

Author's response

This file contains our point-by-point responses to the reviews, and a marked-up manuscript version where all our changes are tracked in red.

Author's response to comments by Reviewer #1

5

Rev #1: In this paper the Authors investigate the obliquity of major continental rift systems from the onset of Pangea breakup to present by using global plate reconstructions. In particular they quantify rift obliquity by analysing the local extension direction and the assumed rift trend by using the software pyGPlates. The Authors find that the majority of rift systems are oblique by more than 20°, therefore suggesting that rift obliquity is the rule, not the exception. This has important implications for the interpretation of most rift systems on Earth, for which a complex 3D evolution must be considered. Overall, I enjoyed reading the manuscript, which is well written, illustrated and clear; it offers very interesting insights into the process of continental rifting. I therefore support its publication. I only have some minor suggestions, which could improve this interesting work, and which are listed below.

15

Authors: We thank Reviewer #1 for this motivating assessment. All suggestions have been addressed in the manuscript and our responses are listed below.

20

Rev #1: Pag,2, Line 9. I suggest not to use the term 'transversely' here. It can be somehow misleading - 'transversal' is normally used to indicate structures trending almost orthogonal to the rift trend. I suggest to replace it with 'obliquely' or similar

Authors: Done.

25

Rev #1: Pag,2, Line 12. Maybe a reference to the work by Corti 2008 could be appropriate here

Authors: Done.

30

Rev #1: Caption Figure 1. Instead of using the notation sigma H and h, I suggest to clearly indicate sigma Hmin and max

35

Authors: Done.

Rev #1: Pag,2, Line 7. Some references here?

40

Authors: References added (Chaboureaud et al., 2013; Quirk et al., 2013).

45

Rev #1: Pag 3. In section 2 (or maybe in the Discussion) the Authors could discuss in some more detail the similarities or differences with the methods used to calculate obliquity in previous works. I refer in particular to the work by Jeanniot and Buiter (2018), where a similar analysis is presented.

Authors: We extended the comparison to Jeanniot and Buiter (2018) in the discussion section and highlighted similarities or differences of our approaches. See paragraph “Jeanniot and Buiter (2018) evaluated the margin width...” in section 5.

50

Rev #1: Pag. 7, Line 4. Reference to the work by Withjack and Jamison 1986 needed (before Tron and Brun, 1991)

55 Authors: Reference added.

Rev #1: Pag. 8, Lines 8 and following. The relations between rift velocity and obliquity are not very clear to me, and could be maybe discussed in some more detail. In particular, I maybe misunderstood something but the first explanation for this behaviour seems not to be consistent with observations (i.e., the higher the obliquity, the lower the velocity), so it is really not clear to me. Also note that the relation between obliquity and velocity is also repeated in section 3.5 (Gulf of California), at the beginning of Pag 15. In order to avoid these repetitions, and not to mix observations with explanation of results, I suggest to think about moving the interpretation of the correlation between velocity and obliquity to the Discussion section.

65

Authors: We formulated the relation between obliquity and velocity more clearly and moved it to the discussion section. See paragraph “In many cases, we find a correlation between the obliquity and the velocity of a rift...” in section 5.

70

Rev #1: Pag. 9, Line 6. . . .Faroe-Shetland basins..

Authors: Done.

75

Figure 4. In panel b, I guess the abscissa represents the Time before present, but it is not very clear in its present form (it seems indeed that the X-axis indicates the Frequency of rift velocity). Please check and fix this

80

Authors: We agree and changed the axis labels of Figure 4. The same problem has been fixed in Figure 6.

85 Rev #1: Pag. 10, Line 4. Early ??? (something missing here)

Authors: Fixed.

90

Author's response to comments by Reviewer #2

95 Rev #2: This paper presents a very interesting global quantitative study of rift obliquity and concludes
that much more rift segments are oblique than previously admitted. This study is well documented and
well described, with focus given on few well-known oblique rift examples. The introduction and
discussion are more focused on the geodynamic implications and the mechanical reason that could
100 explain their observations. I have only a few minor comments, the first one concerns the choice of the
author to consider the COB as the rift trend to define obliquity which should be discuss a little bit more
in view of existing analogue and numerical model and the second concerns the mechanical discussion
at the end of the paper, which is too light and could be improved a lot.

105 Authors: We thank Reviewer #2 for these suggestions. In the revised version we discuss the continent-
ocean boundary as a rift trend proxy and extend the paragraph concerning the underlying mechanical
reasons of oblique rifting.

110 Rev #2: First point : At line 5 page 5 or line 13 page 26 The authors state that the COB is an indicator
of rift trend and use it to define obliquity by comparing with the direction of plate. It is a choice, which is
not better nor worse than another choice but it is arguable, and I would like to see a bit more
argumentation in the text than it is a better choice than the coast line. The COB is an indicative of the
trend of the rift in the lithospheric mantle that is in the very late stage of rifting after the mantle necking.
115 3D models show that the COB might have a different obliquity then the initial trend and that with time
obliquity of rift structure might increase as the lithosphere become weaker and weaker or decrease.

Authors: We added a discussion concerning the advantages and disadvantages of three potential rift
trend proxies: COB, coastline and topographic highs. See paragraph "We define the rift trend as the
120 general direction of a rift segment ..." in section 2.2.

Rev #2: Second point: Based on a previous paper by the first author, this contribution explains the
predominance of obliquity is that oblique rift requires less forces than orthogonal rifting. I think this
analysis is biased and not complete because
125 1/ oblique rifts only emerges when transtension is imposed either by the BC's or the initial weak zones
(thermal or mechanical) imposed on models. If their statement was indeed true, models of propagating
rift segment would all produce oblique rift and none of them do (Van Vijk and blackmann 2005, Allken
et al. 2012, Mondy et al 2017, Le Pourhiet et al. 2018) actually do unless a oblique weak zone is
imposed (Molnar et al. 2017 2018, Balazs et al. 2018) or propagation stagnates (Van Vijk and
130 blackmann 2005, Allken et al. 2012, Le Pourhiet et al. 2018)
2/ the authors completely dismiss mechanical or thermo-mechanical models that simulates oblique
rifting using the standard set up of Le Calvez, and Vendeville, (2002), that is: two offset weak zones
embedded in a rectangular box with imposed cylindrical boundary conditions (now, renamed as
transtensional by Zwaan et al. 2016). In these set up, the linkage zone forming between the weak zone
135 in Allken et al 2012, Liao and Gerya 2016, Le Pourhiet et al. 2017, Amman et al. 2017, or Balazs et al.
2018, are also an oblique rift segment in your definition (COB vs boundary condition). Yet, if ones
consider, the surface area and the number of faults as a proxi, the work required to rift this oblique

segment is much larger than to rift the orthogonal segment. The main difference between these set-ups is that in one case (Brune et al 2012) there is a pre-existing linear weak zone in the mantle lithosphere (i.e. the necking zone is pre-imposed) while in the other, it forms self consistently when crust and mantle deformation couple (i.e. in the late stage of rifting).

I think, that given the expertise of the first author, a more thorough discussion of the role of heritage, rift propagation or lack of it, and linkage as possible explanation of the omnipresence of oblique margin could really improve the paper a lot without lengthening it by much.

Authors: We agree with the reviewer that the initial and boundary conditions exert strong control on model evolution in these kinds of experiments. In the revised version we added a discussion on this point where we compare the different setups and potential causes of oblique rifting. But since the focus of our manuscript lies on the analysis of plate tectonic reconstructions and not on numerical modeling, we do not discuss the results and implications of these models in more detail than necessary. See paragraph "The dynamics of oblique rifting have been previously investigated ..." in section 5.

155

Oblique rifting: the rule, not the exception.

Sascha Brune^{1,2}, Simon E. Williams³, & R. Dietmar Müller^{3,4}

¹GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany

160 ²Institute of Earth and Environmental Science, University of Potsdam, 14476 Potsdam-Golm, Germany

³EarthByte Group, School of Geosciences, University of Sydney, NSW 2006, Australia

⁴Sydney Informatics Hub, University of Sydney, Sydney, NSW, Australia.

Correspondence to: Sascha Brune (brune@gfz-potsdam.de)

Abstract. Movements of tectonic plates often induce oblique deformation at divergent plate boundaries. This is in striking
165 contrast with traditional conceptual models of rifting and rifted margin formation, which often assume 2D deformation
where the rift velocity is oriented perpendicular to the plate boundary. Here we quantify the validity of this assumption by
analysing the kinematics of major continent-scale rift systems in a global plate tectonic reconstruction from the onset of
Pangea breakup until present-day. We evaluate rift obliquity by joint examination of relative extension velocity and local rift
trend using the script-based plate reconstruction software pyGPlates. Our results show that the global mean rift obliquity
170 since 230 Ma amounts to 34° with a standard deviation of 24°, using the convention that the angle of obliquity is spanned by
extension direction and rift trend normal. We find that more than ~70% of all rift segments exceeded an obliquity of 20°
demonstrating that oblique rifting should be considered the rule, not the exception. In many cases, rift obliquity and
extension velocity increase during rift evolution (e.g. Australia-Antarctica, Gulf of California, South Atlantic, India-
Antarctica), which suggests an underlying geodynamic correlation via obliquity-dependent rift strength. Oblique rifting
175 produces 3D stress and strain fields that cannot be accounted for in simplified 2D plane strain analysis. We therefore
highlight the importance of 3D approaches in modelling, surveying, and interpretation of most rift segments on Earth where
oblique rifting is the dominant mode of deformation.

1 Introduction

The relative motion of Earth's tectonic plates often causes oblique deformation at divergent plate boundaries. This is
180 primarily due to the fact that irregularly shaped plate boundaries generally do not align with small-circles of relative plate
movement and that changes in plate motion additionally lead to time-dependent plate boundary obliquity (Díaz-Azpiroz et
al., 2016; Philippon and Corti, 2016). Traditionally, rift evolution and passive margin formation have been investigated using
2D conceptual and numerical models assuming an alignment of relative plate motion and plate boundary normal. These
studies yielded major insights into first-order subsidence patterns (McKenzie, 1978; White, 1993), described key phases
185 controlling the architecture of rifted margins (Lavie and Manatschal, 2006; Huisman and Beaumont, 2011; Brune et al.,
2016) and provided insight into the fault evolution during rifting (Ranero and Pérez-Gussinyé, 2010; Brune et al., 2014;

Bayrakci et al., 2016; Naliboff et al., 2017). The applicability of these concepts and models is often rooted in the assumption that rifts can be understood via plane strain cross-sections orthogonal to the rift trend and that the direction of extension aligns with the orientation of these cross-sections. Many rifts and passive margins however involve segments where the extension direction is not perpendicular to the rift strike such that oblique, non-plane strain configurations occur (Sanderson and Marchini, 1984; Dewey et al., 1998).

Oblique rift segments differ from classical orthogonal examples in several major aspects:

- 1) In contrast to orthogonal rifts, the initial phase of oblique rifting is characterized by segmented en-échelon border faults that strike **at an angle** to the rift trend. The orientation of these faults is controlled by the interplay of inherited heterogeneities with far-field stresses, whereas diverse modelling studies independently suggest a fault orientation that lies in the middle between the rift trend and the extension-orthogonal direction (Withjack and Jamison, 1986; Clifton et al., 2000; Corti, 2008; Agostini et al., 2009; Brune and Autin, 2013). These large en-échelon faults generate pronounced relay structures (Fossen and Rotevatn, 2016) which act as a major control on fluvial sediment transport (Gawthorpe and Leeder, 2000).
- 2) Seismic cross sections at rifted margins are often taken perpendicular to the rift trend, which in most cases is also perpendicular to the coastline. Considering that faults in oblique rifts do not strike parallel to the rift trend, seismic profiles will observe a projection of the fault surface that features a smaller dip angle than the actual 3D fault, an error that might cascade further into seismic restorations.
- 3) Besides these structural-observational implications, oblique rifting appears to be a major factor in governing the geodynamic evolution of extensional systems. This has been shown via several lines of evidence: (i) Oblique rifting has been inferred to enhance strain localisation by enabling the formation of pull-apart basins and large-offset strike-slip faults, for instance during the Gulf of California opening (van Wijk et al., 2017; Umhoefer et al., 2018). (ii) Analytical and numerical modelling suggests that the force required to maintain a given rift velocity is anti-correlated with the rift's obliquity. The reason for this behaviour is that plastic yielding takes place at smaller tectonic force when the extension is oblique to the rift trend (Brune et al., 2012). (iii) At the same extension velocity, oblique rifts deform with a certain rift parallel shear rate, which is balanced by a lower rift-perpendicular extension velocity. This means that oblique segments of a particular rift accommodate lithospheric and crustal thinning at a lower rate than orthogonal segments of the same rift, a difference that effects the thermal configuration and therefore the structural and magmatic evolution of each segment (Montési and Behn, 2007).
- 4) Oblique rifting holds geodynamic implications on the global scale because of its relation to toroidal plate motion, i.e. vertical axis rotation components of plate movements and associated strike-slip deformation. Toroidal motion is enigmatic from the perspective of plate driving forces, because its purely horizontal motion cannot be directly caused by buoyancy forces in Earth's interior (Lithgow-Bertelloni et al., 1993; Bercovici, 2003). Oblique rifts

220 feature strike-slip velocity components and therefore contribute to toroidal motion, while orthogonal rifts are an expression of purely buoyancy-driven (poloidal) flow.

The impact of rift obliquity on the structural architecture of continental extensional systems varies between natural cases. This is mainly due to rift variability in general, which arises from tectonic inheritance (Manatschal et al., 2015; Morley, 225 2016; Hodge et al., 2018; Phillips et al., 2018), or from along-strike changes in rheology, crustal configuration, temperature and rift velocity (e.g. Sippel et al., 2017; Molnar et al., 2017; Brune et al., 2017b; Mondy et al., 2017).

Oblique rifting in presently active rifts can be easily deduced by combining the local rift trend and GNSS-based surface velocities (Diaz-Azpiroz et al., 2016). Prominent examples are the Main Ethiopian rift (Corti, 2008), the Levant rift system 230 including the Dead Sea rift (Mart et al., 2005), the Gulf of California rift (Atwater and Stock, 1998; Fletcher et al., 2007) and the Upper Rhine Graben (Bertrand et al., 2005). Structure and kinematics of past rift systems has been studied by surveying obliquely rifted margins (Fournier et al., 2004; Lizarralde et al., 2007; Klimke and Franke, 2016; Phethean et al., 2016) and transform continental margins (Basile, 2015; Meric de Lépinay et al., 2016). However, quantifying rift obliquity of a 235 available geophysical and geological data sets. Therefore, a global statistical analysis of rift obliquity through geological time has been missing so far.

Here we strive to fill this gap by deducing the first-order obliquity history of Earth's major rifts from the onset of Pangea fragmentation to present-day. We first describe the applied methods and data sets, then we focus on major individual rift 240 systems that lead to the formation of the Atlantic and Indian Ocean basins before we assess rift obliquity evolution and average obliquity on a global scale.

2 Methods and data

2.1. Rift kinematics

We quantify extension velocity using the global kinematic plate reconstruction of Müller et al. (2016). This plate model 245 integrates the latest syn-rift reconstructions for the South Atlantic (Heine et al., 2013), North Atlantic (Hosseinpour et al., 2013; Barnett-Moore et al., 2016), Australia-Antarctica separation and India-Antarctica breakup (Williams et al., 2011; Whittaker et al., 2013; Gibbons et al., 2015), as well as Gulf of California opening (McQuarrie and Wernicke, 2005) among others (Figure 1).

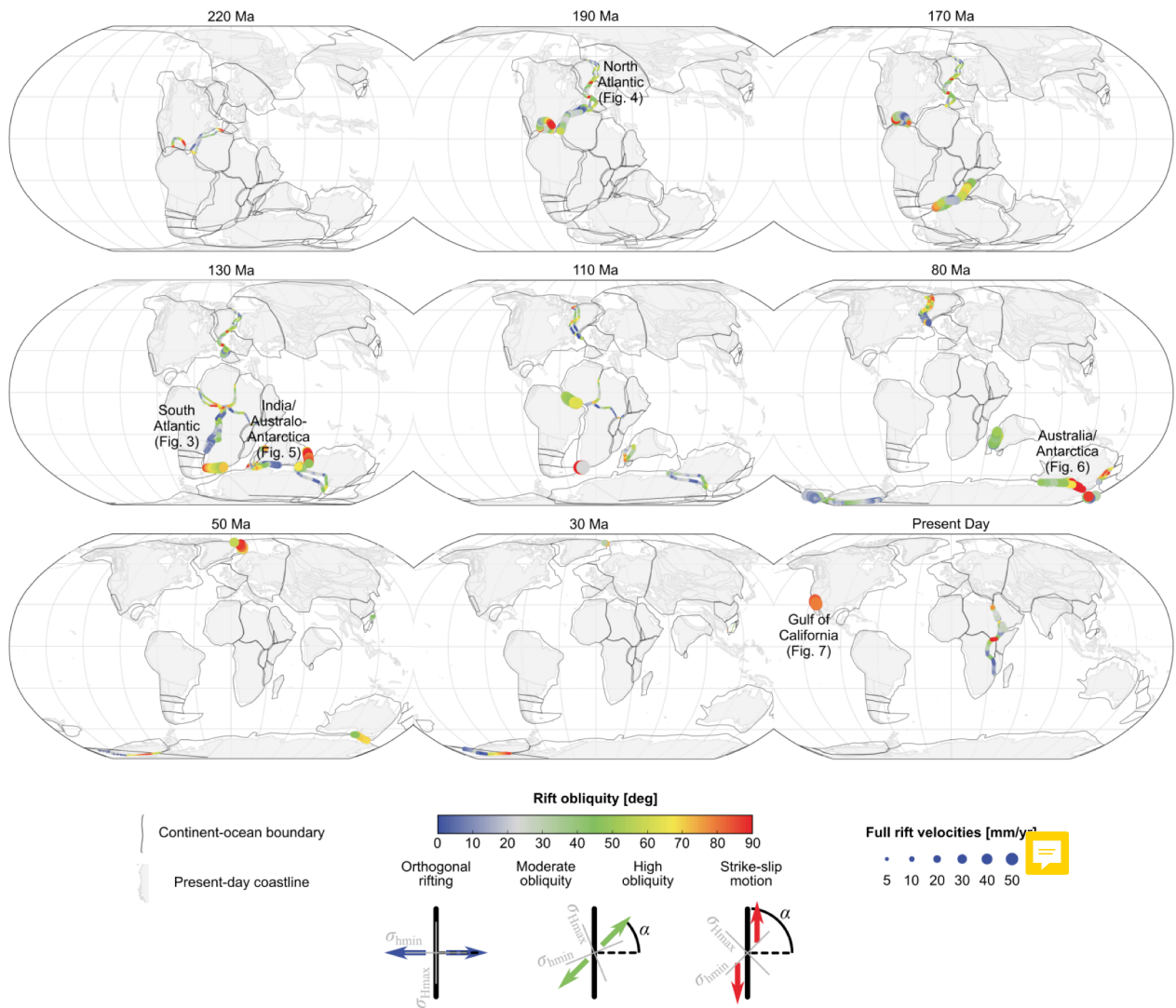


Figure 1. Global overview of rift obliquity and velocity. Rift obliquity is measured as angle α spanned by the relative velocity vector and the rift trend normal. The impact of rift obliquity on the rotation of largest and smallest horizontal stress components (σ_{Hmax} and σ_{hmin} , respectively) is depicted at the bottom of the figure. Rotations from Müller et al. (2016). Continent-ocean boundaries from Brune et al. (2016).

250 Restoration of the relative position of continents prior to rifting in aforementioned regional studies is largely based on deriving the amount of syn-rift extension from present-day crustal thickness (e.g. Williams et al., 2011; Kneller et al., 2012). The kinematic evolution before breakup, i.e. prior to the occurrence of oceanic fracture zones and oceanic magnetic anomalies, has to be inferred via careful joint interpretation of several geological indicators. Rift initiation for instance can be constrained through the ages of syn-rift sediments and rift-related volcanism, which give a minimum age for the

255 beginning of rifting (e.g. Chaboureaud et al., 2013; Quirk et al., 2013). Later syn-rift kinematics can be inferred from seismic tectono-stratigraphy and dating of rocks that have been drilled or dredged within the continent–ocean transition, while additional information can be derived from kinematic indicators at neighbouring plate boundaries (e.g. Heine et al., 2013; Whittaker et al., 2013).

2.2. Rift trend

260 We define the rift trend as the general direction of a rift segment. Considering a typical rift width of ~100 km, the most suitable wavelength to analyse rift trend variations is several hundred kilometres. There are several possible proxies for the rift trend of past continental rift systems: (1) the boundary between continental and oceanic crust, often referred to as continent-ocean boundary (COB), (2) the general trend of the present-day coast line or other bathymetric contours, (3) rift-related topographic highs (Osmundsen and Redfield, 2011). Note that these proxies do not necessarily yield the same rift orientation and that all of them feature certain disadvantages. Mapping the COB for instance requires seismic refraction data and interpolation in-between individual profiles, and considering COBs as sharp boundaries does not reflect the crustal complexity in these areas, which mirrors the convoluted interplay of tectonic, magmatic, and sedimentary processes.

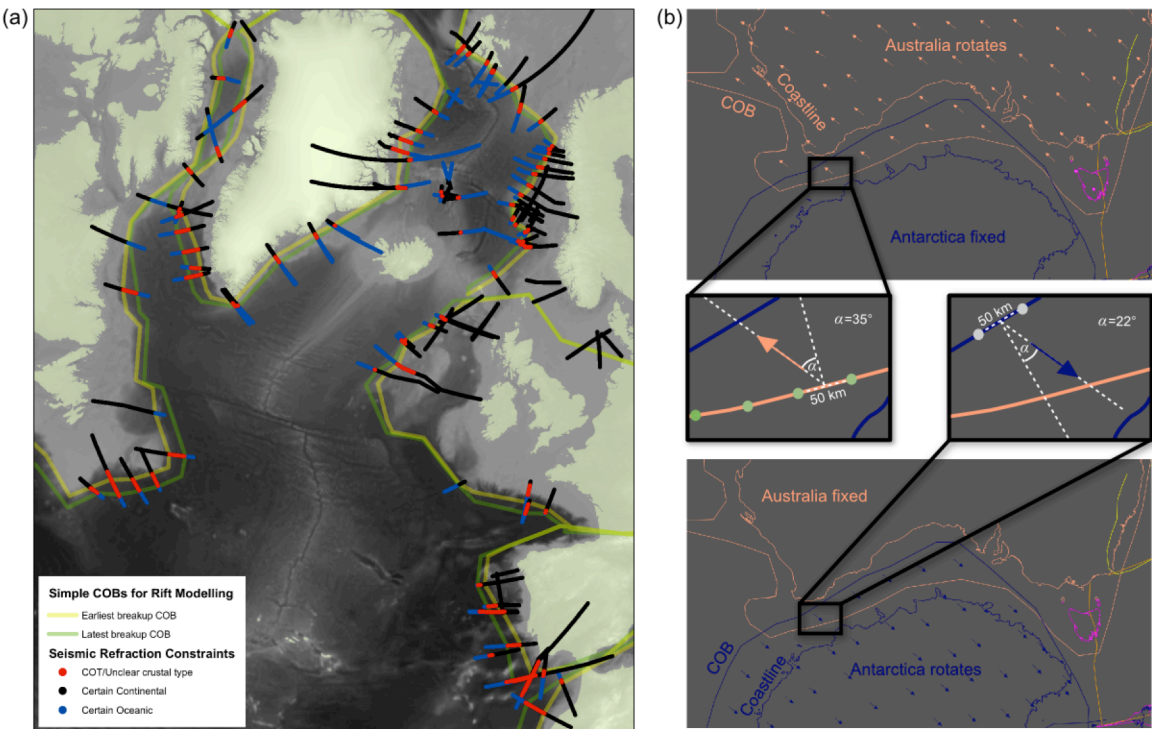


Figure 2. Methods illustration. (a) End-member sets of continent-ocean boundaries are based on seismic refraction data, here exemplified for the North Atlantic. The latest breakup COB constitutes our reference model while the earliest breakup COB is used for robustness tests. (b) Kinematic analysis approach exemplified for Australia-Antarctica rifting.

Coastlines and marginal bathymetry are affected by eustatic sea-level variations, surface processes, as well as tectonic and dynamic topography, while rift-related topographic highs do not exist everywhere and if they do, they are submitted to erosion and post-rift local vertical motions (Jeannot and Buitier, 2018). Therefore, we employ a workflow where we associate rift trend variations with the COB orientation (Figure 2a). We use COBs with deliberately simplified geometries designed to capture the regional geometry of boundaries between continental and oceanic crust, without a detailed assimilation of local data reflecting fine-scale deviations from these regional trends (see description in Brune et al., 2016). This makes our analysis particularly representative for intermediate and final rift stages since the COB trend is indicative of the rift orientation during and after necking of the mantle lithosphere (Le Pourhiet et al., 2017; Ammann et al., 2017), and allows is to more accurately capture the time-dependence of kinematics within rifts that experienced protracted, diachronous breakup. Due to the previously mentioned limitation in defining COBs as single, distinct boundaries, we define two COB end-member sets that reflect the earliest and latest possible breakup based on available seismic refraction data (Brune et al., 2016). Figure 2a depicts both the early and the late breakup COB data sets exemplified for the North Atlantic illustrating that the overall direction of the rift trend is not affected by the precise location of the COB.

The employed reconstruction is using rigid plate polygons and does not directly capture plate boundary deformation. Thus, in a pre-rift reconstruction, present-day COBs from conjugate passive margins will show significant overlap (Figure 1), where the amount of overlap is a proxy for the subsequent extension before breakup. As the plates move apart the overlap decreases, and the moment within the reconstructions where there is no longer overlap in each segment defines the transition from rifting to seafloor spreading. Within this methodology, the two central implications of how we interpret COB geometries for our purposes is that they control the time of breakup along the margins, and that they define the orientation of each rift segment.

2.3 Rift obliquity

Using the COB orientation as a proxy for the rift trend, and accounting for the local direction of relative plate motions, we calculate rift obliquity for all points within an active rift at any time during post-Pangea extension. This workflow is illustrated in Figure 2b, where we first keep Antarctica fixed in order to evaluate the rift obliquity at an Australian COB location and secondly we fix Australia and estimate rift obliquity for a point at the Antarctic COB. Note that the conjugate values for local rift obliquity are very similar but not the same. We therefore average obliquity values from conjugate margins during our statistical analysis. This analysis is repeated in 1 million year intervals until the conjugate COBs do not overlap anymore and the tectonic formation of the rifted margin ends.

We apply our workflow in an automated way using the python library pyGPlates that provides script-based access to GPlates functionality. GPlates is a free plate reconstruction software (www.gplates.org) that allows reconstructing and analysing

300 plate motions through geological time (Müller et al., 2018). In the following, we use a spacing of 50 km between individual sample points where we extract relative plate velocity and obliquity. That spacing is dense enough to capture the relevant changes in rift trend. We also tested smaller point distances, which did not affect our conclusions.

305 The limitations of this analysis workflow coincide with the limits of plate tectonic reconstructions in general. Many rifts and especially failed rifts are not included in plate tectonic reconstructions yet, which somewhat biases our study towards rifted margins. Future improvements in plate tectonic reconstructions and in defining COBs will enhance our results, however, by testing several end-member scenarios in section 4 we can already anticipate that our main conclusions will still hold even though the detailed values might change.

310 In this study we follow the convention that defines the angle of obliquity as the angle between extension direction and local rift trend normal. This means that 0° represents orthogonal rifting while 90° stands for strike-slip motion. Note that this definition follows many previous studies (e.g. Fournier and Petit, 2007; Philippon et al., 2015; Brune, 2016; Zwaan and Schreurs, 2017; Ammann et al., 2017), but is opposite to the convention used in almost as many articles (e.g. Withjack and Jamison, 1986; Tron and Brun, 1991; Teyssier et al., 1995; Clifton and Schlische, 2001; Deng et al., 2018).

315 There is clearly a gradual transition from orthogonal rifting to oblique extension, especially since individual fault evolution is subject to natural variability. In this study, however, where we investigate the frequency of oblique rifting, it appears to be useful to draw a line between orthogonal and oblique rifting. In simplified model settings, previous studies suggested that qualitative differences in the rifting style emerge when rift obliquity exceeds 15 to 20° (Clifton et al., 2000; Agostini et al., 320 2009; Brune, 2014; Zwaan et al., 2016). Keeping in mind that the specific value is somewhat arbitrary, we will use 20° as the critical obliquity separating orthogonal from oblique rifts.

3 Regional analysis of individual rift systems

In this section, our plate tectonic analysis is employed focussing on individual post-Pangea rift systems (Figure 1). In doing so, we relate the structural history of each rift with its obliquity and velocity evolution.

325 **3.1. South Atlantic Rift**

The orientation of the different South Atlantic Rift segments has been affected by reactivation of mobile belts, which formed during the pan-African orogeny in the Neoproterozoic and early Paleozoic (Kröner and Stern, 2004). This reactivation of inherited weaknesses is an ubiquitous process of the Wilson cycle that has also been evoked to explain the formation of the present-day East African Rift System (Daly et al., 1989; Hetzel and Strecker, 1994). It has been suggested that 65% of the

330 South Atlantic Rift developed with near-parallel orientation to the pan-African fabric (de Wit et al., 2008) evidencing the strong control of tectonic inheritance on the South Atlantic rift obliquity.

We find that low obliquity predominates in the central and southern segment of the South Atlantic rift (Figure 3). High rift obliquities are encountered in the Equatorial Atlantic and in the southernmost shear zone that ultimately develops into the Falkland-Agulhas fracture zone. Our analysis shows that the South Atlantic initially features a wide range of rift obliquities (Figure 3b) and trends to higher obliquity after 120 million years ago (Ma) when only the northern and southernmost segments are active. The frequency diagram of rift obliquity displays a bimodal distribution with the 0-25° range representing the southern South Atlantic while the 45-65° range is dominated by Equatorial South Atlantic rift geometry (Figure 3c). The overall mean obliquity at 38° lies in-between these two peaks while 68% of the rift formed at moderate to high rift obliquity larger than 20°.

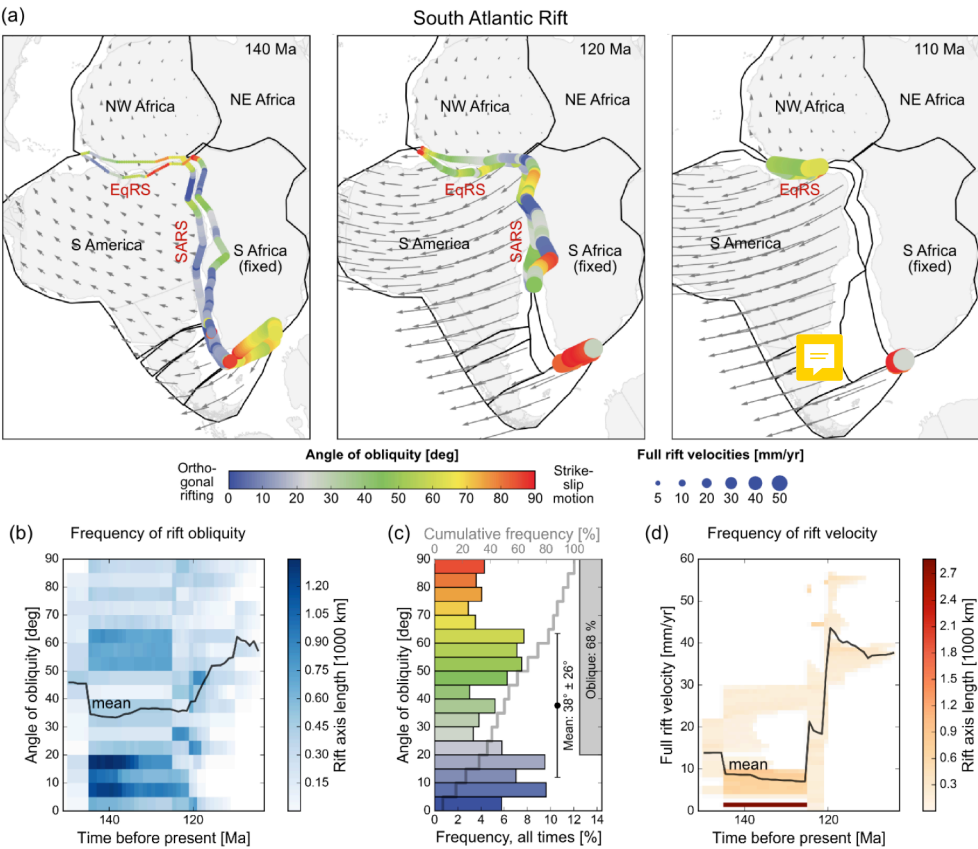


Figure 3. South Atlantic rift. Low rift obliquity prevails in the central and southern segment of the South Atlantic rift whereas high obliquities and strike-slip motion dominates the northern and southernmost segments. Rift velocity and obliquity increase jointly starting at 120 Ma. EqRS – Equatorial Atlantic Rift System; SARS – South Atlantic Rift System.

The rotational rifting of the South Atlantic with an initial Euler pole close to West Africa leads to higher rift velocities in the south than in the north. The mean rift velocity of the entire rift system displays an initial, slow phase lasting more than 20 million years, followed by rift acceleration during a few million years and finally a fast phase of rifting prior to the transition to sea-floor spreading (Heine et al., 2013; Brune et al., 2016). This two-phase evolution can also be seen in alternative reconstructions (Nürnberg and Müller, 1991; Torsvik et al., 2009; Moulin et al., 2010; Granot and Dymment, 2015) although it is partitioned between individual South American blocks for some studies (Brune et al., 2016). Interestingly, the evolution of rift obliquity and velocity appears to be correlated, which we will discuss in section 5.

350

3.2. North Atlantic Rift

The formation of the North Atlantic involved a protracted rift history involving several major plates (Eurasia, Greenland, Iberia, North America). Initial inherited weaknesses from the Caledonian orogeny have been reactivated in episodic continental extension that is recorded in Carboniferous to Permian basins (Doré, 1991; Lundin and Doré, 1997). The Mesozoic is marked by extensive crustal thinning that lead to formation and abandonment of major rift arms like the Rockall Trough, the Porcupine, Orphan, Møre, and Faroe-Shetland basins (Skogseid et al., 2000; Faleide et al., 2008; Peron-Pinvidic et al., 2013). However, Mesozoic rifting also induced continental breakup in the Iberia-Newfoundland segment, the Bay of Biscay, and the North Atlantic rift south of Greenland (Féraud et al., 1996; Tugend et al., 2014; Nirrengarten et al., 2018). Opening of the Labrador Sea and rifting between Greenland and Europe competed for many tens of million years (Dickie et al., 2011; Hosseinpour et al., 2013; Barnett-Moore et al., 2016) before the present-day North East Atlantic mid-ocean ridge formed in Eocene times (Gernigon et al., 2015; Gaina et al., 2017) possibly due to the arrival of the Iceland hotspot (Coffin and Eldholm, 1992; Storey et al., 2007). Final separation between Greenland and Europe took place along the sheared margin of the Fram Strait in Miocene times ~17-15 Ma (Jakobsson et al., 2007; Knies and Gaina, 2008).

Multiple plate motion changes reflect the complex tectonic history of the North Atlantic during the last 200 million years. These changes translate to time-dependent rift obliquity in each of the major rift branches (Figure 4). Between 200 and 120 Ma, the rift branches east and south of Greenland deform at 35° to 60° rift obliquity which leads to a pronounced peak within this obliquity range in Figure 4b and 4c. This changes in the Early Cretaceous with the more northward movement of Greenland and generates almost orthogonal rifting between Greenland and Europe until breakup. Due to the northward propagation of sea-floor spreading, the Iberia-Newfoundland rift is excluded from the later plate motion changes and hence formed during low extension obliquity. The latest stage of continental rifting is marked by more than 30 million years of high-obliquity shear between northern Greenland and northwest Europe.

370

The absolute frequency of rift obliquity is marked by two peaks at 0° and 45° (Figure 4c). While this bears some similarity with the South Atlantic (Figure 3c), the underlying reason for these two distinct peaks is not linked to the different orientation of two rift branches (like in the South Atlantic), but is a result of Greenland's plate motion change at around 120 Ma (Figure 4a,b). Except for Iberia-Newfoundland and the Labrador Sea, which evolved at low obliquity, most rift branches experienced moderate or high rift obliquity during the entire rift history. More than 70% of the rifts involved an obliquity of more than 20° and the overall mean obliquity of the North Atlantic rift amounts to 34° (Figure 4c).

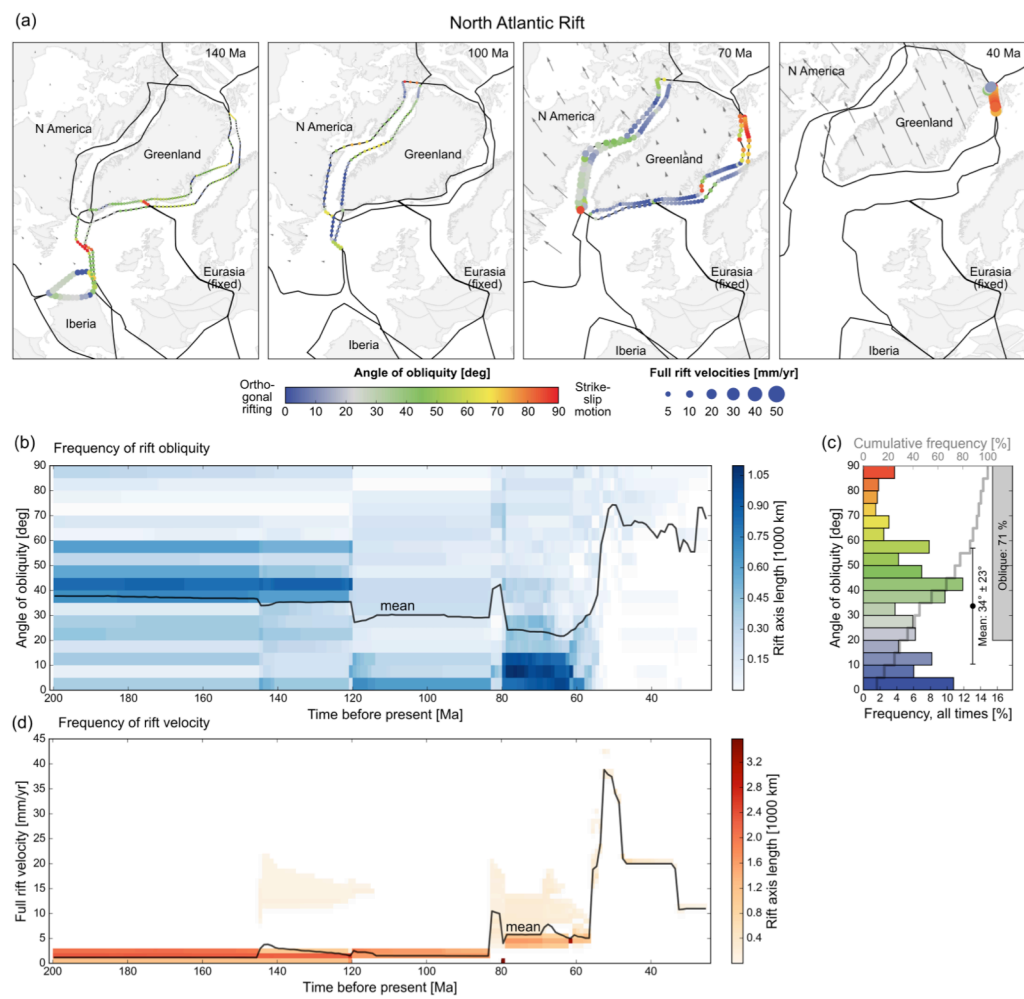


Figure 4. North Atlantic rift. Several changes in plate motion mirror the complex tectonic history of the North Atlantic during the last 200 million years. A distinct increase in syn-rift obliquity occurs at 50 Ma prior to final breakup between northern Greenland and northwest Europe.

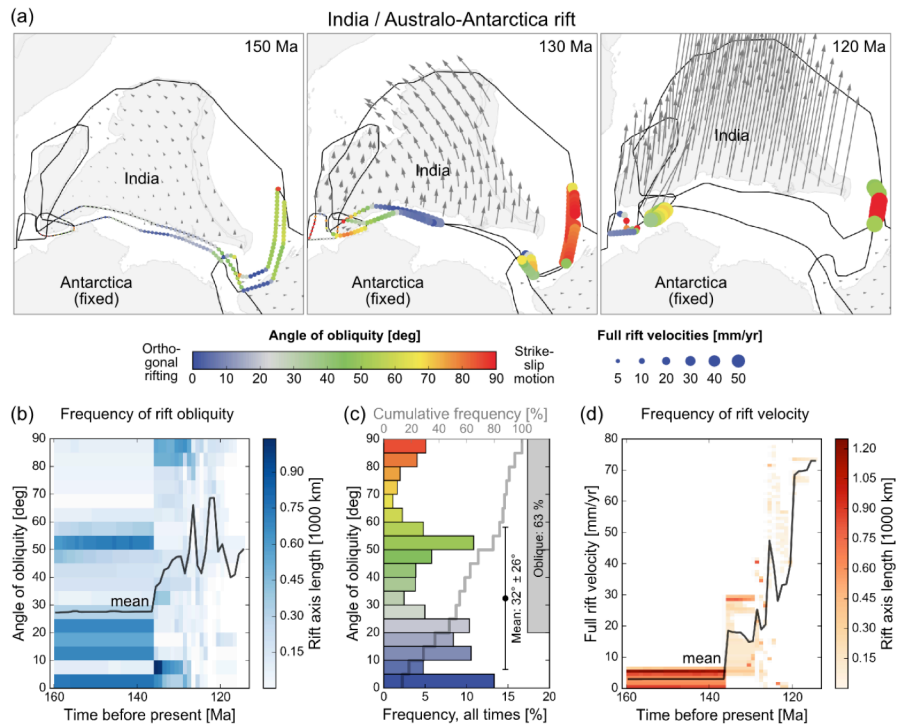


Figure 5. India / Australo-Antarctica rift. Rift obliquity is dominated by two major rift trends – the low obliquity India-Antarctica branch and the highly oblique India-Australia branch. For simplicity, we neglect low-velocity relative motion between Antarctica and Australia, which will be discussed in Figure 6.

3.3. Rifting between India and Australo-Antarctica

Mesozoic rifting within eastern Gondwana lead to continental fragmentation beginning with the separation of India (together with Sri Lanka and Madagascar) from Australia and Antarctica in the **Mid-Jurassic to Early Cretaceous**, (Powell et al., 1988; Gibbons et al., 2013). The timing and kinematics of breakup and spreading between Australia and India is well constrained (Williams et al., 2013; Whittaker et al., 2016) and although the precise geometry of greater India is obscured by subsequent deformation during India-Eurasia collision, the divergence between India and Australia is thought to have involved a significant component of oblique motion along greater India's northern margin recorded by the Wallaby-Zenith Fracture Zone (Ali and Aitchison, 2014). Initial breakup between India and Antarctica is recorded in the Enderby Basin becoming progressively younger to the west (Gibbons et al., 2013; Davis et al., 2016) and involved significant ridge jumps that isolated the Elan Bank microcontinent (Borissova et al., 2003).

Rotational rifting between East India and Australo-Antarctica with an Euler pole close to the southwestern tip of India induces almost orthogonal rifting between India and Antarctica, and predominantly oblique rifting between India and West

Australia (Figure 5). After 135 Ma, continued high obliquity shear along the northern Indian margin and Australia finally
 395 culminates in the formation of the Wallaby–Zenith Fracture Zone, the northern boundary of the Perth abyssal plain. At the
 same time breakup propagates from east to west along the East Indian margin, so that the mean rift obliquity is more and
 more dominated by high-angle shearing.

The rift obliquity distribution in Figure 5c reflects the existence of two major rift trends – the low obliquity India–Antarctica
 400 branch of 0° to 25° and the highly oblique India–Australia branch with more than 45° . The mean obliquity of the entire rift
 system amounts to 32° while more than 60% of the rift evolved at obliquity angles higher than 20° . Prior und during large
 parts of the breakup, the velocity and obliquity of the rift system are positively correlated.

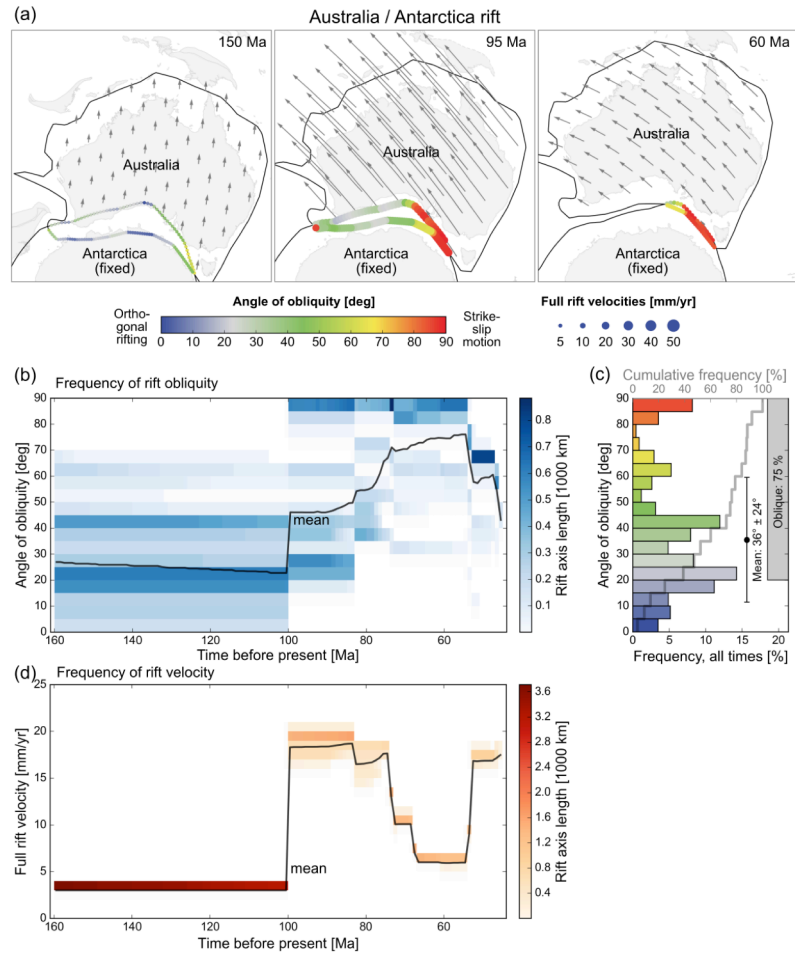


Figure 6. Australia / Antarctica rift. A distinct change in plate motion takes place at 100 Ma generating two discrete phases: (1) slow rifting at moderate obliquity, (2) fast rifting at high obliquity.

3.4. Australia / Antarctica

405 The first phases of rifting between Australia and Antarctica began in the Late Jurassic (Powell et al., 1988; Ball et al., 2013) but continental breakup did not begin until the late Cretaceous and progressed diachronously from west to east. Within this rift system, the signatures of oblique extension have been previously recognised along Australia's southern margin (Willcox and Stagg, 1990; Norvick and Smith, 2001). Lithospheric breakup was complex and protracted (Gillard et al., 2015, 2016), leaving unresolved questions surrounding the nature of the crust in the continent-ocean transition and the oldest interpreted
410 seafloor spreading magnetic lineations. Reconstructions of the rift kinematics must therefore incorporate other geological constraints from along the Australia-Antarctica plate boundary system (Whittaker et al., 2013). This reconstruction, in common with earlier studies (Powell et al., 1988; Royer and Sandwell, 1989), comprises an oblique component of divergence during the Late Cretaceous prior to a change in plate motion direction in the early Cenozoic.

415 The first-order history of rift obliquity can be understood by considering two distinct conditions. (i) Due to the concave shape of the southern Australian margin and their Antarctic conjugates, there are two major rift trends along the Australia-Antarctica rift (Figure 6). (ii) According to the plate tectonic reconstruction (Williams et al., 2011), there has been a significant change in relative plate motion at around 100 Ma from a northward to a northwestward directed plate velocity. The two existing rift trends explain the dichotomy in rift obliquity of 10°-25° and 35°-45° from the onset of rifting until 100
420 Ma (Figure 6b). The plate motion change at 100 Ma however, shifts the rift obliquity in both branches to higher angles of 20°-45° and 80°-90°, respectively.

The velocity history displays a prominent increase at 100 Ma that corresponds to the increased rift obliquity via a plate motion change. An increase in the rate of plate divergence in the Late Cretaceous is corroborated by structural restoration
425 studies based on seismic profiles (Espurt et al., 2012) and the rate of divergence is similar to that interpreted from initial seafloor spreading anomalies (Tikku and Cande, 1999; Whittaker et al., 2013). Interestingly, after more than 20 million years of fast divergence, the relative plate velocity inferred from magnetic anomalies decreases again. If correct, this decrease cannot be related to Australia-Antarctica plate boundary dynamics, since at this time the rift system consists only of the last remaining continental bridge between Tasmania and Antarctica while the majority of the plate boundary already transitioned
430 to sea floor spreading.

A further noteworthy aspect of Australia-Antarctic divergence is the failure of rifting between Tasmania and the southeast Australian mainland. Extension in the Bass and Gippsland basins occurred predominantly in the Early Cretaceous (e.g. Power et al., 2001). In the Late Cretaceous, rifting between Australia and Antarctica localised between western Tasmania
435 and Cape Adare, where breakup eventually occurred. The higher obliquity of the successful plate boundary compared to the

failed rift arm in Bass Strait may explain why this rift was favoured, similar to the successful opening of the Equatorial Atlantic in favour of a Saharan Ocean during South Atlantic formation (Heine and Brune, 2014).

3.5. Gulf of California

440 The Gulf of California constitutes the youngest rift system in our analysis, which is why its temporal evolution is known in much greater detail than the previous case examples. The first phase of the Gulf of California rift is closely linked to the Greater Basin and Range extensional zone. Tectono-stratigraphy and dated rift-related magmatic rocks show that the onset of continental extension must have occurred before the mid-Miocene (Ferrari et al., 2013; Duque-Trujillo et al., 2015). This first phase of slow rifting is marked by a wide rift style characteristic of the present-day Basin and Range region. An increase in both rift velocity and rift obliquity has been suggested as the underlying reason for basin-ward localisation and finally the transition to sea floor spreading in the southern Gulf of California (Bennett and Oskin, 2014; Darin et al., 2016; van Wijk et al., 2017). This change in plate motion at ~12 Ma has been explained by the final cessation of subduction in this region so that most of the relative plate motion between Pacific and North America had to be taken up by transform motion between Baja California and the North American mainland (Atwater and Stock, 1998; Oskin and Stock, 2003).

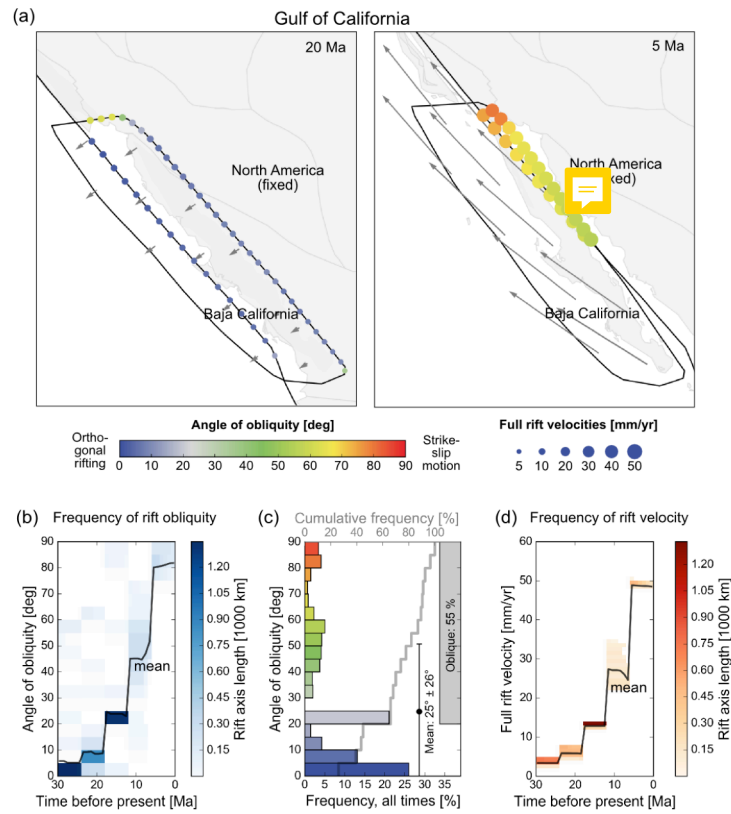


Figure 7. Gulf of California rift. The initial rift phase is characterised by slow, predominantly orthogonal extension and associated with a wide rift. An increase in rift obliquity enhances localisation between 20 and 10 Ma inducing continental breakup. The obliquity and velocity of this rift increases almost proportionally.

450 The transition from orthogonal to highly oblique rifting is captured by the tectonic reconstruction (McQuarrie and Wernicke, 2005) our plate model is built on (Figure 7a). According to that reconstruction, the transition occurs during a time frame of less than 10 million years between 20 and 10 Ma (Umhoefer, 2011). That transition is mirrored in our analysis by a gradual increase in rift obliquity from less than 10° prior to 18 Ma to $20\text{--}25^\circ$ between 18 and 12 Ma up to $40\text{--}90^\circ$ from 12 Ma until present-day (Figure 7b).

455

A striking feature of the Gulf of California rift is that throughout the existence of this plate boundary the velocity evolved almost proportional to the rift obliquity (Figure 7b,d) hinting at a causal relationship between these two variables.

Observations from the Gulf of California rift corroborate the idea that localization within the lithosphere is enhanced by obliquity-related formation of pull-apart basins and associated energy-efficient strike-slip faults (Bennett and Oskin, 2014;

460 van Wijk et al., 2017). We discuss the relation of rift obliquity and extension velocity in more detail in the discussion section 5.

4 Global analysis

In this section we evaluate global rift obliquity since the onset of Pangea fragmentation in terms of temporal and spatial variability. Analysing all rift systems of our global plate tectonic model during the last 230 million years, we here test the robustness of our study by additionally considering the impact on passive margin area and by employing an alternative set of continent-ocean boundaries.

The extent of major rift systems varied through time (Figure 8a), with a pronounced peak between 160 and 110 million years ago when many rifts of the Atlantic and Indian Ocean were simultaneously active. Figure 8b illustrates that almost all angles of obliquity are represented at any given time. Interestingly, obliquities in the range between 70° and 85° seem to be underrepresented while almost pure strike-slip systems are an ubiquitous feature. This finding might be explained by the fact that the transition from normal faulting to strike-slip faulting in ideal materials occurs at around 70° (Withjack and Jamison, 1986). We therefore speculate that once major continental strike-slip faults form, the plate boundary adjusts to a velocity-parallel configuration entailing the formation of a transform margin (Gerya, 2013; Le Pourhiet et al., 2017; Ammann et al., 2017), which also explains the relatively high peak at 90° obliquity (Figure 8b,c).

In our reference model, we compute a mean global obliquity of 34° with a standard deviation of 24° since the inception of Pangea breakup. We also find that 69% of all rifts deform in oblique rift mode, i.e. with obliquities exceeding 20° (Figure 8c), illustrating that oblique rifting appears to be the rule on Earth rather than the exception.

So far, we analysed the frequency of obliquity with respect to rift length, where transform margins and rifted margins are given the same relative importance. Now we focus briefly on the surface area that is generated during passive margin formation, which is also a proxy for the size of sedimentary basins. We note that it is the rift-orthogonal velocity component, which leads to lithospheric stretching and generates passive margin area, while the rift parallel component merely induces an along-strike offset. Hence we compute how many square kilometres of passive margin are generated per million year by multiplying the rift length of each small rift segment with its segment-orthogonal velocity component. The resulting distribution reflects the relative importance of rift obliquity weighted by passive margin area, which essentially leads to a shift towards lower obliquity values. Nevertheless, we find an average obliquity of 29° and a total of 67% of passive margin area affected by obliquity angles larger than 20° (Figure 8d,e).

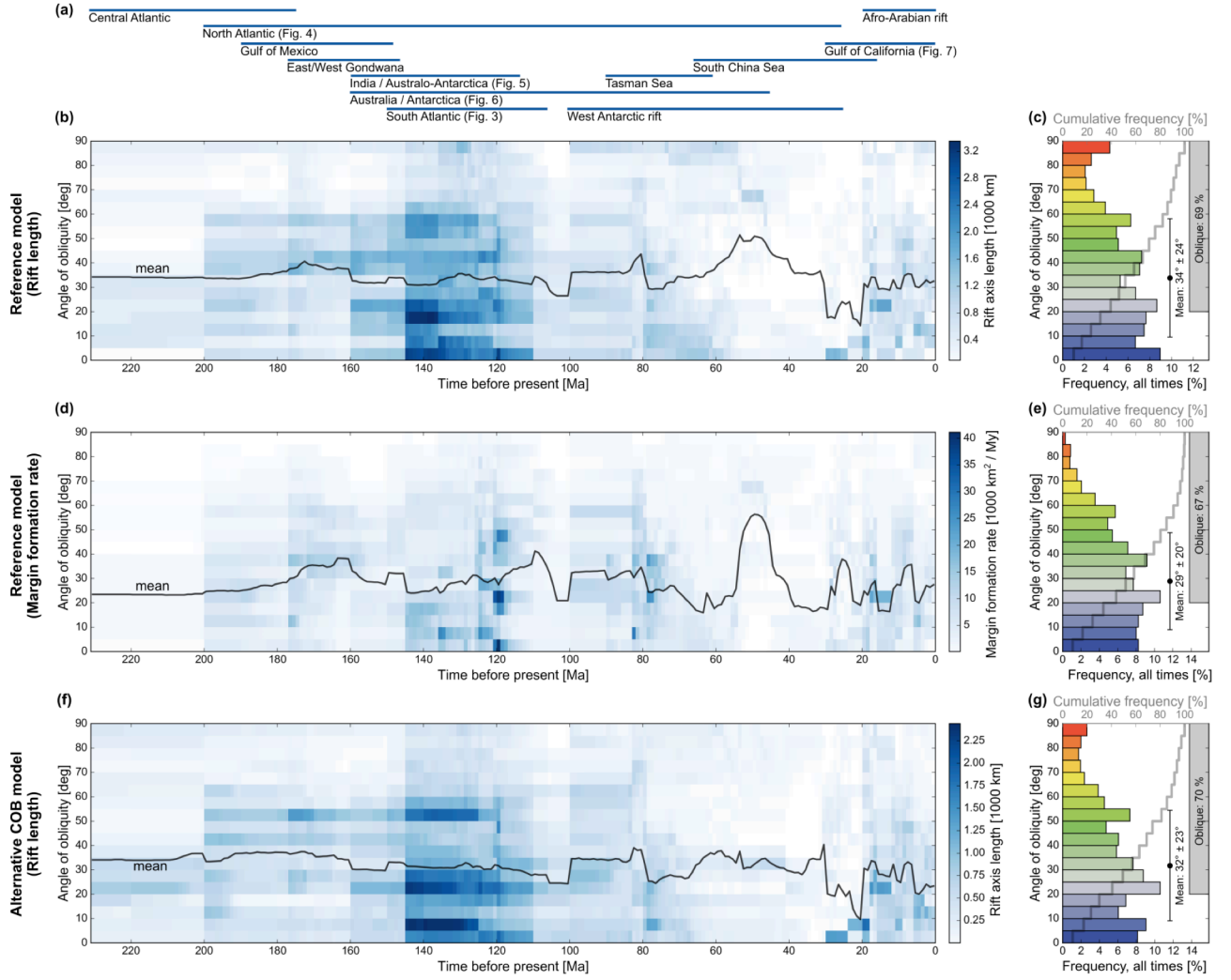


Figure 8. Global analysis of rift obliquity. (a) Variations of major rift system activity. Note that many rifts of the Atlantic and Indian Ocean were simultaneously active between 160 and 110 Ma. (b,c) Rift obliquity in terms of rift length for the reference model employing late-breakup COBs (see Sect. 2.2 and Figure 1 and 2 for more details). (d,e) The reference model analysed in terms of margin formation rate (i.e. rift segment length multiplied with segment-orthogonal velocity component). (f,g) An alternative model employing early-breakup COBs. All three models result in global mean rift obliquities of $\sim 30^\circ$ and oblique rifting for more than $\sim 70\%$ illustrating the robustness of our results.

We test the impact of an alternative set of continent-ocean boundaries (Figure 2), which represents the continent-ward end member and hence stands for an earlier breakup time (Section 2.2). While the total rift length is reduced with respect to the reference model, we find that the first-order pattern of obliquity evolution is not affected (Figure 8f,g). Also, the mean rift

495 obliquity of 32° and the rift length percentage affected by oblique deformation (70%) is almost identical to the late-breakup end-member.

Finally, we map the time-averaged obliquity at each rift element (Figure 9). The advantage of this approach is that one can easily identify each point's rift obliquity that dominated the tectonic evolution, however, one has to keep in mind that changes in rift obliquity are not visualised. Figure 9 shows that only a few rifts exhibit a pure rift-orthogonal extension velocity such as the Labrador Sea, the east Indian margin and some locations in the North and South Atlantic. Instead, many rifted margins feature moderate rift obliquity between 20° and 40° like the West Iberia margin, the Red Sea, as well as the central and southern segment of the South Atlantic. To a large extent, however, the dominant rift obliquity exceeds even 40°, for instance in the Gulf of Mexico, the Equatorial South Atlantic, the Gulf of Aden, the east African margins, the West Antarctic Rift, the Tasman Sea and also the sheared margins of the Fram Strait, Madagascar, Patagonia, and Western Australia.

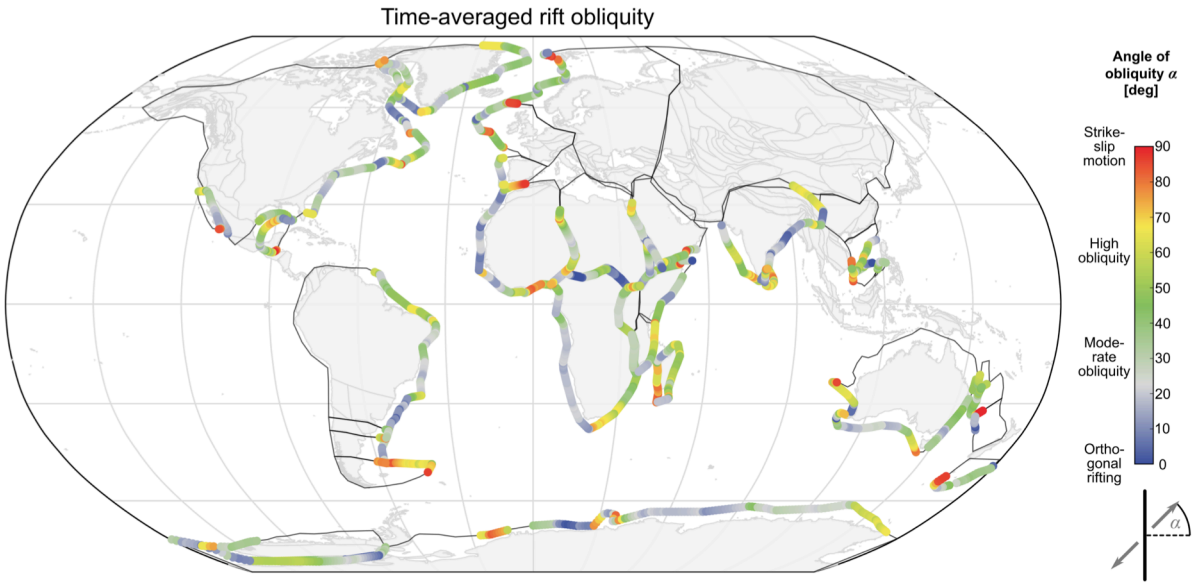


Figure 9. Global map of mean rift obliquity. For each rift point we display the time-averaged rift obliquity illustrating the prevalence of oblique rifting since Pangea fragmentation. Note that temporal changes of rift obliquity cannot be visualised in this plot.

5 Discussion

510 Previous studies quantified the present-day plate boundary obliquity in general terms and on long wavelength by considering extensional, compressional, and transform plate boundary types. Woodcock (1986) noted that 59% of all present-day plate

boundaries feature obliquities larger than 22 degrees. A more detailed recent study found even higher obliquity by showing that 65% of present-day plate boundaries exhibit $>30^\circ$ obliquity (Philippon and Corti, 2016). In the latter study, this result was further decomposed by plate boundary type illustrating that 73% of rifts and mid-ocean ridges extend at more than 30° obliquity. While these previous studies did not focus on rift obliquity, they nevertheless are consistent with our results by highlighting that oblique plate boundary deformation constitutes the rule and not the exception.

Jeanniot and Buiter (2018) evaluated the margin width of transtensionally formed rifted margins and thereby estimated the rift obliquity of 26 major rift segments worldwide. In general, their approach is very similar to ours: they defined linearized rift segments that follow the trend of continent-ocean boundaries, accounting additionally for coastlines and topographic highs, and they estimated the direction of relative plate divergence using the GPlates graphical user interface. They find a weak positive correlation between obliquity and width of a rift system; however, at highly oblique margins this relationship breaks down and these margins are not only significantly narrower than orthogonal margins, but they also exhibit large-offset transform faults. Our approach differs from Jeanniot and Buiter (2018) in that our linearized rift segments are considerably smaller (on the order of several hundred kilometres), that we employ a script-based approach using the python-interface of GPlates and that we include a few more regions, but most importantly that we explicitly focus on the temporal evolution of rift obliquity. Nonetheless, for the time-averaged obliquity (Figure 9) we find a very good correspondence with their results, which illustrates the robustness of both approaches with respect to the exact definition of the rift trend and the linearized rift segment length.

The dynamics of oblique rifting have been previously investigated using numerical and analogue modelling methods. In these experiments, rift obliquity is imposed either through oblique lateral boundary conditions (Schreurs and Colletta, 1998; Brune, 2014; Zwaan et al., 2016), boundaries with a velocity discontinuity (Tron and Brun, 1991; Bonini et al., 1997; Le Calvez and Vendeville, 2002; Le Pourhiet et al., 2012), an oblique arrangement of weak elongate zones (van Wijk, 2005; Corti, 2008; Agostini et al., 2009; Ammann et al., 2017; Brune et al., 2017a; Balázs et al., 2018) or offset weak seeds (Allken et al., 2012; Gerya, 2013; Le Pourhiet et al., 2017). The majority of these studies focus on emergent fault patterns and their evolution, and relate the existence of oblique rifts and rifted margins to tectonic inheritance, segment linkage, rift propagation, and changes in extension direction. Some models, however, were designed to investigate the required driving force during oblique extension (Brune et al., 2012) and the competition between simultaneously active, neighbouring rift systems (Heine and Brune, 2014). These models suggest oblique rifting as a mechanically preferred type of continental extension and we speculate that this could be a reason for the unexpectedly high percentage of oblique rifts and rifted margins in our analysis. The underlying cause for preferentially oblique rifting has been addressed by means of analytical modelling suggesting that plastic yielding takes place at less tectonic force when the relative plate velocity is oblique to the rift trend (Brune et al., 2012). This process exerts additional control on rift strength that is otherwise governed by thermo-rheological properties, strain localisation and inherited weaknesses (Buck, 2015; Burov, 2015; Brune, 2018). As a

consequence, during rift competition, oblique rifting should prevail over orthogonal rifting if all other rift parameters are similar. This appears to be the case for the West African and Equatorial Atlantic rift systems, which were active at the same time until localisation along the more oblique Equatorial Atlantic rift induced the failure of the West African rift (Heine and Brune, 2014). A similar example is continental rifting between Australia and Antarctica, where early extension formed failed rift basins within the present-day Bass Strait (e.g. Norvick and Smith, 2001) that competed with the more oblique and eventually successful rift between Tasmania and Antarctica.

In many cases, we find a correlation between the obliquity and the velocity of a rift (Figs. 3-7). This result can be understood when considering that the effective rift-perpendicular velocity that leads to lithospheric thinning is smaller than in neighbouring purely orthogonal rift segments (Montési and Behn, 2007). Therefore, oblique segments need more time to reach breakup. This is why final continental rupture of highly oblique examples, such as (1) the Fram Strait opening in the North Atlantic, (2) shearing between the Patagonian shelf and South Africa, (3) the separation of Tasmania and the Antarctic Cape Adare region, or (4) rifting between Greater India and West Australia postdate continental breakup in neighbouring segments by several tens of million years. This means that the average obliquity of an entire rift system increases after the beginning of breakup because the orthogonal segments tend to break early and do not contribute to the mean rift obliquity anymore. Since rifting typically starts slowly and accelerates prior to break-up (Brune et al., 2016), the long-lived oblique segments often witness the final, fast stages of rifting. This argument applies to the final rift stages of the South and North Atlantic and the separation of India from Australia but it does not explain the correlation between obliquity and velocity prior to breakup of major rift segments, such as seen for Australia-Antarctica at 100 Ma (Figure 5) or the Gulf of California at 18 to 5 Ma (Figure 7). In both situations, a change in the direction of plate divergence induced higher rift obliquity and simultaneously the rift velocity increased. This might be explained by the aforementioned idea that oblique rifting requires less tectonic force, which leads to a higher rift velocity at constant extensional stress (Brune et al., 2012). We suggest that the change in extension direction sparked a significant loss in rift strength (Brune et al., 2016), which ultimately generated a speed-up of Baja California relative to North America and of Australia relative to Antarctica.

Oblique rifting is closely linked to toroidal plate motion, i.e. the spin of plates and associated strike-slip deformation. The concept of decomposing Earth's plate motions into toroidal (plate boundary parallel) and poloidal (plate boundary perpendicular) components is motivated by the insight that toroidal motion does not affect the buoyancy configuration of Earth's mantle. It is hence not directly driven by mantle convection and in a homogeneous plate-mantle system, energy consumption due to toroidal motion should therefore be minimized (O'Connell et al., 1991). Large lateral rheological contrasts within and between Earth's plates have been invoked to explain some part of the toroidal motion component (Becker, 2006; Rolf et al., 2017). However, an additional part of the toroidal plate motion might be due to rift obliquity: since oblique rifting reduces rift strength, it favours the development of oblique plate boundaries, which enhances large-scale plate rotation and associated toroidal surface velocity components. Lithgow-Bertelloni and Richards (1993) showed that the

580 toroidal component of plate motions slowly declined since 120 Ma, despite large variations in the poloidal component of
plate velocities. Notwithstanding significant uncertainty, the ratio of toroidal/poloidal velocities appears to be especially high
between 120 and ~80 Ma. This period corresponds to a distinct decline in the lengths of rifts involved in Pangea breakup
(Figure 8, and Brune et al., 2017c). Hence we speculate that the toroidal/poloidal ratio could be higher during continental
585 continents become dispersed.

6 Conclusions

In this study we evaluated the rift obliquity of major continent-scale rift systems by analysing a global plate tectonic
reconstruction from the onset of Pangea fragmentation to present-day. We find that the classical 2D assumption where the
extension direction is perpendicular to the rift trend is not justified in most cases. Instead, the majority of rift systems leading
590 to continental breakup during the last 230 million years involved moderate to high rift obliquity. Approximately 70% of all
rift segments involved a distinct obliquity higher than 20° while the global average in terms of rift obliquity is 34°. This high
contribution of oblique deformation can be explained through the generally irregular shape of plate boundaries, possibly
related to tectonic inheritance, and by the concept of obliquity-dependent plate boundary strength. Oblique deformation
generates intrinsically 3D stress and strain fields that hamper simplified tectonic interpretation via 2D cross sections, models
595 and seismic profiles. Our results indicate that oblique plate boundary deformation should be considered the rule and not the
exception when investigating the dynamics of rifts and rifted margins.

Acknowledgements

This research has been funded by the German Academic Exchange Service (DAAD), Project 57319603. S.B. was supported
through the Helmholtz Young Investigators Group CRYSTALS (VH-NG-1132). S.E.W. and R.D.M. were supported by
600 Australian Research Council grant IH130200012. We thank two anonymous reviewers for their constructive and motivating
comments that significantly helped to improve this manuscript.

References

- 605 Agostini, A., Corti, G., Zeoli, A., and Mulugeta, G., 2009, Evolution, pattern, and partitioning of deformation during oblique
continental rifting: Inferences from lithospheric-scale centrifuge models: *Geochemistry Geophysics Geosystems*, v.
10, p. Q11015, doi:10.1029/2009GC002676.
- Ali, J.R., and Aitchison, J.C., 2014, Greater India's northern margin prior to its collision with Asia: *Basin Research*, v. 26, p.
73–84, doi:10.1111/bre.12040.
- 610 Allken, V., Huismans, R.S., and Thieulot, C., 2012, Factors controlling the mode of rift interaction in brittle-ductile coupled
systems: A 3D numerical study: *Geochemistry Geophysics Geosystems*, v. 13, p. Q05010,
doi:10.1029/2012GC004077.

- Ammann, N., Liao, J., Gerya, T., and Ball, P., 2017, Oblique continental rifting and long transform fault formation based on 3D thermomechanical numerical modeling: *Tectonophysics*, doi:10.1016/j.tecto.2017.08.015.
- Atwater, T., and Stock, J., 1998, Pacific-North America Plate Tectonics of the Neogene Southwestern United States: An Update: *International Geology Review*, v. 40, p. 375–402, doi:10.1080/00206819809465216.
- Balázs, A., Matenco, L., Vogt, K., Cloetingh, S., and Gerya, T., 2018, Extensional polarity change in continental rifts: inferences from 3D numerical modeling and observations: *Journal of Geophysical Research: Solid Earth*, doi:10.1029/2018JB015643.
- Ball, P., Eagles, G., Ebinger, C., McClay, K., and Totterdell, J., 2013, The spatial and temporal evolution of strain during the separation of Australia and Antarctica: *Geochemistry, Geophysics, Geosystems*, v. 14, p. 2771–2799, doi:10.1002/ggge.20160.
- Barnett-Moore, N., Müller, D.R., Williams, S., Skogseid, J., and Seton, M., 2016, A reconstruction of the North Atlantic since the earliest Jurassic: *Basin Research*, p. 1–26, doi:10.1111/bre.12214.
- Basile, C., 2015, Transform continental margins - part 1: Concepts and models: *Tectonophysics*, v. 661, p. 1–10, doi:10.1016/j.tecto.2015.08.034.
- Bayrakci, G. et al., 2016, Fault-controlled hydration of the upper mantle during continental rifting: *Nature Geoscience*, v. 9, p. 384–388, doi:10.1038/ngeo2671.
- Becker, T.W., 2006, On the effect of temperature and strain-rate dependent viscosity on global mantle flow, net rotation, and plate-driving forces: *Geophysical Journal International*, v. 167, p. 943–957.
- Bennett, S.E.K., and Oskin, M.E., 2014, Oblique rifting ruptures continents: Example from the Gulf of California shear zone: *Geology*, v. 42, p. 215–218, doi:10.1130/G34904.1.
- Bercovici, D., 2003, The generation of plate tectonics from mantle convection: *Earth and Planetary Science Letters*, v. 205, p. 107–121, doi:10.1016/S0012-821X(02)01009-9.
- Bertrand, G., Horstmann, M., Hermann, O., and Behrmann, J.H., 2005, Retrodeformation of the southern Upper Rhine Graben: new insights on continental oblique rifting: *Quaternary Science Reviews*, v. 24, p. 345–352, doi:10.1016/j.quascirev.2004.07.011.
- Bonini, M., Souriot, T., Boccaletti, M., and Brun, J.P., 1997, Successive orthogonal and oblique extension episodes in a rift zone: Laboratory experiments with application to the Ethiopian Rift: *Tectonics*, v. 16, p. 347–362, doi:10.1029/96TC03935.
- Borissova, I., Coffin, M.F., Charvis, P., and Operto, S., 2003, Structure and development of a microcontinent: Elan Bank in the southern Indian Ocean: *Geochemistry, Geophysics, Geosystems*, v. 4, doi:10.1029/2003GC000535.
- Brune, S., 2014, Evolution of stress and fault patterns in oblique rift systems: 3-D numerical lithospheric-scale experiments from rift to breakup: *Geochemistry, Geophysics, Geosystems*, v. 15, p. 3392–3415, doi:10.1002/2014GC005446.
- Brune, S., 2018, Forces within continental and oceanic rifts: Numerical modeling elucidates the impact of asthenospheric flow on surface stress: *Geology*, v. 46, p. 191–192, doi:10.1130/focus022018.1.
- Brune, S., 2016, Rifts and rifted margins: A review of geodynamic processes and natural hazards (J. C. Duarte & W. P. Schellart, Eds.): *Plate Boundaries and Natural Hazards*, v. 219, p. 11–37, doi:10.1002/9781119054146.ch2.
- Brune, S., and Autin, J., 2013, The rift to break-up evolution of the Gulf of Aden: Insights from 3D numerical lithospheric-scale modelling: *Tectonophysics*, v. 607, p. 65–79, doi:10.1016/j.tecto.2013.06.029.
- Brune, S., Corti, G., and Ranalli, G., 2017a, Controls of inherited lithospheric heterogeneity on rift linkage: Numerical and analog models of interaction between the Kenyan and Ethiopian rifts across the Turkana depression: *Tectonics*, v. 36, p. 2017TC004739, doi:10.1002/2017TC004739.

- Brune, S., Heine, C., Clift, P.D., and Pérez-Gussinyé, M., 2017b, Rifted margin architecture and crustal rheology: Reviewing Iberia-Newfoundland, Central South Atlantic, and South China Sea: *Marine and Petroleum Geology*, v. 79, p. 257–281, doi:10.1016/j.marpetgeo.2016.10.018.
- Brune, S., Heine, C., Perez-Gussinye, M., and Sobolev, S.V., 2014, Rift migration explains continental margin asymmetry and crustal hyper-extension: *Nature Communications*, v. 5, doi:10.1038/ncomms5014.
- Brune, S., Popov, A.A., and Sobolev, S.V., 2012, Modeling suggests that oblique extension facilitates rifting and continental break-up: *Journal of Geophysical Research*, v. 117, p. B08402, doi:10.1029/2011JB008860.
- Brune, S., Williams, S.E., Butterworth, N.P., and Müller, R.D., 2016, Abrupt plate accelerations shape rifted continental margins: *Nature*, v. 536, p. 201–204, doi:10.1038/nature18319.
- Brune, S., Williams, S.E., and Müller, R.D., 2017c, Potential links between continental rifting, CO₂ degassing and climate change through time: *Nature Geoscience*, v. 10, p. 941–946, doi:10.1038/s41561-017-0003-6.
- Buck, W.R., 2015, The Dynamics of Continental Breakup and Extension, *in* *Treatise on Geophysics*, 2nd Edition, Vol 6 - Crust and Lithosphere Dynamics, Oxford, Elsevier.
- Burov, E.B., 2015, Plate Rheology and Mechanics, *in* Schubert, G. ed., *Treatise on Geophysics* (Second Edition), Oxford, Elsevier, p. 95–152, doi:10.1016/B978-0-444-53802-4.00112-3.
- Chaboureaud, A.-C., Guillocheau, F., Robin, C., Rohais, S., Moulin, M., and Aslanian, D., 2013, Paleogeographic evolution of the central segment of the South Atlantic during Early Cretaceous times: Paleotopographic and geodynamic implications: *Tectonophysics*, v. 604, p. 191–223, doi:10.1016/j.tecto.2012.08.025.
- Clifton, A.E., and Schlische, R.W., 2001, Nucleation, growth, and linkage of faults in oblique rift zones: Results from experimental clay models and implications for maximum fault size: *Geology*, v. 29, p. 455–458, doi:10.1130/0091-7613(2001)029<0455:NGALOF>2.0.CO;2.
- Clifton, A.E., Schlische, R.W., Withjack, M.O., and Ackermann, R.V., 2000, Influence of rift obliquity on fault-population systematics: results of experimental clay models: *Journal of Structural Geology*, v. 22, p. 1491–1509, doi:10.1016/S0191-8141(00)00043-2.
- Coffin, M.F., and Eldholm, O., 1992, Volcanism and continental break-up: a global compilation of large igneous provinces: Geological Society, London, Special Publications, v. 68, p. 17–30, doi:10.1144/GSL.SP.1992.068.01.02.
- Corti, G., 2008, Control of rift obliquity on the evolution and segmentation of the main Ethiopian rift: *Nature Geoscience*, v. 1, p. 258–262, doi:10.1038/ngeo160.
- Daly, M.C., Chorowicz, J., and Fairhead, J.D., 1989, Rift basin evolution in Africa: the influence of reactivated steep basement shear zones: Geological Society, London, Special Publications, v. 44, p. 309–334, doi:10.1144/GSL.SP.1989.044.01.17.
- Darin, M.H., Bennett, S.E.K., Dorsey, R.J., Oskin, M.E., and Iriondo, A., 2016, Late Miocene extension in coastal Sonora, México: Implications for the evolution of dextral shear in the proto-Gulf of California oblique rift: *Tectonophysics*, v. 693, p. 378–408, doi:10.1016/j.tecto.2016.04.038.
- Davis, J.K., Lawver, L.A., Norton, I.O., and Gahagan, L.M., 2016, New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean: *Gondwana Research*, v. 34, p. 16–28, doi:10.1016/j.gr.2016.02.010.
- Deng, C., Gawthorpe, R., Fossen, H., and Finch, E., 2018, How does the orientation of a pre-existing basement weakness influence fault development during renewed rifting? Insights from three-dimensional discrete element modeling: *Tectonics*, v. 0, doi:10.1029/2017TC004776.
- Dewey, J.F., Holdsworth, R.E., and Strachan, R.A., 1998, Transpression and transtension zones: Geological Society, London, Special Publications, v. 135, p. 1–14, doi:10.1144/GSL.SP.1998.135.01.01.

- 695 Díaz-Azpiroz, M., Brune, S., Leever, K.A., Fernández, C., and Czeck, D.M., 2016, Tectonics of oblique plate boundary systems: *Tectonophysics*, v. 693, Part B, p. 165–170, doi:10.1016/j.tecto.2016.07.028.
- Dickie, K., Keen, C.E., Williams, G.L., and Dehler, S.A., 2011, Tectonostratigraphic evolution of the Labrador margin, Atlantic Canada: *Marine and Petroleum Geology*, v. 28, p. 1663–1675, doi:10.1016/j.marpetgeo.2011.05.009.
- Doré, A.G., 1991, The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 87, p. 441–492, doi:10.1016/0031-0182(91)90144-G.
- 700 Duque-Trujillo, J., Ferrari, L., Orozco-Esquivel, T., López-Martínez, M., Lonsdale, P., Bryan, S.E., Kluesner, J., Piñero-Lajas, D., and Solari, L., 2015, Timing of rifting in the southern Gulf of California and its conjugate margins: Insights from the plutonic record: *Geological Society of America Bulletin*, v. 127, p. 702–736, doi:10.1130/B31008.1.
- 705 Espurt, N., Callot, J.-P., Roure, F., Totterdell, J.M., Struckmeyer, H.I.M., and Vially, R., 2012, Transition from symmetry to asymmetry during continental rifting: an example from the Bight Basin–Terre Adélie (Australian and Antarctic conjugate margins): *Terra Nova*, v. 24, p. 167–180, doi:10.1111/j.1365-3121.2011.01055.x.
- Faleide, J.I., Tsikalas, F., Breivik, A.J., Mjelde, R., Ritzmann, O., Engen, O., Wilson, J., and Eldholm, O., 2008, Structure and Evolution of the Continental Margin off Norway and the Barents Sea: *Episodes*, v. 31, p. 82–91.
- 710 Féraud, G., Beslier, M.-O., and Cornen, G., 1996, 40Ar/39Ar dating of gabbros from the ocean/continent transition of the western Iberia Margin: Preliminary results, *in* *Proceedings of the Ocean Drilling Program. Scientific results, Ocean Drilling Program*, v. 149, p. 489–495.
- 715 Ferrari, L., López-Martínez, M., Orozco-Esquivel, T., Bryan, S.E., Duque-Trujillo, J., Lonsdale, P., and Solari, L., 2013, Late Oligocene to Middle Miocene rifting and synextensional magmatism in the southwestern Sierra Madre Occidental, Mexico: The beginning of the Gulf of California rift: *Geosphere*, p. GES00925.1, doi:10.1130/GES00925.1.
- Fletcher, J.M., Grove, M., Kimbrough, D., Lovera, O., and Gehrels, G.E., 2007, Ridge-trench interactions and the Neogene tectonic evolution of the Magdalena shelf and southern Gulf of California: Insights from detrital zircon U-Pb ages from the Magdalena fan and adjacent areas: *Geological Society of America Bulletin*, v. 119, p. 1313–1336, doi:10.1130/B26067.1.
- 720 Fossen, H., and Rotevatn, A., 2016, Fault linkage and relay structures in extensional settings—A review: *Earth-Science Reviews*, v. 154, p. 14–28, doi:10.1016/j.earscirev.2015.11.014.
- Fournier, M., Bellahsen, N., Fabbri, O., and Gunnell, Y., 2004, Oblique rifting and segmentation of the NE Gulf of Aden passive margin: *Geochemistry, Geophysics, Geosystems*, v. 5, p. Q11005, doi:10.1029/2004GC000731.
- 725 Fournier, M., and Petit, C., 2007, Oblique rifting at oceanic ridges: Relationship between spreading and stretching directions from earthquake focal mechanisms: *Journal of Structural Geology*, v. 29, p. 201–208, doi:10.1016/j.jsg.2006.07.017.
- Gaina, C., Nasuti, A., Kimbell, G.S., and Blischke, A., 2017, Break-up and seafloor spreading domains in the NE Atlantic: *Geological Society, London, Special Publications*, v. 447, p. SP447.12, doi:10.1144/SP447.12.
- 730 Gawthorpe, R.L., and Leeder, M.R., 2000, Tectono-sedimentary evolution of active extensional basins: *Basin Research*, v. 12, p. 195–218.
- Gernigon, L., Blischke, A., Nasuti, A., and Sand, M., 2015, Conjugate volcanic rifted margins, seafloor spreading, and microcontinent: Insights from new high-resolution aeromagnetic surveys in the Norway Basin: *Tectonics*, v. 34, p. 2014TC003717, doi:10.1002/2014TC003717.
- 735 Gerya, T.V., 2013, Initiation of transform faults at rifted continental margins: 3D petrological-thermomechanical modeling and comparison to the Woodlark Basin: *Petrology*, v. 21, p. 550–560, doi:10.1134/S0869591113060039.

- Gibbons, A.D., Whittaker, J.M., and Müller, R.D., 2013, The breakup of East Gondwana: Assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model: *Journal of Geophysical Research: Solid Earth*, v. 118, p. 808–822, doi:10.1002/jgrb.50079.
- 740 Gibbons, A.D., Zahirovic, S., Müller, R.D., Whittaker, J.M., and Yatheesh, V., 2015, A tectonic model reconciling evidence for the collisions between India, Eurasia and intra-oceanic arcs of the central-eastern Tethys: *Gondwana Research*, v. 28, p. 451–492, doi:10.1016/j.gr.2015.01.001.
- Gillard, M., Autin, J., and Manatschal, G., 2016, Fault systems at hyper-extended rifted margins and embryonic oceanic crust: Structural style, evolution and relation to magma: *Marine and Petroleum Geology*, v. 76, p. 51–67, doi:10.1016/j.marpetgeo.2016.05.013.
- 745 Gillard, M., Autin, J., Manatschal, G., Sauter, D., Munschy, M., and Schaming, M., 2015, Tectonomagmatic evolution of the final stages of rifting along the deep conjugate Australian-Antarctic magma-poor rifted margins: Constraints from seismic observations: *Tectonics*, v. 34, p. 2015TC003850, doi:10.1002/2015TC003850.
- Granot, R., and Dymant, J., 2015, The Cretaceous opening of the South Atlantic Ocean: *Earth and Planetary Science Letters*, v. 414, p. 156–163, doi:10.1016/j.epsl.2015.01.015.
- 750 Heine, C., and Brune, S., 2014, Oblique rifting of the Equatorial Atlantic: Why there is no Saharan Atlantic Ocean: *Geology*, v. 42, p. 211–214, doi:10.1130/G35082.1.
- Heine, C., Zoethout, J., and Müller, R.D., 2013, Kinematics of the South Atlantic rift: *Solid Earth*, v. 4, p. 215–253, doi:10.5194/se-4-215-2013.
- 755 Hetzel, R., and Strecker, M.R., 1994, Late Mozambique Belt structures in western Kenya and their influence on the evolution of the Cenozoic Kenya Rift: *Journal of Structural Geology*, v. 16, p. 189–201, doi:10.1016/0191-8141(94)90104-X.
- Hodge, M.S., Fagereng, Å., Biggs, J., and Mdala, H., 2018, Controls on early-rift geometry: new perspectives from the Bilila–Mtakataka fault, Malawi: *Geophysical Research Letters*, doi:10.1029/2018GL077343.
- 760 Hosseinpour, M., Müller, R.D., Williams, S.E., and Whittaker, J.M., 2013, Full-fit reconstruction of the Labrador Sea and Baffin Bay: *Solid Earth*, v. 4, p. 461–479, doi:10.5194/se-4-461-2013.
- Huisman, R.S., and Beaumont, C., 2011, Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins: *Nature*, v. 473, p. 74–78, doi:10.1038/nature09988.
- Jakobsson, M. et al., 2007, The early Miocene onset of a ventilated circulation regime in the Arctic Ocean: *Nature*, v. 447, p. 986–990, doi:10.1038/nature05924.
- 765 Jeannot, L., and Buiter, S.J.H., 2018, A quantitative analysis of transtensional margin width: *Earth and Planetary Science Letters*, v. 491, p. 95–108, doi:10.1016/j.epsl.2018.03.003.
- Klimke, J., and Franke, D., 2016, Gondwana breakup: no evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and Kenya: *Terra Nova*, v. 28, p. 233–244, doi:10.1111/ter.12214.
- 770 Kneller, E.A., Johnson, C.A., Karner, G.D., Einhorn, J., and Queffelec, T.A., 2012, Inverse methods for modeling non-rigid plate kinematics: Application to mesozoic plate reconstructions of the Central Atlantic: *Computers & Geosciences*, v. 49, p. 217–230, doi:http://dx.doi.org/10.1016/j.cageo.2012.06.019.
- Knies, J., and Gaina, C., 2008, Middle Miocene ice sheet expansion in the Arctic: Views from the Barents Sea: *Geochemistry, Geophysics, Geosystems*, v. 9, doi:10.1029/2007GC001824.
- Kröner, A., and Stern, R.J., 2004, Pan-African Orogeny, *in* *Encyclopedia of Geology*, Elsevier.
- 775 Lavier, L.L., and Manatschal, G., 2006, A mechanism to thin the continental lithosphere at magma-poor margins: *Nature*, v. 440, p. 324–328, doi:10.1038/nature04608.

- Le Calvez, J.H., and Vendeville, B.C., 2002, Experimental designs to model along-strike fault interaction: *Journal of the Virtual Explorer*, v. 07, doi:10.3809/jvirtex.2002.00043.
- 780 Le Pourhiet, L., Huet, B., May, D.A., Labrousse, L., and Jolivet, L., 2012, Kinematic interpretation of the 3D shapes of metamorphic core complexes: *Geochemistry Geophysics Geosystems*, v. 13, p. Q09002, doi:10.1029/2012GC004271.
- Le Pourhiet, L., May, D.A., Huille, L., Watremez, L., and Leroy, S., 2017, A genetic link between transform and hyper-extended margins: *Earth and Planetary Science Letters*, v. 465, p. 184–192, doi:10.1016/j.epsl.2017.02.043.
- 785 Lithgow-Bertelloni, C., Richards, M.A., Ricard, Y., O’Connell, R.J., and Engebretson, D.C., 1993, Toroidal-poloidal partitioning of plate motions since 120 MA: *Geophysical Research Letters*, v. 20, p. 375–378, doi:10.1029/93GL00168.
- Lizarralde, D. et al., 2007, Variation in styles of rifting in the Gulf of California: *Nature*, v. 448, p. 466–469, doi:10.1038/nature06035.
- 790 Lundin, E.R., and Doré, A.G., 1997, A tectonic model for the Norwegian passive margin with implications for the NE Atlantic: Early Cretaceous to break-up: *Journal of the Geological Society*, v. 154, p. 545–550, doi:10.1144/gsjgs.154.3.0545.
- Manatschal, G., Lavier, L., and Chenin, P., 2015, The role of inheritance in structuring hyperextended rift systems: Some considerations based on observations and numerical modeling: *Gondwana Research*, v. 27, p. 140–164, doi:10.1016/j.gr.2014.08.006.
- 795 Mart, Y., Ryan, W.B.F., and Lunina, O.V., 2005, Review of the tectonics of the Levant Rift system: the structural significance of oblique continental breakup: *Tectonophysics*, v. 395, p. 209–232, doi:10.1016/j.tecto.2004.09.007.
- McKenzie, D., 1978, Some remarks on the development of sedimentary basins: *Earth and Planetary Science Letters*, v. 40, p. 25–32, doi:10.1016/0012-821X(78)90071-7.
- 800 McQuarrie, N., and Wernicke, B.P., 2005, An animated tectonic reconstruction of southwestern North America since 36 Ma: *Geosphere*, v. 1, p. 147–172, doi:10.1130/GES00016.1.
- Mericer de Lépinay, M., Loncke, L., Basile, C., Roest, W.R., Patriat, M., Maillard, A., and De Clarens, P., 2016, Transform continental margins - Part 2: A worldwide review: *Tectonophysics*, doi:10.1016/j.tecto.2016.05.038.
- 805 Molnar, N.E., Cruden, A.R., and Betts, P.G., 2017, Interactions between propagating rotational rifts and linear rheological heterogeneities: Insights from three-dimensional laboratory experiments: *Tectonics*, v. 36, p. 2016TC004447, doi:10.1002/2016TC004447.
- Mondy, L.S., Rey, P.F., Duclaux, G., and Moresi, L., 2017, The role of asthenospheric flow during rift propagation and breakup: *Geology*, v. 46, p. 103–106, doi:10.1130/G39674.1.
- Montési, L.G.J., and Behn, M.D., 2007, Mantle flow and melting underneath oblique and ultraslow mid-ocean ridges: *Geophysical Research Letters*, v. 34, p. L24307, doi:10.1029/2007GL031067.
- 810 Morley, C.K., 2016, The impact of multiple extension events, stress rotation and inherited fabrics on normal fault geometries and evolution in the Cenozoic rift basins of Thailand: *Geological Society, London, Special Publications*, v. 439, p. SP439.3, doi:10.1144/SP439.3.
- Moulin, M., Aslanian, D., and Unternehr, P., 2010, A new starting point for the South and Equatorial Atlantic Ocean: *Earth-Science Reviews*, v. 98, p. 1–37, doi:10.1016/j.earscirev.2009.08.001.
- 815 Müller, R.D. et al., 2016, Ocean Basin Evolution and Global-Scale Plate Reorganization Events Since Pangea Breakup: *Annual Review of Earth and Planetary Sciences*, v. 44, p. 107–138, doi:10.1146/annurev-earth-060115-012211.

- Müller, R.D., Cannon, J., Qin, X., Watson, R.J., Gurnis, M., Williams, S., Pfaffelmoser, T., Seton, M., Russell, S.H.J., and Zahirovic, S., 2018, GPlates – Building a Virtual Earth Through Deep Time: *Geochemistry, Geophysics, Geosystems*, v. (in press), doi:10.1029/2018GC007584.
- 820 Naliboff, J.B., Buiter, S.J.H., Péron-Pinvidic, G., Osmundsen, P.T., and Tetreault, J., 2017, Complex fault interaction controls continental rifting: *Nature Communications*, v. 8, p. 1179, doi:10.1038/s41467-017-00904-x.
- Nirrengarten, M., Manatschal, G., Tugend, J., Kusznir, N., and Sauter, D., 2018, Kinematic Evolution of the Southern North Atlantic: Implications for the Formation of Hyperextended Rift Systems: *Tectonics*, p. 2017TC004495, doi:10.1002/2017TC004495.
- 825 Norvick, M.S., and Smith, M.A., 2001, Mapping the plate tectonic reconstruction of southern and southeastern Australia and implications for petroleum systems: *The APPEA Journal*, v. 41, p. 15–35, doi:10.1071/aj00001.
- Nürnberg, D., and Müller, R.D., 1991, The Tectonic Evolution of the South-Atlantic from Late Jurassic to Present: *Tectonophysics*, v. 191, p. 27–53, doi:10.1016/0040-1951(91)90231-G.
- O’Connell, R.J., Gable, C.W., and Hager, B.H., 1991, Toroidal-Poloidal Partitioning of Lithospheric Plate Motions, *in* *Glacial Isostasy, Sea-Level and Mantle Rheology*, Springer, Dordrecht, NATO ASI Series, p. 535–551, doi:10.1007/978-94-011-3374-6_25.
- 830 Oskin, M., and Stock, J., 2003, Marine incursion synchronous with plate-boundary localization in the Gulf of California: *Geology*, v. 31, p. 23–26, doi:10.1130/0091-7613(2003)031<0023:MISWPB>2.0.CO;2.
- Osmundsen, P.T., and Redfield, T.F., 2011, Crustal taper and topography at passive continental margins: *Terra Nova*, v. 23, p. 349–361, doi:10.1111/j.1365-3121.2011.01014.x.
- 835 Peron-Pinvidic, G., Manatschal, G., and Osmundsen, P.T., 2013, Structural comparison of archetypal Atlantic rifted margins: A review of observations and concepts: *Marine and Petroleum Geology*, doi:10.1016/j.marpetgeo.2013.02.002.
- Phethean, J.J.J., Kalnins, L.M., van Hunen, J., Biffi, P.G., Davies, R.J., and McCaffrey, K.J.W., 2016, Madagascar’s escape from Africa: A high-resolution plate reconstruction for the Western Somali Basin and implications for supercontinent dispersal: *Geochemistry, Geophysics, Geosystems*, v. 17, p. 5036–5055, doi:10.1002/2016GC006624.
- 840 Philippon, M., and Corti, G., 2016, Obliquity along plate boundaries: *Tectonophysics*, v. 693, Part B, p. 171–182, doi:10.1016/j.tecto.2016.05.033.
- Philippon, M., Willingshofer, E., Sokoutis, D., Corti, G., Sani, F., Bonini, M., and Cloetingh, S., 2015, Slip re-orientation in oblique rifts: *Geology*, v. 43, p. 147–150, doi:10.1130/G36208.1.
- 845 Phillips, T.B., Jackson, C.A.-L., Bell, R.E., and Duffy, O.B., 2018, Oblique reactivation of lithosphere-scale lineaments controls rift physiography – the upper-crustal expression of the Sorgenfrei–Tornquist Zone, offshore southern Norway: *Solid Earth*, v. 9, p. 403–429, doi:https://doi.org/10.5194/se-9-403-2018.
- Powell, C.M., Roots, S.R., and Veevers, J.J., 1988, Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean: *Tectonophysics*, v. 155, p. 261–283, doi:10.1016/0040-1951(88)90269-7.
- 850 Power, M.R., Hill, K.C., Hoffman, N., Bernecker, T., and Norvick, M., 2001, The Structural and Tectonic Evolution of the Gippsland Basin: Results from 2D Section Balancing and 3D Structural Modelling; <http://archives.datapages.com/data/petroleum-exploration-society-of-australia/conferences/001/001001/pdfs/373.htm> (accessed June 2018).
- 855 Quirk, D.G. et al., 2013, Rifting, subsidence and continental break-up above a mantle plume in the central South Atlantic: *Geological Society, London, Special Publications*, v. 369, p. 185–214, doi:10.1144/SP369.20.
- Ranero, C.R., and Pérez-Gussinyé, M., 2010, Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins: *Nature*, v. 468, p. 294–299, doi:10.1038/nature09520.

- Rolf, T., Capitanio, F.A., and Tackley, P.J., 2017, Constraints on mantle viscosity structure from continental drift histories in spherical mantle convection models: *Tectonophysics*, doi:10.1016/j.tecto.2017.04.031.
- Royer, J.-Y., and Sandwell, D.T., 1989, Evolution of the eastern Indian Ocean since the Late Cretaceous: Constraints from Geosat altimetry: *Journal of Geophysical Research: Solid Earth*, v. 94, p. 13755–13782, doi:10.1029/JB094iB10p13755.
- Sanderson, D.J., and Marchini, W.R.D., 1984, Transpression: *Journal of Structural Geology*, v. 6, p. 449–458, doi:10.1016/0191-8141(84)90058-0.
- Schreurs, G., and Colletta, B., 1998, Analogue modelling of faulting in zones of continental transpression and transtension: Geological Society, London, Special Publications, v. 135, p. 59–79.
- Sippel, J., Meeßen, C., Cacace, M., Mechie, J., Fishwick, S., Heine, C., Scheck-Wenderoth, M., and Strecker, M.R., 2017, The Kenya rift revisited: insights into lithospheric strength through data-driven 3-D gravity and thermal modelling: *Solid Earth*, v. 8, p. 45–81, doi:10.5194/se-8-45-2017.
- Skogseid, J., Planke, S., Faleide, J.I., Pedersen, T., Eldholm, O., and Neverdal, F., 2000, NE Atlantic continental rifting and volcanic margin formation: Geological Society, London, Special Publications, v. 167, p. 295–326, doi:10.1144/GSL.SP.2000.167.01.12.
- Storey, M., Duncan, R.A., and Tegner, C., 2007, Timing and duration of volcanism in the North Atlantic Igneous Province: Implications for geodynamics and links to the Iceland hotspot: *Chemical Geology*, v. 241, p. 264–281, doi:10.1016/j.chemgeo.2007.01.016.
- Teyssier, C., Tikoff, B., and Markley, M., 1995, Oblique plate motion and continental tectonics: *Geology*, v. 23, p. 447–450, doi:10.1130/0091-7613(1995)023<0447:OPMACT>2.3.CO;2.
- Tikku, A.A., and Cande, S.C., 1999, The oldest magnetic anomalies in the Australian-Antarctic Basin: Are they isochrons? *Journal of Geophysical Research: Solid Earth*, v. 104, p. 661–677, doi:10.1029/1998JB900034.
- Torsvik, T.H., Rousse, S., Labails, C., and Smethurst, M.A., 2009, A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin: *Geophysical Journal International*, v. 177, p. 1315–1333.
- Tron, V., and Brun, J.-P., 1991, Experiments on oblique rifting in brittle-ductile systems: *Tectonophysics*, v. 188, p. 71–84, doi:10.1016/0040-1951(91)90315-J.
- Tugend, J., Manatschal, G., Kuszniir, N.J., Masini, E., Mohn, G., and Thinon, I., 2014, Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees: *Tectonics*, v. 33, p. 2014TC003529, doi:10.1002/2014TC003529.
- Umhoefer, P.J., 2011, Why did the Southern Gulf of California rupture so rapidly?—Oblique divergence across hot, weak lithosphere along a tectonically active margin: *GSA Today*, v. 21, p. 4–10, doi:10.1130/G133A.1.
- Umhoefer, P.J., Darin, M.H., Bennett, S.E.K., Skinner, L.A., Dorsey, R.J., and Oskin, M.E., 2018, Breaching of strike-slip faults and successive flooding of pull-apart basins to form the Gulf of California seaway from ca. 8–6 Ma: *Geology*, v. 46, p. 695–698, doi:10.1130/G40242.1.
- White, N., 1993, Recovery of strain rate variation from inversion of subsidence data: *Nature*, v. 366, p. 449–452, doi:10.1038/366449a0.
- Whittaker, J.M., Williams, S.E., Halpin, J.A., Wild, T.J., Stilwell, J.D., Jourdan, F., and Daczko, N.R., 2016, Eastern Indian Ocean microcontinent formation driven by plate motion changes: *Earth and Planetary Science Letters*, v. 454, p. 203–212, doi:10.1016/j.epsl.2016.09.019.
- Whittaker, J.M., Williams, S.E., and Müller, R.D., 2013, Revised tectonic evolution of the Eastern Indian Ocean: *Geochemistry, Geophysics, Geosystems*, v. 14, p. 1891–1909, doi:10.1002/ggge.20120.
- van Wijk, J.W., 2005, Role of weak zone orientation in continental lithosphere extension: *Geophysical Research Letters*, v. 32, doi:10.1029/2004GL022192.

- van Wijk, J., Axen, G., and Abera, R., 2017, Initiation, evolution and extinction of pull-apart basins: Implications for opening of the Gulf of California: *Tectonophysics*, v. 719–720, p. 37–50, doi:10.1016/j.tecto.2017.04.019.
- 905 Willcox, J.B., and Stagg, H.M.J., 1990, Australia's southern margin: a product of oblique extension: *Tectonophysics*, v. 173, p. 269–281, doi:10.1016/0040-1951(90)90223-U.
- Williams, S.E., Whittaker, J.M., Granot, R., and Müller, D.R., 2013, Early India-Australia spreading history revealed by newly detected Mesozoic magnetic anomalies in the Perth Abyssal Plain: *Journal of Geophysical Research: Solid Earth*, v. 118, p. 3275–3284, doi:10.1002/jgrb.50239.
- 910 Williams, S.E., Whittaker, J.M., and Müller, R.D., 2011, Full-fit, palinspastic reconstruction of the conjugate Australian-Antarctic margins: *Tectonics*, v. 30, p. TC6012, doi:10.1029/2011TC002912.
- de Wit, M.J., Stankiewicz, J., and Reeves, C., 2008, Restoring Pan-African-Brasiliano connections: more Gondwana control, less Trans-Atlantic corruption: *Geological Society, London, Special Publications*, v. 294, p. 399–412.
- Withjack, M.O., and Jamison, W.R., 1986, Deformation produced by oblique rifting: *Tectonophysics*, v. 126, p. 99–124, doi:10.1016/0040-1951(86)90222-2.
- 915 Woodcock, N.H., 1986, The Role of Strike-Slip Fault Systems at Plate Boundaries: *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, v. 317, p. 13–29.
- Zwaan, F., and Schreurs, G., 2017, How oblique extension and structural inheritance influence rift segment interaction: Insights from 4D analog models: *Interpretation*, p. SD119–SD138, doi:10.1190/INT-2016-0063.1.
- 920 Zwaan, F., Schreurs, G., Naliboff, J., and Buiter, S.J.H., 2016, Insights into the effects of oblique extension on continental rift interaction from 3D analogue and numerical models: *Tectonophysics*, v. 693, Part B, p. 239–260, doi:10.1016/j.tecto.2016.02.036.