the open/gentle character of the Caledonian folds reworking the late Paleoproterozoic thrust systems at the GIFR, which indicate mild Caledonian deformation (Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, models like that of the rotation of Baltica in the Cambrian–Ordovician (e.g., Torsvik & Rehnström, 2001; Trench & Torsvik, 1992) are no longer viable alternatives. This has implications for ophiolites and eclogite- and blueschist-facies metamorphism as it may indicate that some presumed ophiolites, e.g., km-wide blueschist units in western Svalbard ( Agard *et al.*, 2005; Horsfield, 1970; Kosminska *et al.*, 2014), may simply correspond to lava flows and/or igneous rocks intruded into continental crust, which were later imbricated during subsequent (Caledonian) orogenesis. This may suggest that some presently assumed ophiolites may not necessarily reflect the closure of paleo-oceans (sutures). If these presumed ophiolites have indeed been deposited onto or intruded into and imbricated together with continental crust, they would have been relatively difficult to quickly subduct to great depth ($\geq$ 50–70 km) due to the relative buoyancy of continental crust. Thus far, rapid subduction to great 50– 70 km depth was generally considered necessary to explain the occurrence of blueschist metamorphism (e.g., Agard *et al.*, 2005; Agard *et al.*, 2009). Hence, alternative models may therefore need to be further explored for the formation of some high-pressure metamorphic rocks ( Jamtveit *et al.*, 2018; Luisier *et al.*,

2019; Moulas *et al.*, 2013; Yamato & Brun, 2016), and the interpretation of some rock units as ophiolites may need to be reexamined. In addition, models involving large lateral movements of various terranes hundreds to thousands of kilometers in different directions over a few tens of million years (e.g., Harland *et al.*, 1992; Majka *et al.*, 2021) can no longer be used to explain local heterogeneities in basement rocks in continuous or recently disrupted orogenic bridges (e.g., Timanian orogenic bridge; Koehl, 2020; Koehl *et al.*, 2022). The occurrence of a continuous/recently ruptured late Neoproterozoic orogenic bridge throughout the Barents Sea, Svalbard, and the Fram Strait suggests that such (presumably early Paleozoic) terrane movements are unlikely. Else the Timanian Orogen would have been disrupted and breakup in the Fram Strait would have been achieved quicklier, which is not the case ( Koehl, 2020; Koehl, 2024 awaiting peer review; Koehl *et al.*, 2021; Koehl *et al.*, 2022; Koehl & Mottram, 2024). The overestimation of the extent of oceanic crust on Earth, especially at orogenic bridges (e.g., Foulger *et al.*, 2003; Foulger *et al.*, 2020a; Foulger *et al.*, 2020b; Geoffroy *et al.*, 2022a) and magmatic passive margins (e.g., Geoffroy *et al.*, 2022a; Geoffroy *et al.*, 2022b; Koopmann *et al.*, 2014; Reeve *et al.*, 2021), suggests that the intensity, amount, and speed of seafloor spreading at mid-ocean ridges may have been overestimated in many paleogeographic reconstructions. Future reconstructions should therefore address this issue by including updated (extended) domains of continental (including hybrid) crust. Another implication of OrBiT already noted previously is on faunal barriers ( Koehl, 2024) and the use of faunal assemblages in paleogeographic reconstructions, e.g., to infer continental block separation ( Fortey & Cocks, 2003), and on faunal spreading between the continents via orogenic bridges, which remain emerged longer than adjacent areas along the strike of the rift ( Jacobs *et al.*, 2024). Some previous works typically argued that discrete faunal assemblages implied $\geq$ 1000 km distance between continental blocks ( Fortey & Cocks, 2003; Popov & Cocks, 2017). An example is the distinct assemblages of trilobite between Svalbard and Laurentia, which were dominated by Olenellus svalbardensis Kielan in the early Cambrian ( Birkenmajer, 1978; Birkenmajer & Orlowski, 1977; Fritz, 1972; Kielan, 1960; Poulsen, 1974) and by bathyurid trilobite in the Early Ordovician ( Fortey & Bruton, 1973), and Baltica, which was dominated by Holmia, Schmidtiellus, and Kjerulfia genera and ptychopariid trilobites in the early Cambrian ( Ahlberg, 1980; Ahlberg *et al.*, 1986) and asaphid trilobites in the Early Ordovician ( Fortey & Cocks, 2003). The continuous character of late Neoproterozoic Timanian thrust systems through the Barents Sea, Svalbard, and possibly the Fram Strait clearly indicates that Svalbard, Laurentian, and Baltica have been connected since at least the late Neoproterozoic ( Koehl *et al.*, 2022; Koehl, 2024 awaiting peer review; Koehl & Mottram, 2024). Koehl (2024) further illustrated the potential role of WNW–ESE-striking late Neoproterozoic thrust systems of the Timanian Orogen in forming a series of faunal barrier. These impeded exchange and mixing between fauna in Laurentia and Svalbard, which are located in the northern part of the Timanian Orogen and Baltica, which is located mostly south of the Timanian Orogen ( Koehl, 2024). The impact of climatic belt on fauna distribution was also suggested to be underestimated when considering the implications of the paleontological record for paleogeographic reconstructions ( Koehl, 2024). Further considerations need to be given to preexisting orogens when producing new paleogeographic reconstructions. Many of these commonly include cryptic, unrealistic transform plate boundaries (e.g., Cao *et al.*, 2021; Domeier, 2016; Domeier, 2018; Domeier & Torsvik, 2014; Merdith *et al.*, 2021; Torsvik & Cocks, 2016; Young *et al.*, 2019). These cryptic transform boundaries generally do not fulfill the requirement set by OrBiT, i.e., formation of

major transform faults parallel to preexisting, rift-orthogonal orogens. This suggests that they are unlikely to have formed.".

***Competing Interests:*** No competing interests were disclosed.

Reviewer Report 23 August 2024

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The manuscript of Koehl & Foulger proposes a new theory which would provide a "major update" to the current theory of plate-tectonics. They first discuss some issues of the current plate tectonic theory before presenting their new theory which postulate that the style of rifting is controlled by preexisting orogens. Orogenic belt perpendicular to rifting would result in the formation of *Orogenic Bridges* which prevent the formation of oceanic crust and lead to the formation of major transform faults. The authors then discuss different Orogenic Bridges, the issue of localizing the Continent-Ocean-Transition (COT), the formation of triple junctions, and the presence of mantle plumes before making predictions about the future tectonic evolution of several areas of the planet. They then use their theory to reject the tectonic interpretation of several transform zones around the world. Finally, they use their results to question paleotectonic interpretations and to question the former mobility of continents.

Overall, I think that this manuscript shows insufficiency to properly define the concepts it proposes, it fails to identify its major theory as a hypothesis and thus fails to test it properly. It does not provide any solid evidence for several of the hypotheses presented and some of these can easily be rejected with counterexamples. It then grossly overinterpret these hypotheses, as well as the scope, the certainty and the implications of this theory. I therefore suggest the rejection of this manuscript. Details of this reasoning are found below.

**The concept of "orogenic bridge"**

The authors state that they demonstrate "*the occurrence of ridges of orogenically-thickened, (hyper-) extended continental crust (orogenic bridges) striking perpendicular to propagating rifts offshore.*" This is a circular reasoning because they define orogenic bridges as "*orogenically thickened crust part of a rift-orthogonal orogen, which was (hyper-) extended during rifting*". How are these orogenic bridges different than any other passive margin? How does the fact that they feature basement with rift-perpendicular orogenic orientation make them any special? What makes them more of a bridge than any other margin? What do you mean by bridge? Maybe the authors mean that these bridges

extend further into the oceanic realm than normal passive margins? In that case, this is not correctly defined in the paper, and there are no clear evidence of it, or numerous counterexamples.
While it is proven that you can find continental material far offshore offshore in area of strong volcanic activity like Iceland or the Rio Grande Rise (I'd say above hotspots: Rime et al., 2024), the paper fails to show a systematic link between these areas, transform faults, and perpendicular orogenic belts.
The prime example presented here is the Greenland-Iceland-Faroe Ridge (GIFR). However, the last orogenic belt found along its margins, the Caledonian orogeny, strikes almost parallel to the rift axis (which the authors acknowledge). The authors then invoke the older Ammassalik Belt (in Greenland) and the Tornquist Zone (in Europe). This correlation is not valid because 1) Both have very different ages. They thus don't form a single continuous structure. 2) They were both overprinted by the Caledonian orogeny in the region of the future north Atlantic. So, the GIFR is not correlated with a perpendicular orogenic belt. Furthermore, the transform zone associated with the GIFR mentioned in the text is the Tjörnes fault zone which only shows <100 km offset. I would thus not classify it as one of the most important as transform faults with <100 km offset are found everywhere in the oceans. So actually the GIFR does not fit your definition of an orogenic bridge.
The authors also present the Fram Strait as an orogenic bridge. The region of Svalbard and the Barent Sea is very different from the GIFR. Although rifted, is not hyper-extended and it did not experience as much volcanic activity. I fail to understand how these region are any different than normal passive margins except from the fact that they are situated near very important transform fault and that they feature a parallel orogenic belt. The Fram Strait (just like the Falklands) formed a landbridge (in the sense that the two continental masses remained very close to each other) for a long time just because they are very long transform faults systems. And then simply by geometry, the two continents will slide beside each other (and thus remain close) for a long time while the adjacent rift will form oceans and drift apart. For example, for a transform fault of 200 km offset, the two landmasses would still be connected after 190km of motion while the rifted parts would have drifted away by 190km at the same time. But I'm sure the authors are aware of these trivial tectonics concepts, so I wonder what they mean with the concept of orogenic bridges. Is it just that perpendicular orogenic belts promote large transform faults, and then, because transform faults are large, the two landmasses remain close together for a long time? If so, fine (although you'd have to convince me that large transform do indeed correlate with perpendicular orogens, see below), but then why would you present this as a new "theory of the whole" superseding plate tectonics?

**Orogenic bridge or transform faults?**
In the paper, it is not clear if the authors hypothesize that orogenic belts perpendicular to rift do produce major transform faults, or if they produce land bridges that extend far in the oceanic realm (or whatever an oceanic bridge is, see above for the lack of clarity on this notion), and why they would form one or the other, or both. Only in the conclusion do we learn that "*Rupturing of orogenic bridges results in the formation of major transform faults*".
If that would be the case, the authors do not explain how many major transform fault systems do not feature unconventional, continental crust extending in the oceanic domain: Charlie-Gipps, Vema, La Romanche, Ascension Bode Verde, Owen. The authors suggest that the Vema and La Romanche FZ might feature continental material, but this assertion is based on their own theory " *The OrBiT suggests that elongate lithosphere slivers within these transform fault systems are likely*

*continental*." This is a circular reasoning; you can't use your theory to demonstrate a fact that you then use to support your theory. The bathymetry at least does not show any anomaly that would hint at the presence of continental crust there.
As shown above, the authors also don't explain how the GIFR, classified as an orogenic bridge, only features a relatively minor transform fault.

**Transform Faults and orientation of orogenic belt**

The authors define "*major transform faults*" as "*transform faults showing offset of active mid-ocean ridges greater than a few kilometers*." For me, 20 is greater than a few. And a transform fault with 20km is actually very small, you'll find transform faults >20 km everywhere in the oceans so you can correlate it with anything. But ok, for the next part, let's assume more than a few rather mean >100 or >200 km.
One of the major assumptions on which the authors build their theory is that "*Every major transform fault on Earth strikes parallel to an orogen and related structures*". This very categoric assumption is simply wrong. Many major transform faults on the planet do not obey this rule. I give a few examples below looking only at a few of the most important fault zone (FZ) in the world:

1. Agulhas–Falkland fault zone: The authors link the Agulhas–Falkland fault zone to the allegedly parallel-striking Cape Fold Belt and the Sierra de la Ventana fold-and-thrust belt. Firstly, the authors place the Sierra de la Ventana FTB wrong on their map (according to Stanca et al., 2022 [which the authors cite], it is situated 900 km north of what they show on their map). Then, both the Cape FTB (Johnston, 2000) and the Ventana FTB are not parallel to the Agulhas–Falkland fault zone but oblique by about 40°.
2. The Romanche Fault Zone which the authors associate with the Central African Orogen/Oubangides (BTW, none of the papers cited mention the word "Oubangides") and the Sergipano Belt. However, most of the Sergipano Belt (Bueno et al., 2009) as well as the belt separating the West African Craton and the Sahara Metacraton (Kouémo et al., 2014; Meert & Lieberman, 2008) strike 40° to 50° oblique to the Romanche Fault Zone. Hardly parallel.
3. The Charlie-Gibbs FZ: with more than 300 km of offset, one of the largest in the world, it is not parallel but oblique to the Caledonian orogeny by approx. 30° (both looking at Newfoundland and Scotland)
4. The Owen Fracture zone is oblique by approx. 30° to the orientation of the East African Rift System.
5. The Bodo Verde and Ascension Fracture Zones (each featuring more than 200km of offset) are situated approx. perpendicular to the last orogenic event, the Araçuaí-West Congo orogen and the north of this area represent the São Francisco and Congo craton. (Alkmim et al., 2006)
6. All major fault zones situated between the St Paul and the Vema FZ, some featuring more than 200 km of offset, correlates with cratons (Amazonian and West African) and not with orogenic belts.
7. The Jan Mayen FZ (>250 km offset) is located perpendicular to the Caledonian orogeny.

I don't even speak of huge transform faults in the Pacific that do not correlate with any orogenic belt because the margin of this ocean is subducting. But I'll assume that it is only a problem of phrasing of the following sentence: "*Every major transform fault on Earth strikes parallel to an orogen and related structures*".
If the authors want to convince us that there is indeed a correlation (and there might be one), they should provide some serious and systematic statistics where they **quantitatively** compare the

orientation and offset of all (large) transform faults (at least of the Atlantic and Indian Oceans, datasets exist) with the orientation of orogenic systems on the margins. As shown above, this correlation is not going to be 100% but they'll maybe find a significant correlation between the two. And this would be an interesting study. But at the moment, the categoric and unsubstantiated claim that "*Every major transform fault on Earth strikes parallel to an orogen*" is just wrong.

**Triple junctions**

The authors pretend that triple junctions only form at the intersection of two orogens.
I think that the authors mixed here between transform faults and Mid Ocean Ridge (The Rodrigues Triple Junction shows three ridges but no major transform faults. So why would you need two orientations? BTW, it is shown above that transform fault can also form oblique or perpendicular to orogenic belts) or that they deem impossible to form a Mid Ocean Ridge if not perpendicular to an orogenic belt. The latest is of course wrong (otherwise we would not have the Atlantic Ocean offshore the USA).
For the Bouvet Triple junction, the two orientations mentioned are the Agulhas–Falkland fault zone orientation and the Andrew Bain fault zone orientation. If you measure the angle between these two orientations, it is approximately 20° (and not 45° as mentioned in the manuscript). This difference is small and I doubt it would have a dramatic impact. There are much more important differences in orientations in orogenic belts at the latitude of the Romanche FZ (e.g. Meert & Lieberman, 2008) but no triple junction here. Neither in the north Atlantic at the junction of the Caledonian orogeny and the Tornquist Zone (which are almost perpendicular).
Then if you look at another very prominent triple junction, the Afar Triangle, you'll see that it is only influenced by the East African Orogeny, and not by two different orogenic systems with different orientations (e.g. Johnson et al., 2011; Fritz et al., 2013). We, for example, proposed that the localization of the Afar Triple Junction is, at least partly, controlled by the East African orogeny in conjunction with many different tectonic accidents linked to extensional events (Rime et al., 2023).
There are therefore no solid arguments to state that triple junctions are formed at the intersection of at two (or more) orogenic systems. Certainly not with the wording used here that presents it as an indisputable conclusion.

**"Much of the submarine area around the globe" is continental**

The authors say that "*much of the submarine area around the globe consist of (hyper-) extended and/or extensively intruded (i.e., hybrid) orogenic continental crust*".
This statement is not supported by any meaningful data. Even if the authors mention the difficulties of determining the COT, and that some continental material can be dragged far offshore in area of strong volcanic activity, it is a strong overinterpretation to say that much of the submarine area around the globe consist of continental material. Even if we assume that all areas that are considered as Oceanic Large Igneous Province are continental (good luck convincing me that the Shatsky Rise is continental), they only cover 6% of the oceanic realm (Mooney et al., 2023).
The authors also seem suggest that most of the western Indian Ocean (including Mozambique Basin, the Mascarene Basin and the Somalian Basin) is continental (Fig. 1). I agree that some continental fragments are dispersed in this area (Rime et al., 2024), but the basins in between all have pretty clear oceanic characteristics, including crustal thickness, bathymetry, magnetic anomalies and geophysical characteristics (e.g. Simplson et al., 1979; Scrutton et al., 1981; Masson,

1984; Coofin & Rabinowitz, 1987; König & Jokat, 2010, Seton et al., 2012, Laske et al., 2013). The assertion that they are continental would indeed be quite a change of paradigm, but you'd need a bit more than a figure (to say the least) to suggest it.
It is thus a gross overstatement to say that **much** of the submarine area consists of continental material. If you want to argue for such a groundbreaking hypothesis, you have to present maps, calculate areas (in $km^2$) that you consider as potentially continental and give arguments as to why you reject each specific area as an ocean. And this cannot be done in a few lines.
Even if we assume that this theory is correct, it does not imply that "*The dynamism and intensity of seafloor spreading at mid-ocean ridges may have been overestimated*". If these areas do feature continental crusts, they are hyper-extended and, thus, mobile and transported far away from their margins (see for example the model proposed here: Rime et al., 2024) and it does not prevent the ocean from getting very wide or opening very rapidly.

**The Orogenic Bridge theory – from a hypothesis to a universal truth**
Probably the most important flaw of the paper is that what should have been an hypothesis to be tested, is considered as an universal truth that is even raised above the most important theory of geology: plate tectonics. Wow! Nothing less? I would advise the authors to approach the topic with more humility.
First of all, what is presented here is a hypothesis. As discussed above, the authors did not provide any substantial evidences for several of their hypotheses. Some might be valid (not as categorically as presented, I have shown several counterexamples, but there might be some correlations), but the paper does not present any solid evidence for it. But the authors do not seem to consider it as a hypothesis (the word "hypothesis" is never used with regard to their theory) and that maybe explains why they did not test it properly.
The authors then use this theory to reject existing geological interpretations with an impressive degree of self-confidence. "*Any transform or paleo transform fault that does not fulfill this condition may thus be discarded as a transform fault or even simply as a fault.*" Really? You probably want to change the definition of what a fault is then? I highlighted above how some of the biggest transform faults in the world do not obey this theory. But it is absurd to expand it to any fault or even transform fault globally. Millions of faults (and a bunch of transform faults) are not parallel orogenic belts. This is a gross overinterpretation of an unproven hypothesis.
The authors then go one step further by implying that orogenic bridges cannot be ruptured, without argumentation for this assertion. They reject some important paleotectonic interpretations of earth history based on this, again with a surprising degree of confidence, stating that these interpretation "*are no longer viable solutions*". They discard the opening of the Iapetus Ocean "*because they would require the rupture of an orogenic bridge*". Of course, orogenic bridges can be ruptured. There is a full section of the manuscript discussing "*Ruptured orogenic bridges*". They state that some of the orogenic bridges presented in the paper are "*long-lived, continuous orogenic bridges*" and use this argument to discard the Iapetus Ocean. They did not present any serious evidence that these orogenic bridges were long-lived and continuous (e.g. the one under Iceland is formed by two different orogeneses of two completely different age). If they want to question the existence (or extent) of the Iapetus Ocean, the authors should write a full paper on it (and not a few lines), discussing the existing literature and clearly laying out why they reject the geological and geophysical evidences presented in the literature. They cannot base their argumentation entirely on a novel and unproven hypothesis to disqualify any previous geological or geophysical study conducted on the topic. This aspect of "unbreakable orogenic bridge"

constitutes, again, a gross overinterpretation of the data presented.
The authors then go one more step further and elevate their hypothesis at the level (or above) the theory of plate tectonics in the form of a “major update”. Plate tectonics is the most important theory of geology and explains the movements and deformation of continents with concepts like Mid-Ocean Ridges, subductions, orogens, mantle movement, etc. The hypothesis presented here is nowhere near a “major update” for plate tectonics as it does not have implications for subduction zones, collision zones, mantle movements or most of the mid-ocean ridges. Even if we would assume that the orogenic bridge theory is correct, it would only constitute an update on how inherited structures influence the structure of plate boundaries in extensional domain (a topic that is relevant, but that does not call for an update on the plate tectonics theory: e.g. Brune et al., 2017; Zwaan et al., 2021; Corti et al., 2022; Brune et al., 2023; Pérez-Gussinyé et al., 2023). Again, a bit more humility would help.

**Remark**

They are several more points that would need corrections, but as I deem this manuscript unsuitable for indexing, I did not list them all, nor did I did not check every details of the manuscript, every study site, all references,...
If the authors want to index some of the ideas presented in this manuscript (I would encourage them to look at the correlation between transform faults and orientations of orogenic belts with a quantitative approach), I would suggest to do a completely new manuscript focused on the testing of one hypothesis.

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**Is the work clearly and accurately presented and does it cite the current literature?**

Partly

**Is the study design appropriate and does the work have academic merit?**

No

**Are sufficient details of methods and analysis provided to allow replication by others?**

Yes

**If applicable, is the statistical analysis and its interpretation appropriate?**
Not applicable

**Are all the source data underlying the results available to ensure full reproducibility?**
No source data required

**Are the conclusions drawn adequately supported by the results?**
No

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Tectonics (rifts, passive margins, fold-and-thrust belt, oceanic plateau, plate tectonics)

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.**

Author Response 10 Mar 2025

**Jean-Baptiste Koehl**

Dear Dr. Rime, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

**Comments by the reviewer**
Comment 1: The manuscript of Koehl & Foulger proposes a new theory which would provide a “major update” to the current theory of plate-tectonics. They first discuss some issues of the current plate tectonic theory before presenting their new theory which postulate that the style of rifting is controlled by preexisting orogens. Orogenic belt perpendicular to rifting would result in the formation of Orogenic Bridges which prevent the formation of oceanic crust and lead to the formation of major transform faults.
Response: Disagreed. Orogenic bridges do not prevent the formation of ocean crust but hinder (i.e., delay) it at orogen striking parallel to the propagating rift. Changes: Rewrote the last sentence of the first paragraph in the Introduction chapter into “Since the orogens are consistently older than the rifts and transforms with which they correlate ( Figure 1), they are therefore proposed to have played a central role in controlling the formation of the transform faults and in forcing the rift to step sideways and/or in hindering (i.e., delaying or preventing) continental breakup, acting as potential barriers to rifting.”. Rewrote the first sentence of the fourth paragraph of the “Orogenic bridge theory” section into “Conversely, orogens striking highly oblique to perpendicular to a propagating rift (“rift-orthogonal endmember”) will act as barriers and significantly hinder rift propagation, i.e., significantly delaying breakup or preventing the rift from opening in a linear fashion or from propagating.”. Rephrased one of the last sentences of the “Greenland–Iceland–Faroe

orogenic bridge" sub-section into: "We therefore propose that the GIFR represents a continuous orogenic bridge, which is currently preventing through-going propagation of the mid-Atlantic rift". Rephrased point 2 in the "conclusions" chapter into: "Existing orogenic bridges oriented suborthogonal to a propagating rift form major barriers of thickened continental crust that significantly hinder the opening of a rift and breakup.".

Comment 2: The authors then discuss different Orogenic Bridges, the issue of localizing the Continent-Ocean-Transition (COT), the formation of triple junctions, and the presence of mantle plumes before making predictions about the future tectonic evolution of several areas of the planet. They then use their theory to reject the tectonic interpretation of several transform zones around the world. Response: Partly disagreed. The present study shows that paleo-transform faults are possible to trouble-shoot using the new theory and the newly established global correlation of major transform faults with preexisting, rift-orthogonal orogens should there be doubts around their existence. The present work uses examples of two paleo-transform faults that were invalidated by previous studies, namely the Wegener Fault and De Geer Zone, both of which were rejected by the interpretation of high-resolution geophysical data (e.g., Oakey & Damaske, 2006; Oakey & Stephensen, 2008; Dawes, 2008; Hansen *et al.*, 2011;; Rasmussen & Dawes, 2011; Koehl, 2024 awaiting peer review). The authors of the present manuscript concede that the first paragraph of the "Testing the existence of tentative (paleo) transform faults" section is poorly written. Changes: Rewrote the first paragraph of the "Testing the existence of tentative (paleo) transform faults" section into "OrBiT can help test the plausibility or likelihood of tentative (paleo-) transform faults should any doubts be cast on their existence or kinematics. The theory predicts that the formation of major transform faults is controlled by orogens striking (sub-) orthogonal to propagating rifts. Any transform or paleo-transform fault that does not fulfill this condition is therefore highly unlikely according to OrBiT. Should the theory be further tested and substanciated, it would allow quick and smooth testing/troubleshooting of specific transform faults worldwide. Transform and paleo transform faults not obeying OrBiT's principles (i.e., formation parallel to preexisting rift-orthogonal orogen) would thus be possible to discard as a (paleo) transform faults or even in some cases as faults. Two such examples are the De Geer Zone in western Svalbard and the Wegener Fault between Greenland and Ellesmere Island ( Figure 4).".

Comment 3: Finally, they use their results to question paleotectonic interpretations and to question the former mobility of continents. Response: If the reviewer implies that the authors of the present manuscript reject all past plate tectonic movements, then the authors of the present manuscript do not agree with the reviewer's comment. If the reviewer implies that the authors of the present manuscript reject some doubtful past plate tectonic movements or question the amount of movement/distance over which the continents moved, then the authors of the present manuscript agree with the comment of the reviewer. Changes: The authors of the present manuscript await further clarification and specification of the comment by the reviewer.

Comment 4: Overall, I think that this manuscript shows insufficiency to properly define the concepts it proposes, it fails to identify its major theory as a hypothesis and thus fails to test it properly. Response: Agreed. The authors of the present manuscript fully agree that this should be made clearer that the concept proposed is a new theory that needs to be further

tested. Changes: Completely rewrote the abstract into “Plate tectonics is a centerpiece of Earth’s geodynamics and is of primary importance in making our planet habitable, securing natural resources, mitigating geohazards and climate change, and investigating the evolution of life. Understanding plate tectonics is increasingly important due to the ongoing energy transition. At the core of plate tectonics, the supercontinent cycle suggests that continental landmasses repeatedly accrete into supercontinents and then break up during rifting. Thus far, rifting was thought to gradually unzip continents from one another and to be mostly controlled by geodynamic processes (e.g. subduction, mantle plumes). Orogenic Bridge Theory (OrBiT) suggests another first-order controlling factor and states that preexisting orogens perpendicular to active rifts hinder breakup, forcing rifts to jump, and localizing major transform faults. Such orogens require more time to break due to the thickened character of orogenic crust and obliquity of related structures. Thus, while seafloor spreads on either side of rift-orthogonal orogens, extension continues to stretch the orogenic crust until breakup occurs there later. These regions of stretched continental crust flanked by oceanic crust are called “orogenic bridges”. OrBiT implies that the extent of continental crust may be underestimated and, thus, that our understanding of plate tectonics is incomplete. OrBiT may help predict future plate tectonics, e.g. localization of future rifts and transform faults, which typically host natural resources and cause geohazards. This new theory is based on a new global correlation of major transform faults with rift-orthogonal orogens and ongoing work at various potential orogenic bridges and continental margins. The theory is hereby shared with the scientific community in the hope that it gets further tested”. Added “(or unzipping)” to the last paragraph of the “Greenland–Iceland–Faroe orogenic bridge” sub-section. Rewrote the third sentence of the “Implications for plate tectonics and modeling” section into “Models involving the repeated opening of through-going Phanerozoic oceans, which unzipped continental blocks and/or continents now known to be still connected by continuous (or recently ruptured) Precambrian orogenic bridges are no longer viable solutions to geological observations and geophysical datasets.”. Split the third paragraph of the “Orogenic bridge theory” section into two and rewrote it into “In the present contribution, we review the relationship between major transform faults and preexisting orogens on adjacent margins across all oceans. Orogenic bridge theory (OrBiT) states that the style of continental rifting (e.g., orthogonal, oblique, transform) is intrinsically controlled by preexisting orogens and that, notably, orogens parallel to a propagating rift will facilitate rifting and breakup, whereas orogens perpendicular to the opening rift will result in the development of orogenic bridges (strong barriers), which force the rift to step and/or delay breakup. Preexisting orogenic belts striking parallel to a propagating rift will facilitate the opening and propagation of the rift and control the strike and geometry of structures formed during rifting. These include dominantly extensional structures such as brittle normal faults and ductile detachments bounding sedimentary basins and basement horsts and metamorphic core complexes ( Figure 2a). This endmember (“rift-parallel endmember”) has been in several papers (e.g., Brune *et al.*, 2023; Chenin *et al.*, 2015; Corti *et al.*, 2022; Li *et al.*, 2023; Osagiede *et al.*, 2020; Péron-Pinvidic & Osmundsen, 2020; Péron-Pinvidic *et al.*, 2022; Salazar-Mora *et al.*, 2018).”. Added a new figure detailing the formation of orogenic bridges: “Development of orogenic bridges. (a–b) Orogenic bridges typically form through at least two orogeneses perpendicular to one another, which allows tightening and locking of the crust, e.g., in the case of the GIFR (a) WNW–ESE-striking Laxofordian–Nagssugtoqidian Orogen and (b) NE–SW-striking Caledonian Orogen. (c) Several episodes of post-orogenic extension (e.g., in

the Devonian, Permian–Triassic, and Jurassic–Cretaceous at the GIFR) are accommodated along extensional faults and detachments formed along inherited orogenic structures. (d) Breakup occurs along inherited, reactivated and/or overprinted orogenic structures. In the case of the GIFR breakup occurred first in the Cenozoic at the Reykjanes Ridge south of the GIFR and at the Ægir Ridge northeast of the GIFR. Note that any number of additional orogeneses and/or extensional collapse/rifting may be added in between these events. Abbreviations: GIFR: Greenland–Iceland–Faroe Ridge; TFZ: Tjörnes fault zone. Modified after Koehl *et al.* (2024).” and reference to the figure in the text. Added a new paragraph in the “Implications for plate tectonics and modeling” section: “Another implication of OrBiT already noted previously in Koehl (2024) is on faunal barriers ( Koehl, 2024) and the use of faunal assemblages in paleogeographic reconstructions, e.g., to infer continental block separation ( Fortey & Cocks, 2003), but also on faunal spreading between the continents ( Jacobs *et al.*, 2024). Some previous works typically argued that discrete faunal assemblages implied ≥ 1000 km distance between continental blocks ( Fortey & Cocks, 2003; Popov & Cocks, 2017). An example is the distinct assemblages of trilobite between Svalbard and Laurentia, which were dominated by Olenellus svalbardensis Kielan in the early Cambrian ( Birkenmajer, 1978; Birkenmajer & Orlowski, 1977; Fritz, 1972; Kielan, 1960; Poulsen, 1974) and by bathyurid trilobite in the Early Ordovician ( Fortey & Bruton, 1973), and Baltica, which was dominated by Holmia, Schmidtiellus, and Kjerulfia genera and ptychopariid trilobites in the early Cambrian ( Ahlberg, 1980; Ahlberg *et al.*, 1986) and asaphid trilobites in the Early Ordovician ( Fortey & Cocks, 2003). The continuous character of late Neoproterozoic Timanian thrust systems through the Barents Sea, Svalbard, and possibly the Fram Strait clearly indicates that Svalbard, Laurentian, and Baltica have been connected since at least the late Neoproterozoic ( Koehl *et al.*, 2022; Koehl, 2024 awaiting peer review; Koehl & Mottram, 2024). Koehl (2024) further illustrated the potential role of WNW–ESE-striking late Neoproterozoic thrust systems of the Timanian Orogen in forming a series of faunal barrier. These impeded exchange and mixing between fauna in Laurentia and Svalbard, which are located in the northern part of the Timanian Orogen and Baltica, which is located mostly south of the Timanian Orogen ( Koehl, 2024). The impact of climatic belt on fauna distribution was also suggested to be underestimated when considering the implications of the paleontological record for paleogeographic reconstructions ( Koehl, 2024).”. Also added the new references to the reference list.

Comment 5: It does not provide any solid evidence for several of the hypotheses presented and some of these can easily be rejected with counterexamples. Response: See response to comments 13, 14, and 16. Changes: See response to comments 13, 14, and 16.

Comment 6: It then grossly overinterpret these hypotheses, as well as the scope, the certainty and the implications of this theory. Response: See response to comments 13, 14, and 16. Changes: See response to comments 13, 14, and 16.

Comment 7: I therefore suggest the rejection of this manuscript. Details of this reasoning are found below. Response: The authors of the present manuscript are thankful to the European Commission for having established one of the first peer-reviewed journal disabling manuscript “rejection”. The manuscript will remain published online and hopefully (pending major revisions by the authors as suggested by the reviewers) pass peer review. In most journals, rejected manuscripts are never made public and potentially great ideas have

been dismissed sometimes repeatedly in some smaller communities, either due to a lack of objectivity and/or expertise from the reviewer(s) or lack of resources (may they be time, salary, and/or courage) for the authors to revise and resubmit the manuscript, thus slowing down scientific progress. The authors of the present manuscript are thankful to Open Research Europe and the European Commission for having turned the peer-review process into a much more open and transparent dialog between authors and reviewers. Changes: None required

Comment 8: The concept of "orogenic bridge" The authors state that they demonstrate "the occurrence of ridges of orogenically-thickened, (hyper-) extended continental crust (orogenic bridges) striking perpendicular to propagating rifts offshore." This is a circular reasoning because they define orogenic bridges as "orogenically thickened crust part of a rift-orthogonal orogen, which was (hyper-) extended during rifting". Response: Disagreed. The targeted structures were mapped and established in other peer-reviewed studies, which also documented the primarily contractional kinematics of the targeted structures and their extensional reactivation (e.g., Peace et al., 2018; Koehl et al., 2021, 2022a, 2023b, 2024b, 2025; Koehl, 2024 awaiting peer review). The present manuscript then defines rift-orthogonal orogens as orogenic bridges where they form salients at margins with ruptured orogenic bridges or possibly continuous bridges of continental crust at margins with continuous orogenic bridges on the basis of these previous studies. Since the present manuscript bases the new theory on previous peer-reviewed studies, it cannot be circular reasoning even though the present manuscript includes the definition of "orogenic bridges" in the Introduction chapter. This is done to make the present manuscript clearer and avoid being repetitive in reaching the same conclusion for each discussed potential orogenic bridge. Changes: None.

Comment 9: How are these orogenic bridges different than any other passive margin? How does the fact that they feature basement with riftperpendicular orogenic orientation make them any special? Response: Agreed. The authors of the present manuscript concede that the concept of orogenic bridge is not well defined and explained. See response to comment 4. Changes: See response to comment 4.

Comment 10: What makes them more of a bridge than any other margin? What do you mean by bridge? Maybe the authors mean that these bridges extend further into the oceanic realm than normal passive margins? In that case, this is not correctly defined in the paper, and there are no clear evidence of it, or numerous counterexamples. Response: Disagreed. See also response to comments 4, 13, 14, and 16. Nevertheless, the authors of the present manuscript concede that the definition of orogenic bridges could be further clarified. Changes: Added "and is applied to areas of continental crust that extend further into the oceanic realm than normal passive margins" to the fourth paragraph in the "Orogenic bridge theory" section. See also response to comments 4, 13, 14, and 16.

Comment 11: While it is proven that you can find continental material far offshore offshore in area of strong volcanic activity like Iceland or the Rio Grande Rise (I'd say above hotspots: Rime et al., 2024), the paper fails to show a systematic link between these areas, transform faults, and perpendicular orogenic belts. The prime example presented here is the

Greenland-Iceland-Faroe Ridge (GIFR). Response: See response to comments 13 and 14. Changes: See response to comments 13 and 14.

Comment 12: However, the last orogenic belt found along its margins, the Caledonian orogeny, strikes almost parallel to the rift axis (which the authors acknowledge). Response: Agreed. Changes: None required.

Comment 13: The authors then invoke the older Ammassalik Belt (in Greenland) and the Tornquist Zone (in Europe). This correlation is not valid because 1) Both have very different ages. They thus don't form a single continuous structure. 2) They were both overprinted by the Caledonian orogeny in the region of the future north Atlantic. So, the GIFR is not correlated with a perpendicular orogenic belt. Response: Disagreed. Thrust systems of the Laxfordian Orogen were recently mapped off the Faroe Islands and past the continent ocean boundary (Koehl et al., 2024) and it has been suggested that late Paleoproterozoic thrust systems of the Laxfordian–Svecofennian Orogen might be related to or controlled the formation of the Tornquist Zone (Koehl et al., 2024). Ongoing mapping on seismic reflection data at the Greenland–Iceland–Faroe Ridge shows that late Paleoproterozoic thrust systems continue below southeastern Iceland (Koehl et al., 2025). Of notable interest are the NE–SW-striking folds mapped by Hjartarson et al. (2017) at the Greenland–Iceland–Faroe Ridge. These coincide with hundreds of km, NE–SW-striking, open, Caledonian folds, which rework the late Paleoproterozoic Laxfordian thrusts (Koehl et al., 2024, 2025), thus explaining the thickness of the crust at the Greenland–Iceland–Faroe Ridge (Hjartarson et al., 2017 their figure 3c). Changes: Split the fifth paragraph of the "Greenland–Iceland–Faroe orogenic bridge" sub-section into two and included the findings of Laxfordian thrust systems off the Faroe Islands and Iceland–Faroe Ridge by Koehl et al. (2024, 2025): "In northern Europe, a possible candidate to explain crustal thickening in the GIFR is the correlate of the Ammassalik Belt, the late Paleoproterozoic Laxfordian Orogen on the Rockall Plateau and northern Scotland. This orogen was thought to consists of WNW–ESE-striking, subvertical shear zones showing strike-slip kinematics ( Attfield, 1987; Coward & Park, 1987; Dickin, 1992). However, recent mapping on reprocessed seismic reflection data has revealed that the Laxfordian shear zones onshore northern Scotland are part of much larger structures, namely tens of km thick, WNW–ESE-striking, dominantly NNE-dipping thrust systems around the Faroe Islands ( Koehl *et al.*, 2024). These were reworked into hundreds of km wide, NE–SW-striking open folds during the Caledonian Orogeny and extend beyond the Seaward-Dipping Reflectors and previously assumed continent–ocean boundary off the Faroe Islands ( Koehl *et al.*, 2024). Ongoing seismic mapping at the GIFR indicates that these late Paleoproterozoic structures extend to below southeastern Iceland and thus that the Iceland–Faroe segment of the GIFR is fully continental ( Koehl *et al.*, 2025). Of notable interest, the hundreds of km wide, NE–SW-striking open folds mapped along the entire length of the GIFR by Hjartarson *et al.* (2017) coincide with the Caledonian folds reworking late Paleoproterozoic structures off the Faroes Islands and at the Iceland–Faroe Ridge ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). This may explain the thickness variations of the GIFR along its length (i.e., in a WNW–ESE direction; Hjartason *et al.*, 2017 their figure 3c). In eastern Europe, the WNW–ESE-striking Tornquist Zone, i.e., the Teisseyre–Tornquist Zone ( Krzywiec *et al.*, 2022; Mazur *et al.*, 2015) and its probable continuation the Sorgenfrei–Tornquist Zone ( Ponikowska *et al.*, 2024), extends from the Black Sea ( Mikolajczak *et al.*, 2019; Narkiewicz *et al.*, 2015) to the southern North Sea ( Kalani *et al.*,

2020; Phillips *et al.*, 2018) and is a natural potential continuation for some of the Laxfordian structures at the GIFR and off the Faroe Islands ( Koehl *et al.*, 2024; Koehl *et al.*, 2025). Available seismic reflection data in the central and northern North Sea and west of the Faroe Islands suggest that the Sorgenfrei–Tornquist Zone may continue as far north as the Shetland Plateau (e.g., Bird *et al.*, 2016; Fossen & Hurich, 2005; Gabrielsen *et al.*, 2015; Koehl *et al.*, unpublished manuscript; Serck *et al.*, 2022). The Tornquist Zone accommodated significant contractional deformation and related crustal thickening as early as the Neoproterozoic during the closure of the Tornquist Ocean ( Torsvik & Rehnström, 2003). The Tornquist Zone possibly consists of top-northeast ( Abramovitz *et al.*, 1999; Krzywiec *et al.*, 2017; Lyngsie & Thybo, 2007; Mazur *et al.*, 2015; Mazur *et al.*, 2018) and top-SSW thrusts (Phillips *et al.*, 2018 their figures 2 and 11; Koehl *et al.*, unpublished manuscript).". Also added the new references to the reference list. Also deleted "and the North Sea and regional correlation of this major deformation zone would help clarify the impact of the Tornquist Zone on the crustal structure of the GIFR" and rewrote the last sentence into "Further attention should be given to the expression of Paleoproterozoic structures of the Ammassalik Belt and Laxfordian Orogen on offshore seismic reflection at the GIFR data because of their well constrained top-SSW kinematics and NNE-dipping geometry onshore (e.g., Kalsbeek *et al.*, 1993) and offshore continuation into the GIFR ( Koehl *et al.*, 2024; Koehl *et al.*, 2025), and our present ability to identify deep-seated orogenic structures and thrust systems on seismic reflection data (e.g., Fazlikhani *et al.*, 2022; Freeman *et al.*, 1988; Hedin *et al.*, 2016; Juhlin *et al.*, 2016; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Platt & Cartwright, 1998)." in the last paragraph of the "Greenland–Iceland–Faroe orogenic bridge" sub-section.

Comment 14: Furthermore, the transform zone associated with the GIFR mentioned in the text is the Tjörnes fault zone which only shows < 100 km offset. I would thus not classify it as one of the most important as transform faults with < 100 km offset are found everywhere in the oceans. Response: The authors of the present manuscript concede that the Tjörnes fault zone only shows a potentially minor offset of the rift axis (c. 100 km). However, it still falls into the definition of a major transform fault provided in the present manuscript (typo now corrected into "tens of km" in the "Orogenic bridge theory" section). In addition, the Tjörnes fault zone is by far the largest transform fault in this oceanic sector and is localized at the transition between the thin oceanic crust at the Kolbeinsey segment of the Mid-Atlantic Ridge and the anomalously thick offshore crust at the GIFR. This is, in itself, an argument in favor of the proposed theory that rift-orthogonal orogens hinder rifting and breakup and localize the formation of major transform faults. Indeed, the Tjörnes fault zone only shows a 100 km offset of the mid-ocean ridge, but just like some other major transform faults on Earth, this fault starts with a modest offset, which may increase over time should rifting proceed and succeed in breaking the Laxfordian Orogen crust up at the GIFR. Not to be overlooked, the Kolbeinsey Ridge took over for the extinct Ægir Ridge, which is offset from the Rekjanes Ridge by > 300 km. The authors of the present manuscript concede that these facts should be specified in the present manuscript. Changes: Split the last paragraph of the "Greenland–Iceland–Faroe orogenic bridge" sub-section into three, including a new paragraph: "It is true that the c. 100 km offset of the rift axis along the Tjörnes fault zone is rather small, but it still fit the "tens of km" definition of a major fault suggestrd in the present manuscript. In addition, many major transform faults probably initiated with modest offsets, e.g., Andrew Bain, Charlie Gibbs, and San Andreas fault zones (e.g., Mueller & Jokat, 2019 their figure 15; Seton *et al.*, 2012 their figures 4 and 10; Vormann & Jokat, 2020

their figure 3). Thus, it is probable that the offset at the Tjörnes fault zone will grow over time should seafloor spreading continue and rifting possibly rupturing the Nagssugtoqidian–Laxfordian orogenic bridge at the GIFR. Furthermore, it should be noted that the Kolbeinsey Ridge recently took over (at ca. 22 Ma) for the extinct Ægir Ridge, which is offset from the Reykjanes Ridge by ≥ 350 km (e.g., Blischke *et al.*, 2016; Gernigon *et al.*, 2020). Thus, the present offset at the Tjörnes fault zone may only partly reflect the important segmentation of the northeastern Atlantic rift at the GIFR." Also added the new references to the reference list.

Comment 15: So actually the GIFR does not fit your definition of an orogenic bridge. Response: Disagreed. See response to comments 13 and 14. Changes: See response to comments 13 and 14.

Comment 16: The authors also present the Fram Strait as an orogenic bridge. The region of Svalbard and the Barent Sea is very different from the GIFR. Although rifted, is not hyper-extended and it did not experience as much volcanic activity. Response: Partly agreed. The Fram Strait is indeed different from the GIFR with respect to the amount of rift-related magmatism involved, which is high at the GIFR (e.g., Boldreel and Andersen, 1993) and low in the Fram Strait (Koehl et al., 2021). However, the Fram Strait is hyperextended as documented by the dramatically thin character (< 12 km except at the Hovgård Ridge where it is about 12 km; Ritzmann et al., 2004) of the continental crust on the Greenland side (Dumais et al., 2020) and the occurrence of core complexes (e.g., Koehl,2020; Koehl et al., 2021), which are characteristic of hyperextended margins. Still, both areas present a rift-orthogonal orogen, i.e., the Laxfordian–Ammassalik Orogen at the GIFR and the Timanian Orogen in the Fram Strait. The authors of the present manuscript want to also highlight that the proposed late Neoproterozoic (650–550 Ma) age of the rift-orthogonal orogen in the Fram Strait, which is supported by various geochronological studies throughout Svalbard (Manecki et al., 1998; Majka et al., 2008, 2012; Koglin et al., 2022; Koehl and Mottram, 2024) is a conservative estimate. It is possible that the orogen in the Fram Strait and the Barents Sea may as well be part of the late Paleoproterozoic Svecofennian Orogen, which crops out in western Troms in northern Norway and displays the same structural trend (WNW–ESE) and dominant thrust vergence (top-SSW) as the Timanian Orogen. Noteworthy, the Svecofennian Orogen is a time-equivalent to the Laxfordian and Nagssugtoqidian orogens, which would suggest a first-order impact of this ca. 1.9–1.8 Ga orogenic event on the Orogenic Bridge Theory and resulting plate tectonics if traces of late Paleoproterozoic orogenesis were to be found in Svalbard and the Barents Sea. The authors of the present manuscript concede that this should be better stated in the present manuscript. Changes: Rewrote the first paragraph of the "Timanian orogenic bridge" section into "The recent discovery of continuous, late Neoproterozoic Timanian thrust systems from northwestern Russia to the Svalbard Archipelago throughout the Barents Sea has dramatically changed our perception of the pre-Caledonian tectonic history in this entire region ( Koehl, 2020; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl, 2024 awaiting peer review; Figure 4). Some of these structures can be traced across the magma-poor Fram Strait (e.g., in the Hovgård Ridge; Koehl, 2020 pp. 163–166; Koehl *et al.*, 2021; Koehl, unpublished manuscript) into blocks of continental crust that are now known to be fully attached to Laurentia and Greenland's continental crust ( Dumais *et al.*, 2020; Figure 4). While the Svalbard margin thins rapidly and is relatively narrow (< 200 km), the Greenland margin is

much broader (up to 600 km at the East Greenland Ridge; Figure 4), which is possibly related to the dominant top-east vergence of Caledonian thrusts (rift-parallel endmember of OrBiT; e.g., Ohta *et al.*, 1986; Ohta *et al.*, 1995; Koehl, 2024 awaiting peer review). New magnetic data at the Knipovich Ridge by Dumais *et al.* (2020) and seismic reflection data between the Molloy and Spitsbergen fault zones ( Koehl, 2020 pp. 167–180, Koehl, unpublished manuscript; Koehl *et al.*, 2021 pp. 9–20; Figure 4) show that there is little to no oceanic crust *sensu stricto* along the Molloy Ridge. Seismic reflection data nevertheless shows the occurrence of thin layers of volcanics and possibly mantle exhumed along extensional detachments, e.g., core complex parallel to the Molloy fault zone (Koehl, 2020; Koehl et al., 2021). This together with the dramatically thin character of the continental crust on the northeastern Greenland margin indicate that the crust is hyperextended and is generally thinner than 12 km except at the Hovgård Ridge and East Greenland Ridge where it is about 12 km (Dumais *et al.*, 2020; Døssing *et al.*, 2008; Ritzmann *et al.*, 2004). Furthermore, Timanian subduction-related magmatism was recently identified in northern Greenland ( Estrada *et al.*, 2018a; Rosa *et al.*, 2016), Arctic Canada ( Estrada *et al.*, 2018b), and the Lomonosov Ridge ( Rekant *et al.*, 2019; Figure 4), further supporting the continuation of the Timanian Orogen across the northeastern Atlantic–Arctic rift." and added a third paragraph: "Noteworthy, the proposed late Neoproterozoic (650–550 Ma) age of the rift-orthogonal orogen in the Fram Strait, which is supported by various geochronological studies throughout Svalbard (Manecki *et al.*, 1998; Majka *et al.*, 2008, 2012; Koglin *et al.*, 2022; Koehl & Mottram, 2024) is a conservative estimate. It is possible that the orogen in the Fram Strait and the Barents Sea may as well be part of the late Paleoproterozoic Svecofennian Orogen, which crops out in western Troms in northern Norway and displays the same structural trend (WNW–ESE) and dominant thrust vergence (top-SSW) as the Timanian Orogen (Bergh *et al.*, 2010; Bergh *et al.*, 2022). Noteworthy, the Svecofennian Orogen is a time-equivalent to the Laxfordian and Nagssugtoqidian orogens, which if traces of late Paleoproterozoic orogenesis were to be found in Svalbard and the Barents Sea would suggest a first-order impact of this ca. 1.9–1.8 Ga orogenic event on the Orogenic Bridge Theory and resulting plate tectonics.".

Comment 17: I fail to understand how these region are any different than normal passive margins except from the fact that they are situated near very important transform fault and that they feature a parallel orogenic belt. The Fram Strait (just like the Falklands) formed a landbridge (in the sense that the two continental masses remained very close to each other) for a long time just because they are very long transform faults systems. Response: Two items of importance are pointed out by the reviewer in the present comment. First, the GIFR and Fram Strait involve major transform faults and are therefore transform margins rather than typical orthogonal passive margins. Second, the reviewer is stating that the Falkland Plateau and Fram Strait formed "landbridges" because "the two continental masses remained very close to each other for a long time just because they are very long transform faults systems". This statement assumes that the transform faults caused the formation of what the reviewer calls "landbridges" and were there all along, i.e., as inherited pre-rift structures. Such a claim is not supported by any argument. Instead, we propose that rift-orthogonal orogenic structures of the Cape Fold Belt in the Falkland Plateau and Maurice Ewing Bank were initially adjacent to their counterparts in South Africa prior to the breakup of Pangea and hindered breakup and controlled the formation of the Agulhas–Falkland (transform) fault zone. Younger structures cannot have controlled older structures. Since

the Agulhas–Falkland fault zone is younger than the Cape Fold Belt, it must be the latter which influenced the formation of the former, not the other way around. Not only are the Fram Strait and Falkland Plateau transform margins, but they also both are (hyper-) extended and host rift-orthogonal orogens (Timanian Orogen and Cape Fold Belt respectively). Knowing that prior to Mesozoic–Cenozoic opening of the Atlantic Rift there were continuous orogenic belts in continental crust thickened perpendicularly to the future rift, it is simply not possible that these orogens had no impact at all on subsequent rifting. A logical impact is the hindering of breakup due to the thicker character of the continental crust at these orogens, which would have necessarily required more time to be thinned down to break up. This is reflected by later breakup and transform faulting at these rift-orthogonal orogens. The unsuitability of the dominant structural trends in the rift-orthogonal orogens to accommodate crustal thinning is also argued to have played a major role in delaying breakup. Major low-angle thrusts striking sub-parallel to the extension direction are simply not efficient at thinning the crust or at accommodating transform faulting. However, they are oriented suitably to control the formation of new subvertical transform faults, which may facilitate breakup and the formation of transform margins, as observed both at the Falkland–South Africa conjugate margins and in the Fram Strait. To sum up, the authors of the present manuscript simply propose that the rift-orthogonal Cape Fold Belt and Timanian Orogen hindered rifting and localized the formation of the major transform faults. See also response to comments 4, 16, and 25. Changes: Added “In addition, the low-angle character of thrust faults makes them unsuitable to accommodate transform movements. However, their rift-orthogonal orientation is suitable to control the formation of new subvertical transform faults.” and “Should there be any speed difference between seafloor spreading at mid-ocean ridges and stretching within the thinning orogenic bridge, these may be accommodated by transform faults at the continent–ocean boundary.” to the new sixth paragraph of the “Orogenic bridge theory” section. See also response to comments 4, 16, and 25.

Comment 18: And then simply by geometry, the two continents will slide beside each other (and thus remain close) for a long time while the adjacent rift will form oceans and drift apart. For example, for a transform fault of 200 km offset, the two landmasses would still be connected after 190km of motion while the rifted parts would have drifted away by 190km at the same time. Response: Agreed. Changes: None required.

Comment 19: But I’m sure the authors are aware of these trivial tectonics concepts, so I wonder what they mean with the concept of orogenic bridges. Is it just that perpendicular orogenic belts promote large transform faults, and then, because transform faults are large, the two landmasses remain close together for a long time? If so, fine (although you’d have to convince me that large transform do indeed correlate with perpendicular orogens, see below), but then why would you present this as a new “theory of the whole” superseding plate tectonics? Response: The present manuscript attempts to resolve a > 100 year-long dispute, that of Continental Drift versus Land Bridges. While Wegener’s theory ultimately led to plate tectonics and seems to have “won” over Land Bridge Theory, the authors of the present manuscript suggest that the truth is more complex than a simplistic “black and white” approach, i.e., dismissing all aspects of Land Bridge Theory and accepting all those of Continental Drift. The authors of the present manuscript concede that it is easier for individuals and entire communities to adopt a “black-and-white” approach, i.e., to consider

ideas to be 100% wrong or 100% right with no shades in between. It is safe to assume that the defenders of Land Bridge Theory were, as the supporters of Continental Drift and plate tectonics, smart, some of them brilliant, scientists in their time. It is therefore logical that their gut feeling (i.e., the sum of numerous small pieces of evidence, all of which they could not necessarily set their finger on and express), which led to formulating Land Bridge Theory (Gregory, 1929; von Ihering, 1931; Schuchert, 1932), a gut feeling of the same nature as that which led Wegener to formulate Continental Drift Theory, was to find at least some truth. While Wegener righteously identified that the continents have moved, his main opponents identified that some regions have been connected by continental bridges for long periods of time. What if both were possible? Orogenic Bridge Theory reconciles Land Bridge Theory with Continental Drift Theory, thus ending the debate around who is the smarter. All these early-20$^{th}$-Century geoscientists were all brilliant minds. A hundred years of scientific and technological progress now gives us the perspective they needed. Both had some truth and some wrong, and so it always is in most conflicts. Orogenic Bridge Theory is a tribute to all the great minds of the past, may they have been supporters of Land Bridge Theory or of Continental Drift Theory, building on both theories and making them stronger. The term “Orogenic” implies dynamism as suggested by Continental Drift Theory, while the term “Bridge” suggests some connection between some continents at some point as suggested by Land Bridge Theory. Should the name not be judged appropriate by the community, the authors of the present manuscript are open to receiving advice/suggestions to more adequately reflect all groups and hypotheses involved in this > 100-year-long debate. Again, Orogenic Bridge Theory is not attempting at invalidating Plate Tectonics but complementing it with the missing pieces of the puzzle. It is therefore an update to plate tectonics as stated in the abstract. See also response to comments 13 and 14. Changes: Added ““orogenic” implies dynamism as suggested by Continental Drift Theory, while the” to the fifth paragraph of the “Orogenic bridge theory” section. See also response to comments 13 and 14.

Comment 20: Orogenic bridge or transform faults? In the paper, it is not clear if the authors hypothesize that orogenic belts perpendicular to rift do produce major transform faults, or if they produce land bridges that extend far in the oceanic realm (or whatever an oceanic bridge is, see above for the lack of clarity on this notion), and why they would form one or the other, or both. Only in the conclusion do we learn that “Rupturing of orogenic bridges results in the formation of major transform faults”. Response: Agreed. This is definitely a shortcoming of the manuscript in its present state. The authors of the present manuscript thank the reviewer for a much valuable comment. See response to comments 1, 4, 9, 10, 14, and 17. However, the authors of the present did not mention “oceanic bridges”. Changes: Added “Should there be any speed difference between seafloor spreading at mid-ocean ridges and stretching within the thinning orogenic bridge, these may be accommodated by transform faults at the continent–ocean boundary.” to the new sixth paragraph of the “Orogenic bridge theory” section. See response to comments 1, 4, 9, 10, 14, and 17.

Comment 21: If that would be the case, the authors do not explain how many major transform fault systems do not feature unconventional, continental crust extending in the oceanic domain: Charlie-Gipps, Vema, La Romanche, Ascension Bode Verde, Owen. Response: According to the presented Orogenic Bridge Theory, all the major transform faults on Earth formed along rift-orthogonal orogens, which at some point formed orogenic

bridges (i.e., thinned orogenic crust with orogenic structures sub-orthogonal to the active rift) and hindered rifting because the crust there is thicker than at nearby anorogenic/thinner continental crust segments and crosscut by preexisting structures unsuitably oriented to accommodate crustal thinning and transform faulting. This is illustrated by the presently identified global correlation of all major transform faults on Earth with rift-orthogonal orogens on adjacent margins and, in places, with areas of anomalously thick crust offshore (dashed yellow areas in new Figure 1). There is, thus far, no exception to this correlation. This is stated in the first sentence of the "Orogenic bridge theory" section: "Every major transform fault on Earth strikes parallel to an orogen and related structures on one or several adjacent rifted margins.". Noteworthy, the authors of the present manuscript were able to reject every counter example proposed by ChatGPT. Changes: Added "all" in the last sentence of the rewritten abstract, "The map shows the coincidence of all major transform faults on Earth with rift-orthogonal orogens on adjacent continental margins." in the caption of Figure 1, and "" .

Comment 22: The authors suggest that the Vema and La Romanche FZ might feature continental material, but this assertion is based on their own theory " The OrBiT suggests that elongate lithosphere slivers within these transform fault systems are likely continental." This is a circular reasoning; you can't use your theory to demonstrate a fact that you then use to support your theory. The bathymetry at least does not show any anomaly that would hint at the presence of continental crust there. Response: Bathymetric data alone do not constitute a sufficient argument to reject the possible presence of continental crust along the Vema and Romanche fault zones. The authors of the present manuscript concede however that the targeted sentence is poorly written. Changes: Rewrote "would already be" into "would be easier to" and added "due to its different rheology" and "In such a scenario, transform-parallel ribbons of continental crust become detached from adjacent continental margins and are entrained along major transform faults due to the occurrence of transform-parallel, preexisting zones of the weakness in the continental crust, such as major (mylonitic) thrust systems. These preexisting structures would facilitate rupture and dislocation of the crust along an axis parallel to the proto-transform faults and allow the inclusion and entrainment of such transform-parallel continental ribbons into oceanic crust during seafloor spreading (Figure 10)." to the "East African–Antarctica orogenic bridge" sub-section.

Comment 23: As shown above, the authors also don't explain how the GIFR, classified as an orogenic bridge, only features a relatively minor transform fault. Response: See response to comment 13 and 14. Changes: See response to comment 13 and 14.

Comment 24: Transform Faults and orientation of orogenic belt The authors define "major transform faults" as "transform faults showing offset of active mid-ocean ridges greater than a few kilometers." For me, 20 is greater than a few. And a transform fault with 20km is actually very small, you'll find transform faults >20 km everywhere in the oceans so you can correlate it with anything. But ok, for the next part, let's assume more than a few rather mean >100 or >200 km. Response: Agreed. This was corrected. Changes: Added "tens of" in the first paragraph of the "Orogenic bridge theory" section.

Comment 25: One of the major assumptions on which the authors build their theory is that

"Every major transform fault on Earth strikes parallel to an orogen and related structures". This very categoric assumption is simply wrong. Many major transform faults on the planet do not obey this rule. I give a few examples below looking only at a few of the most important fault zone (FZ) in the world: Agulhas–Falkland fault zone: The authors link the Agulhas–Falkland fault zone to the allegedly parallel-striking Cape Fold Belt and the Sierra de la Ventana fold-and-thrust belt. Firstly, the authors place the Sierra de la Ventana FTB wrong on their map (according to Stanca et al., 2022 [which the authors cite], it is situated 900 km north of what they show on their map). Then, both the Cape FTB (Johnston, 2000) and the Ventana FTB are not parallel to the Agulhas–Falkland fault zone but oblique by about 40°.
Response: Partly agreed. The Sierra de la Ventana fold-and-thrust belt was indeed confused with its time equivalent in Patagonia.
However, the folds and thrusts of the Cape Fold Belt evidenced in seismic reflection data in the Falkland Plateau by Stanca et al. (2022 their figure 5a–d) and off South Africa by Paton et al. (2022 their figure 1a–b and 4a and c–d) strike parallel to the Agulhas–Falkland fault zone, i.e., E–W in the Falkland Plateau and NE–SE off South Africa. In addition, as raised by Prof. Jolivet (reviewer 2), Buiter and Torsvik (2014) have already pointed out that the Agulhas–Falkland fault zone formed along a "Late Palaeozoic–Early Mesozoic suture between Patagonia and Western Gondwana", i.e., the Cape Fold Belt.
Changes: Updated the located of the Sierra de la Ventana fold-and-thrust belt in Figure 1. Reworked the last sentence of the second paragraph of the "Cape–Falkland orogenic bridge" sub-section into "In the west, onshore southern South America, the Cape Fold Belt correlates with contemporaneous structures onshore Patagonia, which shows both comparable structural trends and similar timing of formation ( Castillo et al., 2017; du Toit, 1927; Grillo Vidal et al., 2024; Figure 1 and Figure 5a)." and added Grillo Vidal et al. (2024) to the reference list. Replaced "South America (Sierra de la Ventana fold-and-thrust belt)" by "Patagonia" in the next paragraph and deleted "Sierra de la Ventana fold-and-thrust belt and with the" in the paragraph after that. Replaced "to the Sierra de la Ventana Fold-and-Thrust Belt in" by "onshore" and "Limarino *et al.*, 1999; Lopez-Gamundi, 2006; Rapela *et al.*, 2003; von Gosen *et al.*, 1990" by "Grillo Vidal *et al.*, 2024" in the first paragraph of the "Bouvet Triple Junction" sub-section, and deleted "and Sierra de la Ventana Fold-and-Thrust Belt" in the next paragraph. Rewrote the first sentence of the fourth paragraph in the "Bouvet Triple Junction" sub-section into "Major transform faults offsetting the southern segment of the Atlantic mid-ocean ridge and the American–Antarctic Ridge strike parallel to one another ( Figure 5b), and both groups of transform faults parallel the late Paleozoic, E–W-striking Cape Fold Belt and its onshore continuation in Patagonia ( Castillo *et al.*, 2017; Grillo Vidal *et al.*, 2024; Stanca *et al.*, 2022; Figure 5).".
Also added "Notably, the Agulhas–Falkland fault zone parallels thrusts of the Cape Fold Belt both onshore and offshore southern South Africa (Paton *et al.*, 2022) and on the Falkland Plateau and Maurice Ewing Bank (Stanca *et al.*, 2022 their figures 4a, 5b, 12b–c, and 13a–c), which strike respectively NE–SW and E–W (Figure 5a). These late Paleozoic–earliest Mesozoic thrusts therefore likely controlled the strike and geometry of the Agulhas–Falkland fault zone. This relationship was previously noted by Buiter & Torsvik (2014) who suggested that the Agulhas–Falkland fault zone formed along an inherited suture zone between the Falkland Plateau and South Africa." to the third paragraph of the "Cape–Falkland orogenic bridge" sub-section, and Paton et al. (2022) and Buiter and Torsvik (2014).

Comment 26: 2. The Romanche Fault Zone which the authors associate with the Central African Orogen/Oubangides (BTW, none of the papers cited mention the word "Oubangides") and the Sergipano Belt. However, most of the Sergipano Belt (Bueno et al., 2009) as well as the belt separating the West African Craton and the Sahara Metacraton (Kouémo et al., 2014; Meert & Lieberman, 2008) strike 40° to 50° oblique to the Romanche Fault Zone. Hardly parallel.
Response: Disagreed. The structures of the Sergipano Belt in northeasternmost Brazil strike E–W (Oliveira et al., 2006 their figure 2 and Finoto Bueno et al., 2009 their figures 1, 4, and 10), i.e., parallel to the Romanche fault zone. What the reviewer may be referring to as oblique fabrics occurs in between the main shear zones (e.g., Patos and Pernambucano shear zones) in the Sergipano Belt. These fabrics do not represent the may zones of weakness in the crust and are probably oblique shear fabrics or folding related to strike-slip reactivation of the main shear zones and their reworking during subsequent events. In western Africa, structures such as the Adamaoua Fault (Oliveira et al., 2006 their figure 6) or Central Cameroon Shear Zone (Kouémo et al., 2014 their fig. 1) strike ENE–WSW, i.e., sub-parallel to the Romanche fault zone, not 40–50° off as suggested by the reviewer. The authors of the present manuscript concede that this could be further specified in the manuscript.
The term "Oubangides" is mentioned simply to make it easier for those who know this orogen under this name. The authors of the present manuscript encourage the reviewer to search this term in Google. Many (including recent) publications use this term.
The belt separating the West African Craton from the Sahara Metacraton strikes N–S, i.e., parallel to the South Atlantic rift and therefore explains why the rift opened there. However, this issue belongs to the "rift-parallel endmember" of Orogenic Bridge Theory, which is more accepted and well-studied, and is thus not the focus of the present manuscript.
Changes: Added reference to the reference suggested by the reviewer to the manuscript and reference list (Finoto Bueno et al., 2009). Also added a new sub-section entitled "Sergipano–Central African orogenic bridge".

Comment 27: 3. The Charlie-Gibbs FZ: with more than 300 km of offset, one of the largest in the world, it is not parallel but oblique to the Caledonian orogeny by approx. 30° (both looking at Newfoundland and Scotland).
Response: Disagreed. The Charlie Gibbs fault zone is parallel to the Caledonian fabrics and structures in nearby onshore areas in both Europe and Canada. In western Ireland, the location of the westwards offshore continuation of the Iapetus Suture coincides with that of the Charlie Gibbs fault zone and both display matching E–W strikes (e.g., Tietzsch-Tyler, 1996; Chew and Stillman, 2009). In Newfoundland, seismic reflection data analysis suggests that the Charlie Gibbs fault zone merges with the Paleozoic Dover Fault (Keen et al., 2014). Onshore Newfoundland, the Dover Fault separates the Ganderia terrane from the Avalonia terrane, which were presumably accreted to Newfoundland in the early–mid Paleozoic respectively during the closure of the Iapetus and Rheic oceans (e.g., van Staal et al., 2012). Given the similar strike and proximity of the Red Indian Line (Iapetus Suture in Newfoundland) with the Dover Fault, it is also possible that the Charlie Gibbs fault zone merges with the Iapetus Suture in Newfoundland as well (van Stall et al., 2021). In addition, Variscan structures both in southern England and Ireland and in Newfoundland display an E–W strike matching that of the Charlie Gibbs fault zone (Lefort and Haworth, 1984; Lefort et al. 1993; Miliorizos et al., 2004). Thus, both Caledonian–Appalachian and

Variscan–Alleghenian preexisting orogenic structures may have contributed to localize the formation of the Charlie Gibbs fault zone.
Changes: Added a new section entitled “Appalachian–Caledonian orogenic bridge”.

Comment 28: 4. The Owen Fracture zone is oblique by approx. 30° to the orientation of the East African Rift System.
Response: Disagreed. Once again, the curvature of the Earth makes it difficult to visualize the geometrical relationships between the described elements, but the Owen fault zone and other transform faults crosscutting the Gulf of Aden Rift are indeed parallel to orogenic structures of the East African Orogen and to the northern segment of the East African Rift System (see figure below).

Figure 1 and 2

*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248220.17238__Jean-Baptiste_Koehl_to_Valentine.pdf*

Figure caption: Topographic map showing that the Owen fault zone (easternmost dashed red line) parallels the northern segment of the East African Rift System (westernmost dashed red line), whose formation was controlled by parallel N–S-striking orogenic structures of the East African Orogen. From GoogleEarth.
Changes: Added mention of the Owen fault zone and transform faults truncating the Gulf of Aden Rift in the new “Afar Triple Junction” sub-section: “Furthermore, they also parallel the NNE–SSW-striking transform faults truncating the Gulf of Aden Rift, including the Owen fault zone ( Fournier *et al.*, 2011) and, thus, may as well have controlled the formation of these structures.”.

Comment 29: 5. The Bodo Verde and Ascension Fracture Zones (each featuring more than 200km of offset) are situated approx. perpendicular to the last orogenic event, the Araçuaí-West Congo orogen and the north of this area represent the São Francisco and Congo craton. (Alkmim et al., 2006).
Response: Agreed that the Bodo Verde and Ascencion fault zones are perpendicular to the Aracuai–West Congo Orogen, but they are anyway parallel to the Sergipano Belt in northeastern Brazil and Central African Orogen/Oubangides in western Africa, thus supporting the proposed relationship between rift-orthogonal orogens and major transform faults. The authors of the present manuscript concede that mention of these fault zones could be made. See also response to comment 26.
Changes: Added a new “Sergipano–Central African orogenic bridge” sub-section. See also response to comment 26.

Comment 30: 6. All major fault zones situated between the St Paul and the Vema FZ, some featuring more than 200 km of offset, correlates with cratons (Amazonian and West African) and not with orogenic belts.
Response: Disagreed. See response to comment 26.
Changes: See response to comment 26.

Comment 31: 7. The Jan Mayen FZ (>250 km offset) is located perpendicular to the Caledonian orogeny.
Response: Agreed, but the Jan Mayen fault zone is parallel to late Paleoproterozoic orogenic structures in northern and southern Scandinavia (Svecofennian–Svecokarelian Orogen; Bergh et al., 2010; Saintot et al., 2011; Johansson et al., 2015) and at the Greenland–Iceland–Faroe Ridge and northern Scotland (Coward and Park, 1987; Koehl et al., 2024, 2025). In addition, this transform fault as depicted in Blischke et al. (2022 their figure 5a) dips very gently at depth and displays a geometry more typical of inverted thrusts. This and the occurrence of wiggly seismic reflections along the entire length of the Jan Mayen Microcontinent Complex strongly suggest that deep rift-orthogonal orogenic structures controlled the formation of the Jan Mayen fault zone. Like in Scotland, northern Norway, and elsewhere, these late Paleoproterozoic orogenic structures were reworked during the Caledonian Orogeny (e.g., Koehl et al., 2024, 2025). Knowing that the Baltica Craton was formed at least in the late Paleoproterozoic, it is simply logical that late Paleoproterozoic structures found at the surface in northwestern Norway (West Troms Basement Complex; Bergh et al., 2010, 2015) and southern Sweden (Saintot et al., 2011; Johansson et al., 2015) continue at depth below Caledonian nappes and were reworked by Caledonian contraction, their original geochronological signal having been completely overprinted in some places. Thus, it is only natural to expect rift-orthogonal Svecofennian–Svecokarelian orogenic structures along the entire length of the western coast of Norway at depth, i.e., near the location of the Jan Mayen Microcontinent Complex and Jan Mayen fault zone. The authors of the present manuscript concede that this could be specified in the "Greenland–Iceland–Faroe orogenic bridge" sub-section.
Changes: Added "Previous studies have suggested that the continental crust in Iceland is connected to the Jan Mayen Microcontinent Complex ( Torsvik *et al.*, 2015). Northeast of Jan Mayen, the West and East Jan Mayen fault zones are parallel to late Paleoproterozoic orogenic structures in northern and southern Scandinavia (Svecofennian–Svecokarelian Orogen; Bergh *et al.*, 2010; Johansson *et al.*, 2015; Saintot *et al.*, 2011) and at the Greenland–Iceland–Faroe Ridge and northern Scotland (Coward and Park, 1987; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Figure 4). In addition, these transform faults as depicted in Blischke *et al.* (2022 their figure 5a) dip very gently at depth and display a geometry more typical of thrust faults. This and the occurrence of wiggly seismic reflections along the entire length of the Jan Mayen Microcontinent Complex probably representing contractional asymmetric folds (e.g., ) strongly suggest that deep rift-orthogonal orogenic structures controlled the formation of the Jan Mayen fault zones. Like in northern Scotland, northern Norway, and elsewhere, these late Paleoproterozoic orogenic structures were mildly reworked during the Caledonian Orogeny (e.g., Koehl *et al.*, 2024; Koehl *et al.*, 2025). Knowing that the Baltica Craton was already formed in the late Paleoproterozoic, it is logical that late Paleoproterozoic structures analogous to those found at the surface in northwestern Norway (West Troms Basement Complex; Bergh *et al.*, 2010; Bergh *et al.*, 2015) and southern Sweden (Johansson *et al.*, 2015; Saintot *et al.*, 2011) continue at depth below Caledonian nappes to the northwest where they were reworked by Caledonian contraction, their original geochronological signal most likely completely overprinted in some (most?) places. Thus, late Paleoproterozoic rift-orthogonal orogenic structures should be expected at depth along the entire length of the Norwegian continental shelf in the northwest, including adjacent to the Jan Mayen Microcontinent Complex and Jan Mayen fault zones. The presence of such structures should be possible to test using the dense coverage of

2D–3D seismic reflection data in Norway. Noteworthy, the Jan Mayen Microcontinent Complex represents a ruptured segment of the discussed late Paleoproterozoic orogenic bridge between Greenland and Europe and was rifted in the Cenozoic from Europe by seafloor spreading at the extinct Ægir Ridge and from Greenland by ongoing oceanic crust formation at the Kolbeinsey Ridge ( Figure 4).” to the “Greenland–Iceland–Faroe orogenic bridge” sub-section.

Comment 32: I don’t even speak of huge transform faults in the Pacific that do not correlate with any orogenic belt because the margin of this ocean is subducting. But I’ll assume that it is only a problem of phrasing of the following sentence: “Every major transform fault on Earth strikes parallel to an orogen and related structures”.
Response: Disagreed. As unbelievable as this sounds to the authors of the present manuscript and as unbelievable as it will likely sound to every person reading these lines, all major transform faults in the Pacific Ocean do conform with this pattern. For example, the San Andreas fault parallels the Nevadan Orogen, the Queen Charlotte fault zone parallels the Cordilleran Orogen, and the main transform faults in the southern Pacific (near the Pacific–Nazca–Antarctica triple junction) parallel the Cape Fold Belt and Sierra de la Ventana Fold-and-Thrust Belt in South America and E–W-striking late Paleozoic orogenic structures in Papua and Papua New Guinea. The authors of the present manuscript concede that this should be specified in the present manuscript.
Changes: Added a new sub-section: “***Pacific–Nazca–Antarctica triple junction***
The mid-ocean ridge segments merging at the Pacific–Nazca–Antarctica triple junction are crosscut by transform faults that parallel the Cape Fold Belt and Sierra de la Ventana Fold-and-Thrust Belt in South America (von Gosen et al., 1990; Limarino et al., 1999; Rapela et al., 2003; Lopez-Gamundi, 2006; Castillo et al., 2017) and the late Paleozoic (Variscan?) fold belt of Indonesia and the Antarctic Peninsula (Graham Land) in Antarctica (Page, 1976; Brown et al., 1979; Davies, 1980; Pigram and Davies, 1987; Hill and Raza, 1999; Harahap, 2012). In Papua (Indonesia) and Papua New Guinea, Silurian–Devonian rocks of the Omung Group were tightly folded and metamorphosed to greenschist facies prior to the deposition of late Paleozoic–Mesozoic sedimentary rocks and intrusion by Mesozoic igneous rocks (Page, 1976; Brown et al., 1979; Davies, 1980; Pigram and Davies, 1987; Hill and Raza, 1999). In this present instance, the mid-ocean ridge segments of the triple junction are crosscut by only one trend of transform faults. Nevertheless, the triple junction occurs near the intersection of the E–W-striking, Permian Sierra de la Ventana Fold-and-Thrust Belt (von Gosen et al., 1990; Limarino et al., 1999; Rapela et al., 2003; Lopez-Gamundi, 2006; Castillo et al., 2017; Stanca et al., 2022; Grillo Vidal et al., 2024) and the N–S-striking, Cambrian–Ordovician Pampean and Famatinian orogens (Rapela et al., 1998a, 1998b, 2001; Verdecchia et al., 2011; Ramos, 2018; Oriolo et al., 2021). This RRR triple junction thus does not make exception to the proposed controlling relationship and may have initiated at the intersection of Permian and Cambrian–Ordovician orogens.”.

Comment 33: If the authors want to convince us that there is indeed a correlation (and there might be one), they should provide some serious and systematic statistics where they quantitatively compare the orientation and offset of all (large) transform faults (at least of the Atlantic and Indian Oceans, datasets exist) with the orientation of orogenic systems on the margins.s
Response: Although the authors of the present manuscript concede that such studies would

be a great addition, they would require much more time and manpower than the main author of the present manuscript possesses. This would not have been an issue had the main author of the present manuscript had a permanent position. The authors of the present manuscript have added several new sections and figures, which they believe to bring added weight to their arguments in favor of Orogenic Bridge Theory. The authors of the present manuscript hope that other research groups will pursue this work and further test Orogenic Bridge Theory in the near future.
Changes: None.

Comment 34: As shown above, this correlation is not going to be 100% but they'll maybe find a significant correlation between the two. And this would be an interesting study. But at the moment, the categoric and unsubstantiated claim that "Every major transform fault on Earth strikes parallel to an orogen" is just wrong.
Response: Again, the correlation is 100%. See response to comment 32.
Changes: See response to comment 32.

Comment 35: Triple junctions. The authors pretend that triple junctions only form at the intersection of two orogens. I think that the authors mixed here between transform faults and Mid Ocean Ridge (The Rodrigues Triple Junction shows three ridges but no major transform faults. So why would you need two orientations?
Response: This refers to the common T-like geometry of Ridge–Ridge–Ridge triple junctions, with two of the three arms that are parallel to one another. In this section, the authors of the present manuscript build on the newly established correlation of all major transform faults with rift-orthogonal orogens on adjacent continental margins. Triple junctions involve at least two discrete tectonic strikes because the transform faults crosscutting the triple junction's three arms display at least two discrete strikes (e.g., E–W-striking transform faults offsetting the northern and southwestern arms of the Bouvet Triple Junction and NE–SW-striking transform fault offsetting the southeastern arm, i.e., the South West Indian Ridge; see also Figures 1 and 4 in the present manuscript). See also response to comment 34.
Changes: Added a new Figure 5b centered over the Bouvet Triple Junction and "(b) better illustrate the parallelism between transform faults truncating the South Atlantic Mid-Ocean Ridge and those crosscutting the American–Antarctica Ridge, which is partly impeded in (a) due to the curvature of the Earth surface. The white double arrow in (b) shows that the eastern portions of the Agulhas–Falkland fault zone is parallel to the Conrad fault zone." and "in (a)" and "(a–b)" in the figure caption. Also updated all references to Figure 5 in the text. Also rewrote the first paragraph of the "Implications for RR triple junctions" section into "On restoration prior to breakup, all triple junctions linking three mid-ocean ridge segments (RRR), including paleo and failed triple junctions, appear to originate at the intersection of at least two major orogens that are oblique to one another. Most if not all RRR (may they be active, paleo, or failed) triple junctions display a T-like geometry, that is two mid-ocean ridge segments parallel to one another and a third segment oblique to the other two. As such, of the three mid-ocean ridge segments involved at RRR triple junctions, two are crosscut by transform faults with the same strike. Given the control of rift-orthogonal orogens on the formation of major transform faults, a relationship between at least two orogens and RRR triple junctions is logical. OrBiT therefore predicts that RRR triple junctions form at the intersection of two preexisting orogens oblique to one another. To illustrate this, we explore the situation at the four currently active RRR triple junctions, the Bouvet, Rodrigues,

Galapagos, and Pacific–Nazca–Antarctica triple junctions, as well as at a paleo RRR triple junction (Labrador–Reykjanes–Mid-Atlantic) and two failed RRR triple junctions (western Barents Sea and North Sea rift; Figure 1, Figure 5a–b, and Figure 6).
", and added new "Galapagos triple junction", "Pacific–Nazca–Antarctica triple junction", "Labrador–Reykjanes–Mid-Atlantic paleo triple junction", "Western Barents Sea failed triple junction", "North Sea failed triple junction", and "Afar triple junction" sub-sections.
See also response to comment 34.

Comment 36: BTW, it is shown above that transform fault can also form oblique or perpendicular to orogenic belts) or that they deem impossible to form a Mid Ocean Ridge if not perpendicular to an orogenic belt. The latest is of course wrong (otherwise we would not have the Atlantic Ocean offshore the USA).
Response: This comment is somewhat confusing. Orogenic Bridge Theory suggests that both transform faults (rift-orthogonal endmember) and mid-ocean ridges form parallel to preexisting orogens (rift-parallel endmember). Thus, the authors of the present manuscript think they agree with the reviewer that the opening of the central Atlantic Ocean between North America and western Europe may have been controlled by preexisting orogens (e.g., possibly the Appalachian and/or Variscan–Alleghenian orogens). However, this issue concerns the rift-parallel endmember of Orogenic Bridge Theory, i.e., the case in which a preexisting orogen facilitates rifting and breakup because orogenic structures are oriented parallel to the opening rift. As mentioned in the present manuscript, this endmember is relatively well accepted among the Geoscience community, and it is therefore not the focus of the present manuscript. The authors of the present manuscript concede that this should be better specified in the present manuscript. See also response to comment 5.
Changes: Extensively rewrote the "Orogenic bridge theory" section and added a new figure detailing the formation of orogenic bridges. See also response to comment 5.

Comment 37: For the Bouvet Triple junction, the two orientations mentioned are the Agulhas–Falkland fault zone orientation and the Andrew Bain fault zone orientation. If you measure the angle between these two orientations, it is approximately 20° (and not 45° as mentioned in the manuscript). This difference is small and I doubt it would have a dramatic impact.
Response: Disagreed. The difference in strike between the Andrew Bain fault zone and the Agulhas–Falkland fault zone and fault zones crosscutting the America–Antarctic Ridge is at the very least 35° in GoogleEarth and Google map (see also figs. 4 and 5 in the present manuscript).
Changes: None required.

Comment 38: There are much more important differences in orientations in orogenic belts at the latitude of the Romanche FZ (e.g. Meert & Lieberman, 2008) but no triple junction here. Neither in the north Atlantic at the junction of the Caledonian orogeny and the Tornquist Zone (which are almost perpendicular).
Response: This is an excellent comment by the reviewer and a great opportunity for the authors to further clarify and highlight some very interesting geological relationships in the North Atlantic region. Assuming that the reviewer means at the intersection of the Caledonian Orogen and Laxfordian Orogen (of which the Tornquist Zone is probably a part of), there happens to be a paleo triple junction at the intersection of these two structural

trends at the junction of the extinct Labrador mid-ocean ridge and the Reykjanes Ridge and a failed triple junction in the triple-junction-like North Sea rift. The name of the late Paleoproterozoic orogenic belt in southern Greenland though is the Ketilidian Orogen (Garde et al., 1997, 2002; see Figure 4 in the present manuscript). These are relevant relationships that should be discussed in the present manuscript.
Changes: Added two new "Labrador–Reykjanes–Mid-Atlantic paleo triple junction" and "North Sea failed triple junction" sub-sections. Also updated figure 4 in the present manuscript.

Comment 39: Then if you look at another very prominent triple junction, the Afar Triangle, you'll see that it is only influenced by the East African Orogeny, and not by two different orogenic systems with different orientations (e.g. Johnson et al., 2011; Fritz et al., 2013). We, for example, proposed that the localization of the Afar Triple Junction is, at least partly, controlled by the East African orogeny in conjunction with many different tectonic accidents linked to extensional events (Rime et al., 2023).
There are therefore no solid arguments to state that triple junctions are formed at the intersection of at two (or more) orogenic systems. Certainly not with the wording used here that presents it as an indisputable conclusion.
Response: This is an excellent example and the authors of the present manuscript thank the reviewer for his pertinent comment. The Afar triple junction is not yet a typical triple junction with three mid-ocean ridge segments actively producing oceanic crust. In addition to the late Neoproterozoic East African Orogen, the Arabian–Nubian Shield is transected by a number of NE–SW-striking early Neoproterozoic shear zones and sutures, some of which crop out in Yemen, where they are located in the direct vicinity of and striking parallel to the Gulf of Aden arm of the Afar triple junction. Thus, the formation of the Gulf of Aden Rift may very well have been controlled by this early Neoproterozoic orogen. Thus, the Afar triple junction does conform with the Orogenic Bridge Theory model (i.e., RRR triple junctions forming at the intersection of at least two orogens).
Changes: Added a new paragraph about the East African Orogen and its relationship with the Aqaba–Dead-Sea–Levant transform fault zone and proto transform faults in the Red Sea at the end of the "East African–Antarctica orogenic bridge" sub-section: "In the northern part of the East African Orogen, the Red Sea rift presents some peculiar relationships with preexisting sutures and shear zones in the Arabian–Nubian Shield. There, N–S-striking Neoproterozoic shear zones, such as the Barka (–Adobha) and (Onib–) Hamisana shear zones ( Abdelsalam, 2010; Collins *et al.*, 2021; Johnson & Woldehaimanot, 2003; Stern & Kröner, 1993), coincide with zones of high seismicity and minor steps, bends/kinks, and narrowing of the Red Sea rift, which were interpreted as potential (proto) transform faults ( Bosworth *et al.*, 2005; Dixon *et al.*, 1987; Molnar *et al.*, 2020). N–S-striking, late Neoproterozoic shear zones also parallel the Aqaba–Dead-Sea–Levant fault zone (Molnar *et al.*, 2020), some of which were reactivated in the order of km to tens of km ( Bosworth *et al.*, 2005). Conversely, NW–SE-striking late Neoproterozoic shear zones, e.g., Rehba and Tabalah–Tarj shear zones ( Bosworth *et al.*, 2005; Johnson & Woldehaimanot, 2003) and Najd fault system ( Moore, 1979; Stern, 1985; Hamimi *et al.*, 2021), strike parallel to the segmented Rea Sea spreading center, thus suggesting opening of the rift along preexisting late Neoproterozoic zones of weakness in the crust (rift-parallel endmember of orogenic bridge theory).".
Added a sub-section about the Afar triple junction: "***Afar triple junction***

In the Arabian–Nubian Shield, the N–S-striking late Neoproterozoic shear zones and sutures of the East African Orogen probably controlled the formation of the Aqaba–Dead-Sea–Levant fault zone and related proto transform faults in the Red Sea (see East African–Antarctica orogenic bridge section; Bosworth *et al.*, 2005; Collins *et al.*, 2021; Dixon *et al.*, 1987; Johnson & Woldehaimanot, 2003; Molnar *et al.*, 2020; Stern & Kröner, 1993; Figure 11). In addition, it is well established that these inherited, late Neoproterozoic structures also controlled the geometry of the East African Rift in Nubian basement rocks, e.g., providing suitably oriented N–S-striking foliation, faults, shear zones, and intrusions (e.g., Chorowicz, 2005; Corti *et al.*, 2022).
In addition, the Arabian–Nubian Shield is transected by older, early Neoproterozoic, NE–SW-striking shear zones and suture zones, e.g., Yanbu-Sol Hamed, Bi'r Umq–Nakasib, and Ambur–Delgo sutures ( Collins *et al.*, 2021; Johnson, 2014; Johnson *et al.*, 2011; Robinson *et al.*, 2015; Figure 11). These were reworked by E–W-oriented contraction during the late Neoproterozoic East African Orogeny, e.g., NNW–SSE-striking sinistral Oko shear zone offsetting the Bi'r Umq–Nakasib suture ( Abdelsalam, 2010). In Yemen, NE–SW-striking Neoproterozoic shear zones and/or sutures bound Archean–Mesoproterozoic crust of the Abas and Al Mahfid blocks from more juvenile rocks of the Al Bayda block, which record late Neoproterozoic greenschist-facies metamorphism ( Johnson *et al.*, 2011; Johnson, 2014; Figure 11). These zones of deformation strike parallel to the NE–SW-striking Gulf of Aden Rift. It is therefore possible that the rift localized along was controlled by NE–SW-striking early Neoproterozoic orogenic structures. Thus, the Afar triple junction does conform with orogenic bridge theory in that it initiated at the intersection of the N–S-striking late Neoproterozoic East African Orogen with a NE–SW-striking early Neoproterozoic orogen (Figure 11).".
Also added reference to the work by Rime et al. (2024) when discussing the formation of microcontinents in the new third paragraph of the "East African–Antarctica orogenic bridge" sub-section.

Comment 40: "Much of the submarine area around the globe" is continental. The authors say that "much of the submarine area around the globe consist of (hyper-) extended and/or extensively intruded (i.e., hybrid) orogenic continental crust". This statement is not supported by any meaningful data. Even if the authors mention the difficulties of determining the COT, and that some continental material can be dragged far offshore in area of strong volcanic activity, it is a strong overinterpretation to say that much of the submarine area around the globe consist of continental material.
Response: The authors of the present manuscript agree that this claim should be further specified and supported with key references.
Changes: Included a % estimate of the proposed changes in continental versus oceanic crust ratio for each orogenic bridge and margin discussed. For example, added an introduction paragraph to the "continuous Orogenic Bridge" section: "The concept of continuous orogenic bridge implies that continental crust continues across previously inferred oceanic domain. In such areas, the extent of oceanic crust is proposed to be overestimated by 100% (i.e., no oceanic crust yet). This implies the existence of sections of hybrid continental crust (see Figure 2a and b) capped by thick successions of volcanic rocks (e.g., lava flows) and extensively intruded by igneous rocks (e.g., Seaward-Dipping Reflectors). Sections of hybrid continental crust are locally believed to extend the width of previously assumed oceanic domains. Three potentially continuous orogenic bridge are

discussed here, the Timanian orogenic bridge in the Fram Strait, the Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and the Greenland–Iceland–Faroe orogenic bridge ( Figure 4).” and “In the examples discussed, the overestimation of the extent of oceanic crust is in the order of 20–60%.” to the introduction to the “Disrupted Orogenic Bridge” section. Also added “Given the c. 2800 km distance to the mid-ocean ridge in this area, this suggests an underestimation of the extent of continental crust of 3.5 to 10.7%.” in the second paragraph of the “Passive margins” section, “Considering the c. 3250 km distance between the previous continent–ocean boundary proposed by Schimschal and Jokat (2018; see also figure 1 in Stanca et al. 2022) and the mid-ocean ridge and the c. 1900 km distance between the eastern tip of Maurice Ewing Bank (the continent–ocean boundary proposed in the present manuscript) and the mid-ocean ridge, the extent of oceanic crust on the South American side of this ruptured orogenic bridge is overestimated by c. 41.3%.” to the first paragraph in the “Cape–Falkland orogenic bridge” sub-section and split the paragraph in two, “Thus, the extent of oceanic crust at the Madagascar Ridge is c. 43.5% using a c. 1150 km distance between the previously inferred continent–ocean boundary at the transition zone between the northern and southern parts of the Madagascar Ridge at 31°S and the mid-ocean ridge and a c. 650 km distance between the southern tip of the southern Madagascar Ridge (i.e., the presently proposed continent–ocean boundary).” in between paragraphs 1 and 2 in the “East African–Antarctica orogenic bridge” section (at the end of the second newly added paragraph), “As such, the extent of oceanic crust at the Mozambique Ridge is currently overestimated by c. 55.9 % using a distance of 3400 km between the northern tip of the Mozambique Ridge (i.e., previously proposed continent–ocean boundary) and the mid-ocean ridge and a c. 1500 km distance from the southern tip of the Mozambique Ridge to the mid-ocean ridge (i.e., new continent–ocean boundary).” at the end of the first newly added paragraph after paragraph 1 in the “East African–Antarctica orogenic bridge” section, and “At the Astrid Ridge, the extent of oceanic crust could thus be overestimated by up to 20.6% using a c. 1700 km distance between the previously assumed continent–ocean boundary between the southern and northern parts of the Astrid Ridge (Roeser et al., 1996) and a c. 1350 km distance from the northern tip of the Astrid Ridge (new continent–ocean boundary). At the Gunnerus Ridge and taking into account the Del Cano Rise, oceanic crust extent may be overestimated by as much as 25.0% using a c. 2800 km distance between the southern tip of the Gunnerus Ridge and the mid-ocean ridge and c. 2350 km from the northern tip of the Gunnerus Ridge (new continent–ocean boundary) and including a c. 250 km wide continental crustal domain at Del Cano Rise (Sato et al., 2022).” after the newly added paragraph between paragraphs 2 and 3 in the “East African–Antarctica orogenic bridge” section.

Comment 41: Even if we assume that all areas that are considered as Oceanic Large Igneous Province are continental (good luck convincing me that the Shatsky Rise is continental), they only cover 6% of the oceanic realm (Mooney et al., 2023).
Response: The authors of the present manuscript concede that their claim was confusing and not sufficiently supported by appropriate data and references. The authors of the present manuscript do not argue that all Oceanic Large Igneous Provinces are underlain by continental crust, but that specific areas with anomalously thick crust offshore exceeding the 6 km thickness of typical oceanic crust should be reconsidered and may be cored by continental crust.
The size of the areas argued to be continental by the authors of the present manuscript

exceed that of the areal sum of all Oceanic Large Igneous Provinces from Mooney et al. (2023). Again, the authors of the present manuscript do not argue that all Oceanic Large Igneous Provinces are cored by continental crust. However, they argue that in addition to the area under some of the Oceanic Large Igneous Provinces (e.g., Greenland–Iceland–Faroe, Walvis, Rio Grande, Mozambique, Madagascar, Gunnerus, and Astrid ridges), many broad offshore areas at magma-poor margins (e.g., Fram Strait, Davis Strait, and Maurice Ewing Bank) are also cored by continental crust. Noteworthy, the map by Mooney et al. (2023) does not seem to include the Lomonosov and Alpha–Mendeleev ridges as continental crust although all recent evidence are in favor of a continental nature of the crust there (e.g., Jackson and Chian, 2010; Rekant et al., 2019; Nikishin et al., 2024).
Another point is that although a 6% increase in the amount of continental crust does not seem significant, it would still represent a 20% increase compared to the current c. 29% ratio of continental crust, which does seem significant and would generate tremendous changes in paleogeographic reconstructions, thus severely impeding the moving of old continental blocks, especially Laurentia and Baltica, which, if the present relationship is true, would have remained connected since the late Paleoproterozoic at ca. 1.8 Ga.
Changes: None required.

Comment 42: The authors also seem suggest that most of the western Indian Ocean (including Mozambique Basin, the Mascarene Basin and the Somalian Basin) is continental (Fig. 1). I agree that some continental fragments are dispersed in this area (Rime et al., 2024), but the basins in between all have pretty clear oceanic characteristics, including crustal thickness, bathymetry, magnetic anomalies and geophysical characteristics (e.g. Simplson et al., 1979; Scrutton et al., 1981; Masson, 1984; Coofin & Rabinowitz, 1987; König & Jokat, 2010, Seton et al., 2012, Laske et al., 2013). The assertion that they are continental would indeed be quite a change of paradigm, but you'd need a bit more than a figure (to say the least) to suggest it.
Response: Agreed. This is an excellent comment by the reviewer and the authors of the present manuscript thank him for the opportunity to further illustrate the controlling relationships of preexisting orogens on the formation of major transform faults and mid-ocean ridges.
Pseudo-linear magnetic anomalies alone (Simpson et al., 1979; Scrutton et al., 1981; Coffin and Rabinowitz, 1987; Davis et al., 2016) are not sufficient to infer oceanic crust and may reflect intrusions in continental crust as recently demonstrated by Geoffroy et al. (2021, 2022).
The same goes for seismic refraction data, which are tentative and generally overinterpreted (e.g., Breivik et al., 2005; König and Jokat, 2010; Schimschal and Jokat, 2019).
Finally, plate models (e.g., Seton et al., 2012) build on the previous and, thus, cannot be taken as arguments of the crust's nature in specific area. This would be a textbook example of circular reasoning since plate models are attempts to test whether having specific amounts of continental versus oceanic crust in specific areas may work from a plate kinematic perspective. Should they make it work, they would suggest that the current interpretation of oceanic versus continental crust is possible, but they cannot be taken as conclusive arguments.
In contrast, seismic reflection data directly image the structure and layering of the crust and can, if of sufficient quality and resolution and interpreted to a sufficient extent, be definitive regarding the nature of the crust (e.g., Geoffroy et al., 2022; Koehl et al., 2024b, 2025). Other

examples include the Laccadive–Chagos Ridge off western India, where seismic reflection data and crustal thickness suggest that the crust is fully continental and was intruded by magma in places, e.g., in the Laccadive Basin (Gilbert et al., 2024 their figure 5).
An example that should be mentioned in the Somali Basin is the study by Sauter et al. (2018), which uses deep Ion seismic lines and clearly shows that the quality of seismic reflection data in the area is not optimal as attested by the numerous "?" near the area of thickened crust near the Davie Ridge in their profiles AA', CC', DD', and EE' (their figure 5). A clear inconsistency is their interpretation of an (extensional?) fault as the western boundary of a tentative volcanic edifice in their profile EE'. While the seismic reflections within the tentative volcanic edifice are clearly inconclusive (probable seismic artifacts), there seem to be an extensional fault, though listric instead of steepening downwards (see reinterpreted seismic section below). This would suggest hyperextension, thus in accordance with rifting in the Somali Basin. However, it is not conclusive in terms of the nature of the crust below the fuchsia reflection. The authors of the present manuscript question the nature of anomalously thick crust, which they believe to be continental in many instances. Such crust is found in the southern Somali Basin (Sauter et al., 2018). Another study that should be mentioned rather than that of magnetic anomalies in the Somali Basin is that of seismic velocities by Coffin et al. (1986), which clearly demonstrate the presence of shallow mantle with velocities $\geq 7$ km.s$^{-1}$ below the Somali Basin (their profiles 354, 359, and 380). This study clearly suggests that figure 1 in the present manuscript should be slightly modified to accommodate this narrow oceanic domain. From a kinematic perspective, the main issue with the Somali Basin is that the presumed spreading center is not centered on the crustal domain with typical oceanic thickness in the Western Somali Basin (Sauter et al., 2016 their figure 1). On the contrary, the presumed center is interpreted near a portion of thickened crust in the southern part of the basin, which is, just like the thickened crust at the Davie Ridge (e.g., Klimke et al., 2018), probably not oceanic.

Figure 3 and 4
*https://s3-eu-west-1.amazonaws.com/openreseurope/linked/248220.17238__Jean-Baptiste_Koehl_to_Valentine.pdf*

In contrast in the northernmost Mozambique Basin near the Davie Ridge, seismic reflection data clearly suggest that the crust is continental (e.g., Klimke et al., 2018; https://www.tgs.com/seismic/multi-client/africa-mediterranean-middle-east/east-africa/mozambique). Farther south, modeled densities and seismic reflection data suggest oceanic crust (Matsinhe et al., 2021; Evain et al., 2021). The extent of oceanic crust in the Mozambique Basin is however uncertain due to the sparse coverage of seismic reflection data. What seems to come back repeatedly in existing studies is the existence of an ENE–WSW-striking paleo spreading center in the northern half of the Mozambique Basin (e.g., Simpson et al., 1979; Norton and Sclater, 1979).
Regardless, the Mozambique and Somali basins are perfect examples to illustrate the impact of orogenic bridges on rifting and breakup. If one accepts the existence of extinct, ENE–WSW-striking spreading centers and magnetic anomalies both in the northern Mozambique Basin (e.g., Simpson et al., 1979; Norton and Sclater, 1979) and western Somali Basin (Coffin and Rabinowitz, 1987; Davis et al., 2016; Sauter et al., 2018), a tectonic evolution somewhat similar to that proposed by Seton et al. (2012 their figure 15) and Vormann and Jokat (2021 their figure 3) and described as follows is considered likely. The

Indian rift attempted at cutting through the East African–Antarctica Orogen at suitably oriented zones of weakness. An area with suitably oriented structures is the ENE–WSW-striking Lurio Belt of the Kuunga Orogen in northeastern Mozambique (Sacchi et al., 2000; Viola et al., 2008; Bingen et al., 2009) and its counterpart in western India and Sri Lanka ( Brandt et al., 2014; Dharmapriya et al., 2015; Ghosh et al., 2004; He et al., 2018; Hirayama et al., 2020; Srinivasan and Rajeshdurai, 2010), which consist of structures that may have helped thin the thickened orogenic crust of the East African–Antarctica Orogen. However, upon meeting any major unsuitably oriented structure of the East African–Antarctica Orogen (c. N–S-striking), e.g., at the Davie Ridge (e.g., N–S-striking contractional structures in Klimke et al., 2018 their figures 2–6) and its southern prolongation, the Madagascar Ridge, the rift may have been forced to step laterally, i.e., in the northern Mozambique Basin, where suitably oriented structures of the E–W-striking Kuunga Orogen occur in southern Madagascar (Collins et al., 2003, 2012; Armistead, 2019). There, upon meeting a possible unsuitably oriented major, N–S-striking structure at the Mozambique Ridge (e.g., Matsinhe et al., 2021 their figures 2, 4, and 6), the Indian rift would have again attempted to step sideways or simply died out and eventually proceeded at the location of the South West Indian Ridge. The authors of the present manuscript concede that this should be added to the present manuscript.
Changes: Modified Figure 1 and Figure 6 to include oceanic domains in the Western Somali Basin and Mozambique Basin. Also added “The case of the Mozambique and Somali basins illustrate well the impact of orogenic bridges on rifting. Both basins host extinct, ENE–WSW-striking spreading centers and magnetic anomalies (e.g., Coffin & Rabinowitz, 1987; Davis *et al.*, 2016; Norton & Sclater, 1979; Sauter *et al.*, 2018; Simpson *et al.*, 1979; Figure 6) and a tectonic evolution somewhat similar to that proposed by Seton *et al.* (2012 their figure 15) and Vormann & Jokat (2021 their figure 3) is considered likely. In such as model, the Indian rift attempted at cutting through the East African–Antarctica Orogen at suitably oriented zones of weakness. An area with suitably oriented structures is the Lurio Belt in northeastern Mozambique ( Bingen *et al.*, 2009; Viola *et al.*, 2008; Sacchi *et al.*, 2000) and its counterpart in western India and Sri Lanka (Kuunga Orogen; Brandt *et al.*, 2014; Dharmapriya *et al.*, 2015; Ghosh *et al.*, 2004; He *et al.*, 2018; Hirayama *et al.*, 2020; Srinivasan & Rajeshdurai, 2010), both of which consist of ENE–WSW-striking structures ( Figure 1 and Figure 6). These structures were oriented perpendicular to the c. N–S extension direction and were thus suitable to efficiently thin the thickened orogenic crust of the East African–Antarctica Orogen. However, upon meeting unsuitably oriented, major orogenic structure of the East African–Antarctica Orogen, e.g., N–S-striking contractional structures at the Davie Ridge (Klimke et al., 2018 their figures 2–6) and its southern prolongation, the Madagascar Ridge, the rift may have been forced to step laterally, i.e., in the northern Mozambique Basin, where suitably oriented structures of the E–W-striking Kuunga Orogen occur in adjacent areas onshore southern Madagascar ( Armistead, 2019; Collins *et al.*, 2003; Collins *et al.*, 2012). Nevertheless, upon meeting yet another unsuitably oriented N–S-striking structure at the Mozambique Ridge (e.g., Matsinhe et al., 2021 their figures 2, 4, and 6), the Indian rift eventually stepped farther south into its present-day location at the South West Indian Ridge ( Seton *et al.*, 2012; Figure 1 and Figure 6).” to the “East African–Antarctica orogenic bridge” sub-section and the new references to the reference list.

Comment 43: It is thus a gross overstatement to say that much of the submarine area consists of continental material. If you want to argue for such a groundbreaking hypothesis,

you have to present maps, calculate areas (in km2) that you consider as potentially continental and give arguments as to why you reject each specific area as an ocean. And this cannot be done in a few lines.
Response: Partly agreed. It is possible that the confusion is about the term “much”, which is not specific enough. Based on the preliminary estimates provided with the new version of the manuscript, a rough estimate may be 20% of all offshore areas currently considered to be oceanic crust may in fact be continental. However, obtaining a detailed figure is not the purpose of the present manuscript.
Changes: Replaced “much” by “a fair portion” in the tenth paragraph of the “Orogenic bridge theory” section. In addition, added estimates (in %) of the offshore areas that may be cored by continental crust. See also response to comment 40.

Comment 44: Even if we assume that this theory is correct, it does not imply that “The dynamism and intensity of seafloor spreading at mid-ocean ridges may have been overestimated”. If these areas do feature continental crusts, they are hyper-extended and, thus, mobile and transported far away from their margins (see for example the model proposed here: Rime et al., 2024) and it does not prevent the ocean from getting very wide or opening very rapidly.
Response: Disagreed. Yes, it does. Less oceanic crust on Earth means less magmatism at (both present-day and paleo) mid-ocean ridges. For example, new aeromagnetic data in the Fram Strait clearly show that seafloor production was largely overestimated in this area (Dumais et al., 2020). In addition, should the GIFR and other similar areas (orogenic bridges) and other factors such as “outer SDRs” (Geoffroy et al., 2020) be taken into account in the estimation of the extent of oceanic crust domains, it would significantly affect the continental vs oceanic crust ratio on Earth. Furthermore, should the GIFR actually be a continuous late Paleoproterozoic orogenic bridge as suggested by preliminary analysis of seismic reflection data (Koehl et al., 2024, 2025), it would imply that all the oceans presumed to have opened between Laurentia and Baltica between now and the late Paleoproterozoic were much narrower and far less productive in term of oceanic crust than currently thought, e.g., a speculated 5000 km wide Iapetus Ocean (Torsvik and Trench, 1991; Fortey and Cocks, 2003). Thus, Iapetus was probably not wider than 1000 km as the present-day northeastern Atlantic Ocean at the Mohns Ridge segment between Norway and Greenland. Else the late Paleoproterozoic orogenic bridge would have ruptured and included segments of oceanic crust, which is not in line with current crust thickness estimates across the GIFR (Darbyshire et al., 1998; Foulger et al., 2003, 2020). Regarding dynamism, the authors of the present manuscript concede that less magmatism at mid-ocean ridges (because less oceanic crust on Earth) does not necessarily imply less dynamism because, as mentioned in the present manuscript, orogenic bridges contract and extend together with adjacent oceanic domains (see also new figure detailing the formation of orogenic bridges). However, having a continuous late Paleoproterozoic orogenic bridge at the GIFR pins Baltica and Laurentia together (i.e., nearly in the same relative position) for the past 1.8 Gyr. Thus, models like that of the rotation of Baltica in the Cambrian–Ordovician (e.g., Trench and Torsvik, 1992; Torsvik and Rehnström, 2001) are no longer viable and Orogenic Bridge Theory (via the pinning of Baltica with Laurentia for the past 1.8 Gyr) does imply less dynamism in terms of range of possible relative and absolute plate movements. The authors of the present manuscript concede that this should be better specified in the manuscript.

Changes: Added a new paragraph to the "Implications for plate tectonics and modeling" section: "Less magmatism at (both present-day and paleo) mid-ocean ridges does not necessarily imply less tectonic extension since orogenic bridges contract and extend together with adjacent oceanic domains (Figure 3). However, the pinning of Baltica and Laurentia for the past 1.8 Gyr via continuous late Paleoproterozoic orogenic bridge at GIFR implies significantly less dynamic relative and absolute paleo plate movements. Notably, the Iapetus Ocean was probably much narrower than the previously suggested 5000 km (Torsvik & Trench, 1991; Fortey & Cocks, 2003) and a $\leq$ 1000 km width similar to that of the present-day North Atlantic Ocean is more plausible because it would not have resulted in rupture of the Timanian and Greenland–Iceland–Faroe orogenic bridges. For example, if the late Paleoproterozoic Greenland–Iceland–Faroe orogenic bridge would have ruptured, it would include traces of intense Caledonian deformation with possible suture zones, tight folds, and segments of oceanic crust. This is neither in line with current crustal thickness estimates across the GIFR, which indicate continental crust in Iceland's lower crust (Darbyshire *et al.*, 1998; Foulger *et al.*, 2003; Foulger *et al.*, 2020), nor with the open/gentle character of the Caledonian folds reworking the late Paleoproterozoic thrust systems at the GIFR, which indicate mild Caledonian deformation (Koehl *et al.*, 2024; Koehl *et al.*, 2025). Thus, models like that of the rotation of Baltica in the Cambrian–Ordovician (e.g., Torsvik & Rehnström, 2001; Trench & Torsvik, 1992) are no longer viable alternatives.". Rewrote the last point of the conclusion into "Orogenic bridge theory suggests that the extent of oceanic crust was overestimated and, thus, that the intensity, amount, and speed of seafloor spreading should be toned down in future paleogeographic reconstructions.".

Comment 45: The Orogenic Bridge theory – from a hypothesis to a universal truth. Probably the most important flaw of the paper is that what should have been an hypothesis to be tested, is considered as an universal truth that is even raised above the most important theory of geology: plate tectonics. Wow! Nothing less? I would advise the authors to approach the topic with more humility.
First of all, what is presented here is a hypothesis. As discussed above, the authors did not provide any substantial evidences for several of their hypotheses. Some might be valid (not as categorically as presented, I have shown several counterexamples, but there might be some correlations), but the paper does not present any solid evidence for it. But the authors do not seem to consider it as a hypothesis (the word "hypothesis" is never used with regard to their theory) and that maybe explains why they did not test it properly.
Response: Partly agreed in that it should have been more clearly stated that Orogenic Bridge Theory is a theory that needs further testing. However, a significant portion is already based on scientific evidence and data and is therefore past the stage of hypothesis, e.g., orogenic bridge in the Fram Strait (Dumais et al., 2020; Koehl, 2020, 2024; Koehl et al., 2021, 2022, 2023; Koehl and Mottram, 2024) and continental nature of the GIFR (Darbyshire et al., 1998; Foulger et al., 2003, 2020; Koehl et al., 2024). It can therefore hardly come as a surprise that such a theory is proposed to unify observations and data not conforming with our current understanding of plate tectonics with those conforming with plate tectonics. It remains true that the proposed theory must be further tested, but it is definitely past the stage of simple hypothesis.
The authors of the present manuscript disagree with the comment of the reviewer on "humility". First, Science is about logic and rationality, not about feelings. Therefore, the authors of the present manuscript do not see what humility should have to do with the

validity of scientific hypotheses, theories, facts, and data. If the reviewer is suggesting that the authors of the present manuscript should not challenge previous ideas, hypotheses, and models by respect for the renowned scientists who proposed them, the authors of the present manuscript disagree with the reviewer. The authors of the present manuscript argue that individuals doing science, whoever they may be and whatever their reputation or past contribution may be, regardless of whether they are kind or mean to others, every scientist contributing to Science sooner or later exposes her/himself to rebuttal of her/his work, claims, ideas, hypotheses, and/or models by newer, more modern, and more complete ideas/hypotheses/theories. Thus, not sharing the new correlation discussed in the present manuscript after uncovering it would have been a serious infringement by the authors of the present manuscript to their duty of scientists. The authors of the present manuscript are not naive and are aware that such practices (i.e., toning down new ideas/discoveries) exist, e.g., by insecure/less powerful scientists who choose to look the other way or tone their ideas down to avoid openly disagreeing with scientist(s) with (hiring/financial/other?) power over them and thus possibly increasing their probability of landing a job (thus the say: "I will publish this when I get tenure"). People are people and will be people in that they rarely give jobs to people whom they disagree with, which is a shame since diversity of scientific approach and methods and beliefs has been, is, and will continue to be key to mankind's success.
Second, if the reviewer is suggesting that Alfred Wegener, in his time, should have had more humility to dare disagreeing with renowned geologists such as Prof. Charles Schuchert and Prof. Hermann von Ihering, while Alfred Wegener, himself, was not a geologist, then the authors of the present manuscript would also disagree with the reviewer. The authors of the present manuscript are glad that Alfred Wegener did have the courage and was allowed to propose his (at the time) new and ground-breaking Continental Drift Theory (which he also called a theory, not "Continental Drift Hypothesis"), for which he had fewer evidence than the present study. For example, Wegener did not have a driving mechanism for his theory at the time, and yet, the conclusion seemed already inescapable back then: the continents had moved and were moving. Some conclusions presented in the present manuscript seem similarly inescapable, e.g., rift-orthogonal orogens hinder rifting and localize the formation of major transform faults and RRR triple junctions form at the intersection of two orogens. Orogenic Bridge Theory is not placed "above" plate tectonics. It is simply a significant update to plate tectonics. Thus, looking at it in the form of a book, Continental Drift Theory would be the thrilling beginning, plate tectonics the present page we are reading, and Orogenic Bridge Theory possibly the next page. The authors of the present manuscript hope that the new theory proposed will be further tested by numerous future studies and research groups.
Changes: Rewrote the abstract entirely and included "in the hope that the new theory gets further tested".

Comment 46: The authors then use this theory to reject existing geological interpretations with an impressive degree of self-confidence. "Any transform or paleo transform fault that does not fulfill this condition may thus be discarded as a transform fault or even simply as a fault." Really? You probably want to change the definition of what a fault is then? I highlighted above how some of the biggest transform faults in the world do not obey this theory. But it is absurd to expand it to any fault or even transform fault globally. Millions of faults (and a bunch of transform faults) are not parallel orogenic belts. This is a gross

overinterpretation of an unproven hypothesis.
Response: Given the unusual background of the main author of the present manuscript (structural field geologist and seismic reflection interpreter), the idea of changing the definition of certain geological terms such as “terrane” and “ophiolite” is definitely on his agenda. Being both a university-educated structural field geologist and an industry-educated seismic interpreter, the main author of the present manuscript may confidently affirm that many faults argued to be “major faults” or even “terrane boundaries” or “sutures” are nothing more than small pieces of gigantic structures in the subsurface or, in some cases, not faults at all (especially faults mapped between two rock units without any indication or preserved outcrop of fault rock). A typical example is the Billefjorden Fault Zone in Svalbard (Harland et al., 1974), which, albeit spectacular in size to any human being (km-scale), is a rather unimpressive and minor structure to a trained regional seismic interpreter. It was demonstrated recently that this previously assumed long-lived terrane boundary with a complex tectonic history (Harland et al., 1974, 1992) is in fact a minor fault possibly essentially formed in the early Cenozoic (Koehl, 2021; Koehl and Allaart, 2021; Koehl et al., 2023, 2024a). Thus, the authors of the present manuscript would agree that the definition of “major faults” is a rather subjective term, which should be used with greater care by all geoscientists, especially field geologists when interpreting faults in the field. A compelling comparison is made in Koehl and Mottram (2024) between km-scale asymmetric folds along the tens of km thick, several thousands of km long Kongsfjorden–Cowanodden fault zone on seismic reflection data in Svalbard and the Barents Sea (Koehl et al., 2022) and the Lewis Thrust and related asymmetric folds in Mount Kidd in the Canadian Rockies (e.g., Fitz-Diaz et al., 2011). While the latter appear to be major structures to field geologists, they are certainly no more than very tiny pieces of a much larger structure. The Kongsfjorden–Cowanodden fault zone in Svalbard is a late Neoproterozoic thrust systems that extends at least 2000 km from the Ural Mountains to western Svalbard (Koehl et al., 2022, Koehl and Mottram, 2024) and perhaps to northern Greenland (Rosa et al., 2016; Estrada et al., 2018). This thrust system is tens of km thick and consists of hundreds of Mount-Kidd-type fold-and-thrust structures.
The high degree of self-confidence of the authors of the present manuscript applies to the De Geer Zone and Wegener Fault, both of which are clearly erroneous paleo transform faults inferred from incomplete observations and monodisciplinary approaches or from pure speculation (e.g., Taylor, 1910). Taylor (1910)’s speculation of the De Geer Zone (exclusively based on the linear shape of the bathymetry along the coastline of western Svalbard and northern Greenland) was quoted by numerous subsequent authors, who added no evidence whatsoever to Taylor’s bathymetric argument, but gradually turned his hypothesis into a scientific fact. Both paleo transform faults can thus be confidently rejected (Oakey and Damaske, 2006; Oakey and Stephensen, 2008; Dawes, 2008; Hansen et al., 2011; Rasmussen and Dawes, 2011; Koehl, 2024). The authors of the present manuscript hope that many more (paleo) faults will be confronted with Orogenic Bridge Theory. No other paleo transform comes to mind for now. However, the authors of the present manuscript are open to discussing any other relevant structure.
Orogenic Bridge Theory is not being applied to “any fault or even transform fault” as suggested by the reviewer, but only to major transform faults (definition specified in the present manuscript).
The reviewer will agree that the sentence pointed out states “may be discarded” and not “must be discarded”, thus reflecting the state of “theory” and not of “holy truth” of the

proposed theory. The “may” term implies that such may be the case for various paleo transform faults in the future when confronting them to the principles of Orogenic Bridge Theory. Such faults may either be upheld/validated because conforming to Orogenic Bridge Theory and other lines of evidence supporting these faults are robust, or discarded because not conforming to Orogenic Bridge Theory and evidence suggesting that the evidence used previously to infer these paleo transform faults are not as robust as previously thought.
See response to comments 25 to 31 regarding how the counter examples proposed by the reviewer do conform with the proposed theory.
The authors of the present manuscript do not dispute the fact that some transform faults do not parallel rift-orthogonal orogens on adjacent margins because it is not what their new theory states. The theory states that all major transform faults parallel rift-orthogonal orogens on adjacent margins. Thus, it does not impact on the presently proposed theory that millions of minor transform faults do not parallel orogens on adjacent margins.
Nonetheless, the authors of the present manuscript are open to discussing other counter examples in the present manuscript should any relevant examples other than those discussed in the reviewer’s comments 25 to 31 be brought up by the reviewer.
It is perhaps relevant to mention that the main author of the present manuscript was as surprised as the reviewer when he contemplated for the first time a potential global correlation of all major transform faults on Earth with matching orogens on adjacent margins in February 2022. He was even more baffled when he was able to reject every single counter example that ChatGPT proposed up to summer 2023. ChatGPT agreed to retract all the counter-examples it proposed based on the lines of evidence and literature suggested by the main author of the present manuscript.
Changes: Rewrote the first paragraph of the “Testing the existence of tentative (paleo) transform faults” section into “OrBiT can help test the plausibility or likelihood of tentative (paleo-) transform faults should any doubts be cast on their existence or kinematics. The theory predicts that the formation of major transform faults is controlled by orogens striking (sub-) orthogonal to propagating rifts. Any transform or paleo-transform fault that does not fulfill this condition is therefore highly unlikely according to OrBiT. Should the theory be further tested and substanciated, it would allow quick and smooth testing/troubleshooting of specific transform faults worldwide. Transform and paleo transform faults not obeying OrBiT’s principles (i.e., formation parallel to preexisting rift-orthogonal orogen) would thus be possible to discard as a (paleo) transform faults or even in some cases as faults. Two such examples are the De Geer Zone in western Svalbard and the Wegener Fault between Greenland and Ellesmere Island ( Figure 4).”.

Comment 47: The authors then go one step further by implying that orogenic bridges cannot be ruptured, without argumentation for this assertion.
Response: The authors of the present manuscript did not mean to argue that orogenic bridges cannot be ruptured as shown by their splitting of orogenic bridges into “continuous” and “ruptured” in the discussion section. If the reviewer would point in the text where this is written, that would be helpful, since this is not the message the authors of the present manuscript want to convey to the reader.
Changes: None for the moment. Awaiting further instructions by the reviewer.

Comment 48: They reject some important paleotectonic interpretations of earth history based on this, again with a surprising degree of confidence, stating that these

interpretation “are no longer viable solutions”. They discard the opening of the Iapetus Ocean “because they would require the rupture of an orogenic bridge”. Of course, orogenic bridges can be ruptured. There is a full section of the manuscript discussing “Ruptured orogenic bridges”.
Response: Partly agreed. Indeed, orogenic bridges can be ruptured. However, it is very unlikely that orogenic bridges that are still continuous at present were once ruptured (e.g., late Paleoproterozoic GIFR). Else, breakup would have been easier to achieve there, and oceanic crust would have already spread without the need for transform faulting to accommodate sliding of late Paleoproterozoic continental crust against Cenozoic oceanic crust. The authors of the present manuscript concede that this should be mentioned.
Changes: Split the first paragraph of the “Implications for plate tectonics and modeling” section into two and rewrote as follows: “We propose the existence of long-lived, continuous orogenic bridges, e.g., the late Neoproterozoic Timanian orogenic bridge in the Fram Strait, late Paleoproterozoic Nagssugtoqidian–Torngat orogenic bridge in the Davis Strait, and late Paleoproterozoic Nagssugtoqidian–Laxfordian Greenland–Iceland–Faroe orogenic bridge at the GIFR ( Foulger *et al.*, 2020a; Koehl & Mottram, 2024; Koehl *et al.*, 2024; Koehl *et al.*, 2025; Peace *et al.* 2018). The theory suggests that past plate tectonics was less dynamic than typically suggested by current plate models. Models involving the repeated opening of through-going Phanerozoic oceans between continental blocks and continents still connected by continuous (or recently ruptured) Precambrian orogenic bridges are no longer viable solutions to geological observations and geophysical datasets. For example, the Iapetus Ocean and  northeastern Atlantic Ocean both opened between Norway and Greenland as suggested by the occurrence of Cambrian ophiolites and Caledonian metamorphism and thrusting in mid-Norway (e.g., Furnes *et al.*, 1988; Slagstad *et al.*, 2020). However, despite the occurrence of blueschist-facies metamorphism of Caledonian age suggesting rapid subduction of mafic rocks to great depth in western Svalbard ( Horsfield, 1970; Kosminska *et al.*, 2014), it is unlikely that these two oceans fully opened between Svalbard and Greenland because this would require rupture of a possibly still continuous late Neoproterozoic orogenic bridge (e.g., Timanian orogenic bridge between Svalbard and northern Greenland; Figure 4). This is supported by the mapping of late Neoproterozoic Timanian thrust systems without any offset or truncation ( Koehl, 2020; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl & Mottram, 2024; Koehl, 2024 awaiting peer review) across the previously assumed Caledonian/Iapetus sutures in the Barents Sea and western Svalbard ( Breivik *et al.*, 2005; Horsfield, 1970; Kosminska *et al.*, 2014). It is also supported by the delayed opening of the Fram Strait at ca. 24 Ma ( Engen *et al.*, 2008) or possibly still yet to happen (present study and Koehl *et al.*, 2021), i.e., much later than the opening of the Mohns Ridge between Greenland and Norway and Arctic Ocean at ca. 56 Ma ( Faleide *et al.*, 1993; Faleide *et al.* 2008; Gaina *et al.*, 2002; Srivastana, 1985). If the late Neoproterozoic Timanian orogenic bridge had already been ruptured by the opening of Iapetus, breakup in the Fram Strait would not have taken more time (or at least not much longer) to achieve than between Norway and Greenland and in the Arctic Ocean. This also applies to the Iapetus Ocean and northeastern Atlantic Ocean at GIFR. Furthermore, if breakup had already occurred at the GIFR, transform faulting at the Tjörnes fault zone accommodating sliding of late Paleoproterozoic (or older) continental crust in the southwest against Cenozoic oceanic crust in the northeast would not have been required. Thus, although Iapetus did open and close in some places (Norway–Greenland), it clearly did not in others (GIFR and Fram Strait).

Similarly, models involving large lateral movements of various terranes hundreds to thousands of kilometers in different directions over a few tens of million years (e.g., Harland *et al.*, 1992; Majka *et al.*, 2021) can no longer be used to explain local heterogeneities in basement rocks in continuous or recently disrupted orogenic bridges (e.g., Timanian orogenic bridge; Koehl, 2020; Koehl *et al.*, 2022). The occurrence of a continuous/recently ruptured late Neoproterozoic orogenic bridge throughout the Barents Sea, Svalbard, and the Fram Strait suggests that such (presumably early Paleozoic) terrane movements are unlikely. Else the Timanian Orogen would have been disrupted and breakup in the Fram Strait would have been achieved quicklier, which is not the case ( Koehl, 2020; Koehl, 2024 awaiting peer review; Koehl *et al.*, 2021; Koehl *et al.*, 2022; Koehl & Mottram, 2024).".
Also added additional references to the reference list.
In addition, added a paragraph on potential implications for ophiolites and high-pressure metamorphism and their significance for plate tectonics: "This has implications for ophiolites and eclogite- and blueschist-facies metamorphism as it may indicate that some presumed ophiolites, e.g., km-wide blueschist units in western Svalbard ( Agard *et al.*, 2005; Horsfield, 1970; Kosminska *et al.*, 2014), may simply correspond to lava flows and/or igneous rocks intruded into continental crust, which were later imbricated during subsequent (Caledonian) orogenesis. This may suggest that some presently assumed ophiolites may not necessarily reflect the closure of paleo-oceans (sutures). If these presumed ophiolites have indeed been deposited onto or intruded into and imbricated together with continental crust, they would have been relatively difficult to quickly subduct to great depth ($\geq$ 50–70 km) due to the relative buoyancy of continental crust. Thus far, quick subduction to great 50– 70 km depth was generally considered necessary to explain the occurrence of blueschist metamorphism (e.g., Agard *et al.*, 2005; Agard *et al.*, 2009). Hence, alternative models to the formation of high-pressure metamorphic rocks would therefore need to be further explored ( Jamtveit *et al.*, 2018; Luisier *et al.*, 2019; Moulas *et al.*, 2013; Yamato & Brun, 2016) and the interpretation of rock units as ophiolites further reexamined.".

Comment 49: They state that some of the orogenic bridges presented in the paper are "long-lived, continuous orogenic bridges" and use this argument to discard the Iapetus Ocean. They did not present any serious evidence that these orogenic bridges were long-lived and continuous (e.g. the one under Iceland is formed by two different orogeneses of two completely different age). If they want to question the existence (or extent) of the Iapetus Ocean, the authors should write a full paper on it (and not a few lines), discussing the existing literature and clearly laying out why they reject the geological and geophysical evidences presented in the literature. They cannot base their argumentation entirely on a novel and unproven hypothesis to disqualify any previous geological or geophysical study conducted on the topic. This aspect of "unbreakable orogenic bridge" constitutes, again, a gross overinterpretation of the data presented.
Response: Partly agreed. The authors of the present manuscript do not argue that the Iapetus Ocean never opened anywhere on Earth. They believe that the evidence presented for the opening and closure of the Iapetus Ocean between mid-Norway and southeastern Greenland are robust and conclusive. However, the authors of the present manuscript argue that the occurrence of a continuous late Paleoproterozoic orogenic bridge at the GIFR and a possibly continuous late Neoproterozoic orogenic bridge with thrust systems extending beyond the presumed Caledonian suture without being offset or truncated in the

Fram Strait represent proof that the Iapetus ocean did not open between Greenland and Svalbard and at the GIFR. The authors of the present manuscript did specify “between Laurentia and Svalbard” on page 4 and “between Greenland and Svalbard” page 19 when discussing the Iapetus Ocean. The authors of the present manuscript concede that their agreeing to the opening of the Iapetus Ocean in areas others than the GIFR and the Fram Strait ought to be mentioned in the manuscript to ensure that their arguments are not taken out of context or misunderstood. The authors of the present manuscript thank the reviewer for this valuable comment.
Changes: Added “This does not mean that Iapetus Ocean did not open anywhere, e.g., between Norway and Greenland where more robust evidence was found for opening and subduction (e.g., Furnes *et al.*, 1988; Slagstad *et al.*, 2020).” at the end of the first paragraph of the “Implications for plate tectonics and modeling” section and the new references to the reference list. Also added “This is supported by the mapping off late Neoproterozoic Timanian thrust systems across the previously assumed Caledonian/Iapetus sutures in the Barents Sea and western Svalbard without any offset or truncation ( Koehl, 2020; Koehl *et al.* , 2022; Koehl *et al.*, 2023a; Koehl & Mottram, 2024; Koehl, 2024 awaiting peer review).” earlier in the same paragraph.

Comment 50: The authors then go one more step further and elevate their hypothesis at the level (or above) the theory of plate tectonics in the form of a “major update”. Plate tectonics is the most important theory of geology and explains the movements and deformation of continents with concepts like Mid-Ocean Ridges, subductions, orogens, mantle movement, etc. The hypothesis presented here is nowhere near a “major update” for plate tectonics as it does not have implications for subduction zones, collision zones, mantle movements or most of the mid-ocean ridges. Even if we would assume that the orogenic bridge theory is correct, it would only constitute an update on how inherited structures influence the structure of plate boundaries in extensional domain (a topic that is relevant, but that does not call for an update on the plate tectonics theory: e.g. Brune et al., 2017; Zwaan et al., 2021; Corti et al., 2022; Brune et al., 2023; Pérez-Gussinyé et al., 2023). Again, a bit more humility would help.
Response: The authors of the present manuscript suggest that the amount of evidence not conforming to the current understanding of plate tectonics by the geoscience community is stacking up. The authors of the present manuscript concede that this could be better expressed in the manuscript. The fact that the authors of the manuscript have labelled Orogenic Bridge Theory as a “major update” to plate tectonics does not set this new theory above plate tectonics because it does not separate it from plate tectonics, an update being an improvement or modernization of a previous whole. Orogenic Bridge Theory still abides plate tectonics but adds new processes and features to explain the (thus far) unexplainable datasets and observations. The authors of the present manuscript do not deny that plate tectonics is an important geological theory. They simply argue that in its present state, it does not explain everything. Initially, the main author of the present manuscript was, as the reviewer, inclined to believe that Orogenic Bridge Theory was a simple minor update to plate tectonics. After considering it for some time, one cannot but realize that its implications are far from simple and bear implications for the interpretation of blueschist facies metamorphism (e.g., in Svalbard, where the Iapetus Ocean cannot have opened and where blueschist metamorphism therefore cannot imply deep subduction because located within continental crust). Come then the realization that alternative mechanisms to produce

such high-pressure/low-temperature mineral assemblages must be considered (e.g., overpressure or others; Moulas et al., 2013). This then has implications, e.g., for every fault zone and shear zone on Earth and other planets and for subduction and collision settings, as well as for earthquake generation. In addition, considering that Orogenic Bridge Theory reconciles the continental nature of the GIFR with continental drift and plate tectonics, it is then logical that it has implications for the definition of mid-ocean ridges, e.g., onshore Iceland, which according to this new theory is not yet a fully developed mid-ocean ridge. Since the new theory has implications for most aspects of the surface components of plate tectonics (mid-ocean ridges, subduction, and collision), it is only logical that it should, in its time, also impact on our understanding of mantle movements, albeit not necessarily with any major consequences since Orogenic Bridge Theory may very well work hands in hands with the concept of mantle plumes. Orogenic Bridge Theory is a rapidly developing concept, and new implications are discovered every few weeks or months but are currently pursued only by the authors of the present manuscript and a few others. It is therefore time to give it more perspective by sharing it with the whole wide world and, thus, enhance its development. Regardless of whether the reviewer or the authors of the present manuscript agree to call Orogenic Bridge Theory a “major update to plate tectonics” or not, it certainly is a potential breakthrough.
Regarding the references suggested by the reviewer (Brune et al., 2017; Zwaan et al., 2021; Corti et al., 2022; Brune et al., 2023; Pérez-Gussinyé et al., 2023), none deals with the relationship between transform faults and preexisting structures. Thus, even if the authors of the present manuscript concede that the influence of inheritance on rifting is well investigated, this only applies to the rift-parallel endmember of Orogenic Bridge Theory, which is already acknowledged in the present manuscript to be well studied (see abstract and third paragraph in the “Orogenic bridge theory” section). In contrast, the rift-orthogonal endmember of Orogenic Bridge Theory, i.e., the impact of preexisting orogens on the formation of transform faults was very little studied and even less understood or theorized, a fact that is stressed in Molnar et al. (2020). Thus, Orogenic Bridge Theory will certainly represent a major update to plate tectonics once further tested. The authors of the present manuscript concede that the references suggested by the reviewer could be added where briefly mentioning the rift-parallel endmember of Orogenic Bridge Theory.
See response to comment 45 regarding “humility”.
Changes: Deleted “major” in “major update” in the abstract. In addition, added “considering the increasing number of datasets not conforming to our current understanding of plate tectonics” in the abstract. Also added “(“rift-parallel endmember”)”, “Corti et al., 2022” and “Brune et al., 2023” in the third paragraph of the “Orogenic bridge theory” section and “(“rift-orthogonal endmember”)” and “This endmember has thus far been little studied (Molnar *et al.*, 2020).” to the fifth paragraph. In addition, added a new paragraph at the end of the “Previous work” section: “Other studies investigated the impact of oblique preexisting discontinuities on rift segmentation and obliquity (e.g., Brune *et al.*, 2017; Molnar *et al.*, 2017; Zwaan *et al.*, 2021). However, they did not address the formation of transform faults and the specific influence of preexisting orogens, which the present study attempts to theorize for the first time.”. Also added the suggested references and Molnar et al. (2020) to the reference list.

Comment 51: Remark They are several more points that would need corrections, but as I deem this manuscript unsuitable for indexing, I did not list them all, nor did I did not check

every details of the manuscript, every study site, all references,... If the authors want to index some of the ideas presented in this manuscript (I would encourage them to look at the correlation between transform faults and orientations of orogenic belts with a quantitative approach), I would suggest to do a completely new manuscript focused on the testing of one hypothesis.
Response: See response to comment 33.
Changes: See response to comment 33.

***Competing Interests:*** No competing interests were disclosed.