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*Book chapter*

# Rifting continents

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**Abstract**
Continental rifts can form when and where continents are stretched. If the driving forces can overcome lithospheric strength, a rift valley forms. Rifts are characterised by faults, sedimentary basins, earthquakes and/or volcanism. With the right set of weakening feedbacks, a rift can evolve to break a continent into conjugate rifted margins such as those found along the Atlantic and Indian Oceans. When, however, strengthening processes overtake weakening, rifting can stall and leave a failed rift, such as the North Sea or the West African Rift. A clear definition of continental break-up is still lacking because the transition from continent to ocean can be complex, with tilted continental blocks and regions of exhumed lithospheric mantle. Rifts and rifted margins not only shape the face of our planet, they also have a clear societal impact, through hazards caused by earthquakes, volcanism, landslides and $CO_2$ release, and through their resources, such as fertile land, hydrocarbons, minerals and geothermal potential. This societal relevance makes an understanding of the many unknown aspects of rift processes as critical as ever.

**Keywords**
Continental extension, continental break-up, rifted margin, sedimentary basin, rift, Wilson Cycle

## 1. Introduction

The early maps of the world drew attention to what was to become a recurring argument in favour of mobile continents: how the American continents and Europe with Africa seem to fit like pieces of a puzzle, even though they are separated by the Atlantic Ocean. Already in 1596, the map maker Ortelius suggested that the Americas were torn away from Europe and Africa by "earthquakes and floods", with the traces of the ruptures shown in the opposite coasts. This not only pointed out how well the coastlines on each side of the Atlantic Ocean fit but called upon tectonic processes – earthquakes and resulting floods – to have rifted the continents apart. We now know that rifting of continents is indeed accompanied by earthquakes and that

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


landslides on rifted margins can trigger tsunamis and floods. But we do not know whether Ortelius envisaged the many millions of years that rifting can take. In the centuries that followed, similar suggestions were made for connections between continents. Snider-Pellegrini (1858), for example, fitted continents in a Late Carboniferous supercontinent, based on identical plant fossils in Europe and the United States, and Suess (1885) coined "Gondwanaland" for the union of South America, Africa, India, Australia, and Antarctica. In 1912 Wegener proposed that the continents had been joined in a supercontinent: the early Carboniferous 'Pangea'. The evidence for the supercontinent was multifold, using not only how coastlines and fossils fit between continents, but also correlations in mountain chains and glacial sediments. The latter placed South Africa, South America, Australia and India near the south pole. Wegener (1912) unfortunately encountered much scepticism for proposing that the continents had drifted from the Pangea configuration to their present-day position.

We should keep in mind that at these times there was no general recognition, let alone a tested and physics-based explanation, for the horizontal movements of tectonic plates. Ocean basins and mountains were explained by vertical movements, such as those caused by local isostasy or an expanding or shrinking Earth (Dana, 1863; Mantovani, 1889). The formulation of the mantle convection theory, with large-scale flows driven by energy from radiogenic decay and residual heat from Earth's formation, provided an explanation for horizontal plate motions (Holmes, 1931; Dietz, 1961; Hess, 1962). Proof came in the 1950's and 1960's from continental paleomagnetic poles and marine magnetic anomalies (Heezen et al., 1959; Vine and Matthews, 1963; Runcorn, 1965). A consistent picture of a dynamic planet emerged, on which continents can assemble and break apart. But which factors and processes control where and when rifting begins and a continent breaks apart?

Continental rifting starts when continents are stretched. At present, stretching, or extension, occurs in the Gulf of Corinth (Greece), the Baikal Rift (Central Asia), and the East African Rift, among many other places (Fig. 1a). The extending region forms a rift valley where sedimentary basins may develop, and if stretching remains localised, the continent breaks and rifted margins form (Fig. 1c). The factors and processes which control whether rifts will successfully form new oceans, such as the Atlantic and Indian Oceans, or whether break-up never occurs, leaving only a 'failed rift', such as the North Sea or the West African Rift System (Fig. 1a), are not fully constrained. We could point to various reasons for the ongoing investigations into the causes of rifting, but an important one is probably that the geological and geophysical observations can sometimes be difficult to unravel. Rifting processes vary temporally and spatially and may be expressed differently in the geological record, even when underlying physical principles are the same.

The timespan of rifting varies tremendously, from the opening of the Northeast Atlantic Ocean between Norway and Greenland which took over 300 Myrs (Faleide et al., 2010), to the opening of the Equatorial Atlantic Ocean between the Gulf of Guinea and Northeast Brazil which took only ~20 Myr (Moulin et al., 2010). The long evolution of the Norwegian-Greenland rift was polyphase, including various phases of tectonic activity interspersed with phases of relative tectonic quiescence and phases of massive magmatic activity. Break-up between Norway and

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


Greenland (55-53 Ma) occurred just after the flood basalt eruption of the North Atlantic Igneous Province (63-61 Ma) (Torsvik and Cocks, 2005; Saunders et al., 1997). Intrusion of warm magmas may have helped the continent to finally break up (Buiter and Torsvik, 2014), though other continents break up without flood basalt magmatism, such as the formation of the Iberia-Newfoundland or Gulf of Guinea-Northeast Brazil rifted margins. Not only does the amount of magma vary among rifted margins, the amount of sediment deposition can vary widely as well. The Mid Norwegian margin, for example, shows basins with over 10 km thickness of sediments, whereas the Northern Norwegian margin has relatively little sediments (Straume et al., 2019).

Added to the variability in rifts is the observation that rifts usually do not form in pristine undeformed continental rocks (as far as these may be found), but rather on the contrary, it seems that deformation breeds further deformation. The Northeast Atlantic Ocean, for example, opened mainly but not completely, along the old traces of the Appalachian and Caledonian Mountains. These mountains in turn had formed by closure of an earlier ocean, the Iapetus Ocean (Harland and Gayer, 1972). The North Atlantic region thus preserves a history of an ocean that closed and reopened: the Wilson Cycle (Wilson, 1966; the cycle is named after Tuzo Wilson by Dewey and Burke, 1974). The preferential localisation of plate-scale deformation in similar locations (Audet and Bürgmann, 2011; Buiter and Torsvik, 2014), implies that mountains can turn into rifts and rifts into mountains, repeatedly. The structural, compositional and thermal inheritance of previous deformation phases can impact rifting processes by providing a more complex initial crustal and lithospheric architecture and rheology, including fault systems, sedimentary basins, and ophiolites (Manatschal et al., 2015).

Rifting can thus be long-lived or fast, magma-rich or magma-poor, sediment-rich or sediment-poor, and precede or follow other plate-scale, inherited deformation. In this chapter, we discuss the variability of continental rifting from the initial stages of rift inception to basin formation (Section 2) and final break-up, forming conjugate rifted margins (Section 3). Our discussion includes cases of rift success (leading to continental break-up) and failure (leading to failed rifts) and addresses the interaction of rifting with inheritance, erosion and sedimentation, mantle flow, and melting, to finally discuss the societal effects of rifts (Section 4).

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


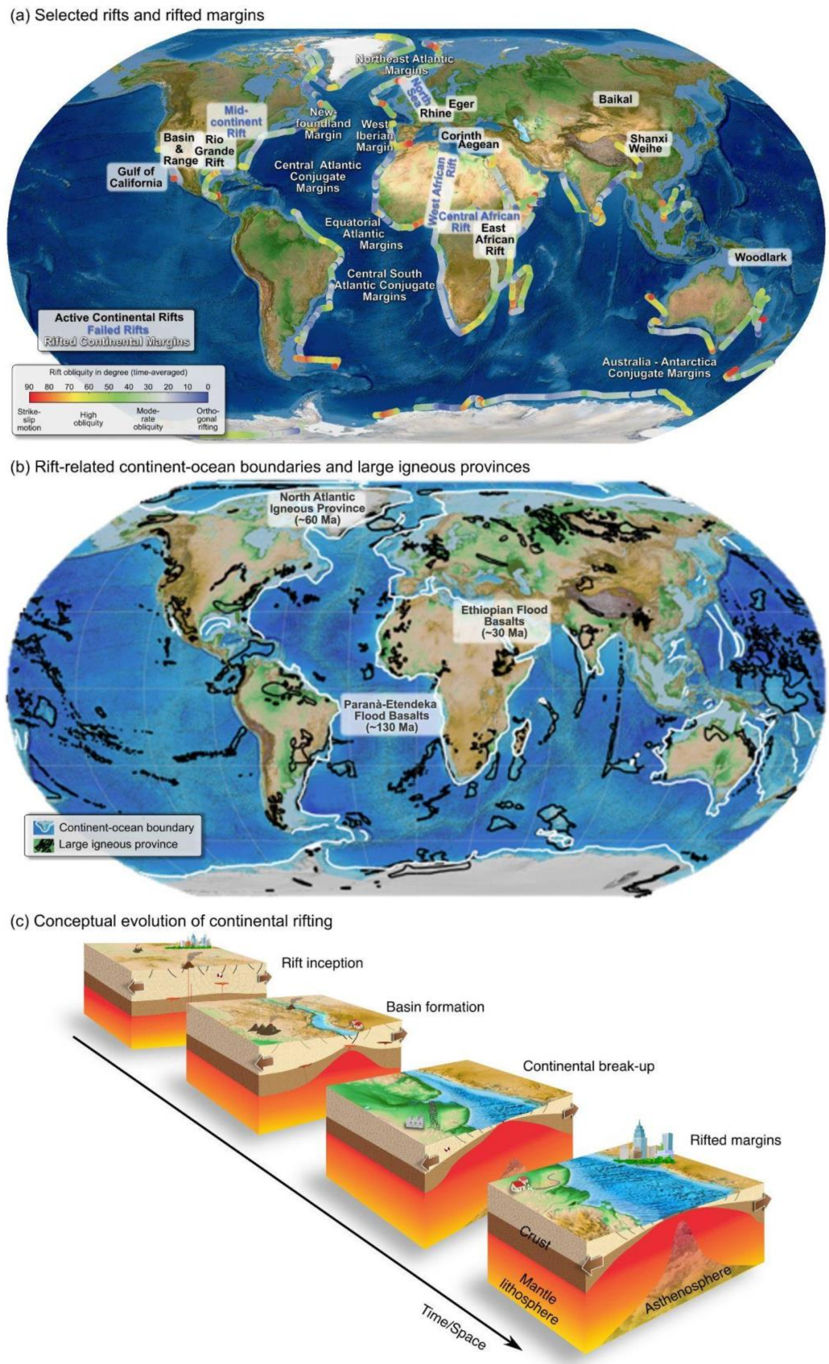


***Figure 1: Overview of past and present rifts and their evolution. (a) Selected rifts and rifted margins.*** *Currently active rifts cluster in East Africa, Western North America, Central and Southern Europe. Aborted, so-called 'failed' rift systems achieved significant amounts of*

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


*crustal thinning, but stopped extending before the lithosphere was broken. Rifted margins, in contrast, were formed by rifts that led to continental break-up and can host major sedimentary basins. Colours along rifts and rifted margins indicate the time-averaged rift obliquity (based on Brune et al., 2018).* ***(b) Rift-related continent-ocean boundaries (COBs) and large igneous provinces (LIPs).*** *Continent-ocean boundaries (white lines) mark the transition of highly stretched and intruded continental lithosphere to oceanic lithosphere that is newly formed at mid-oceanic spreading centres. Large igneous provinces (black contours) are regions that experienced massive basaltic volcanism during a comparably short time frame of a few million years. Some LIPs coincide with onset of rifting, others with continental break-up (see Section 3). In oceanic domains, LIPs are often connected to an age-progressive hotspot track (also black contours). It is generally thought that LIPs are formed due to the impingement of a mantle plume head at the lithosphere, while hotspot tracks are caused by plate motion above the tail of a mantle plume. Image generated with GPlates (https://www.gplates.org/) using data from Müller et al. (2016), Johansson et al. (2018), Bryan and Ernst (2008), and Courtillot and Renne (2003).* ***(c) Conceptual evolution of continental rifts.*** *Inception of rifting involves localisation of an array of normal faults that may be accompanied by magmatic intrusions and volcanism. Stretching of the crust results in isostatic subsidence and formation of sedimentary basins. Continental break-up takes place when the continental lithosphere is broken and sea floor spreading initiates. Following break-up, rifted continental margins experience cooling and further subsidence, which may be enhanced due to continuous sedimentation. Sketches modified from Brune et al. (2022).*

## 2. Continental rifting

### 2.1 Geological features of rifts

There is a large variety of continental rifts worldwide, from the narrow and deep Baikal rift in Central Asia, the laterally extensive Basin and Range Province in mountainous Western North America, to the low-lying salt pans of the Afar region in northern Ethiopia (Figs 1, 2). Despite this variability, all continental rifts form when the lithosphere is pulled apart, hence all rifts contain the following characteristic geological features: faults, basins, and volcanoes.

The most prominent rift features are normal faults: brittle structures that accommodate extension by localised shear deformation (Scholz, 2019) (Fig. 3). The major faults can reach several tens of kilometres deep as evidenced onshore in outcrops and offshore by seismic reflection images and seismicity. At their upper end, these large faults may generate kilometre-scale surface topography, while at their lower end they are rooted in ductile shear zones. The largest rift faults are commonly located at the edges of the rift valley constituting so-called border faults (Fig. 3). In the East African Rift System for instance, border faults may create impressive topographic relief of more than two kilometres (Corti, 2009; Ebinger and Scholz, 2011). Secondary deformation in the rift valley is accommodated by intra-rift faults (Fig. 3) that commonly increase their activity during later stages of rifting.

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


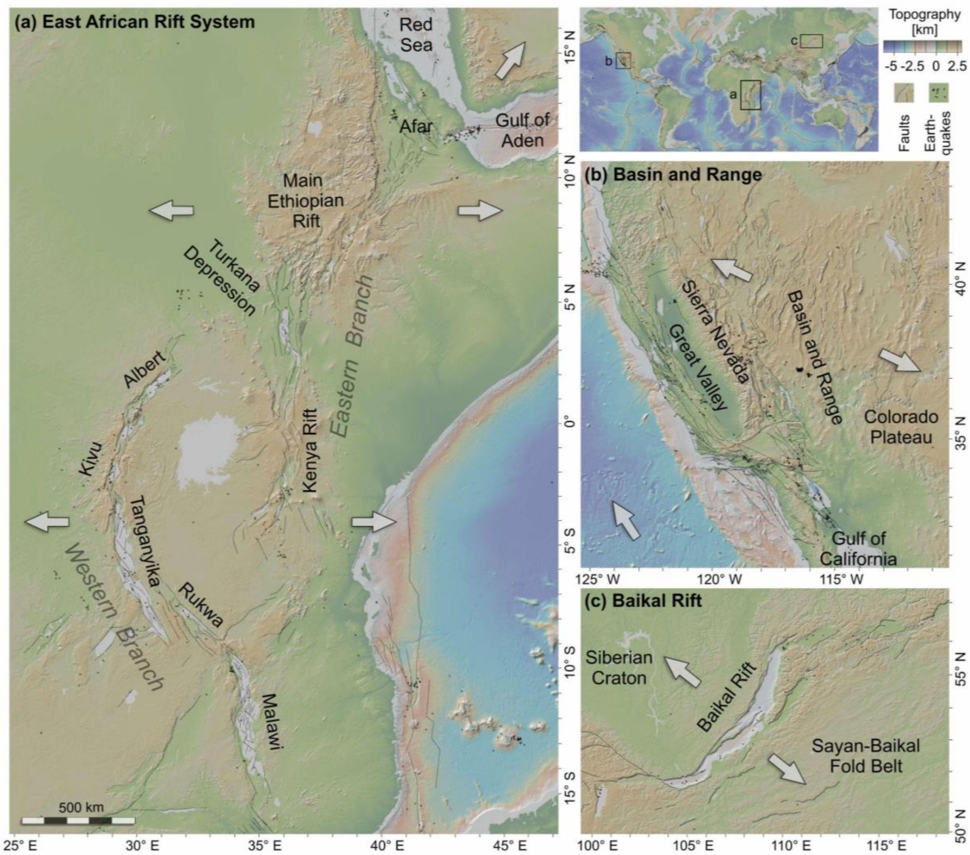


***Figure 2: Examples of continental rifts. (a)*** *The East African Rift System constitutes the largest currently active rift system worldwide. It comprises a magma-rich Eastern branch and a magma-poor Western branch. Most rift segments fall into the narrow rift category with a basin width of less than 100 km. Slip along massive border faults created elongate rift valleys with deep lakes and thick successions of sediments and volcanic deposits.* ***(b)*** *The Basin and Range region comprises large parts of the US American and Mexican cordillera. With more than 500 km width it is the type example of a wide rift. A broad array of subparallel faults created the characteristic horst and graben morphology that is mirrored in the name of the region.* ***(c)*** *The Baikal Rift in Central Asia is located at the suture of the Siberian Craton and the Palaeozoic Sayan-Baikal fold belt. It features narrow fault-bounded basins and hosts the deepest and most voluminous freshwater lake of the world. Images have been created with GeoMapApp version 3.6.14 (www.geomapapp.org) using topography data of Ryan et al., (2009). Fault traces are depicted as black lines based on the GEM Global Active Faults Database (Styron and Pagani, 2020). Earthquakes are shown as black dots based on the USGS-ANSS catalogue (time range 1960-2021; magnitude larger than 5; https://earthquake.usgs.gov/earthquakes/). White arrows (simplified from Stamps et al., 2018; McQuarrie and Wernicke, 2005; Sankov et al., 2014) depict large-scale extension directions. Maps are shown in Mercator projection at approximately the same scale.*

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


Sedimentary basins are a second key feature of rift environments. Active normal faulting leads to relative subsidence of rocks above the fault (the hanging wall) and thereby creates a depression that is often filled with fresh water, such as in the deepest lakes of the world – Lake Baikal (Central Asia), Lake Tanganyika and Lake Malawi (East African Rift) (Fig. 2). In addition, rift depressions can accommodate up to several kilometres of alluvial, lacustrine or marine sediments. Stratigraphic sedimentary layers formed during this process can be identified in seismic reflection images or directly accessed in drilling campaigns and provide an important record for tectonic evolution (Gawthorpe and Leeder, 2000). Sedimentary basins in rifts and rifted margins host a major fraction of sedimentary rocks worldwide (Straume et al., 2019) and fluid flow within these basins plays a major role in the generation of georesources (Section 4).

All rifts exhibit magmatic and volcanic features, such as dikes, sills, calderas, cones and lava flows (Fig. 3). However, the degree of magmatism can vary drastically – from kilometre-thick flood basalts of the Ethiopian traps (Sembroni et al., 2016) to mere exhalations of volcanic gases, such as in the Central European Eger Rift (Kämpf et al., 2013). The amount of volcanism is controlled by partial melting of mantle rocks, which is decisively governed by mantle temperature and to a lesser degree by mantle ascent rate. Hence, volcanic rifts such as the eastern branch of the East African Rift, and magma-rich rifted margins such as the Norwegian-Greenland conjugates, are often found in close proximity to mantle plumes (Steinberger and Steinberger, this volume), where the mantle temperature is elevated above ambient temperatures by more than 100 °C (Rooney et al., 2012).

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


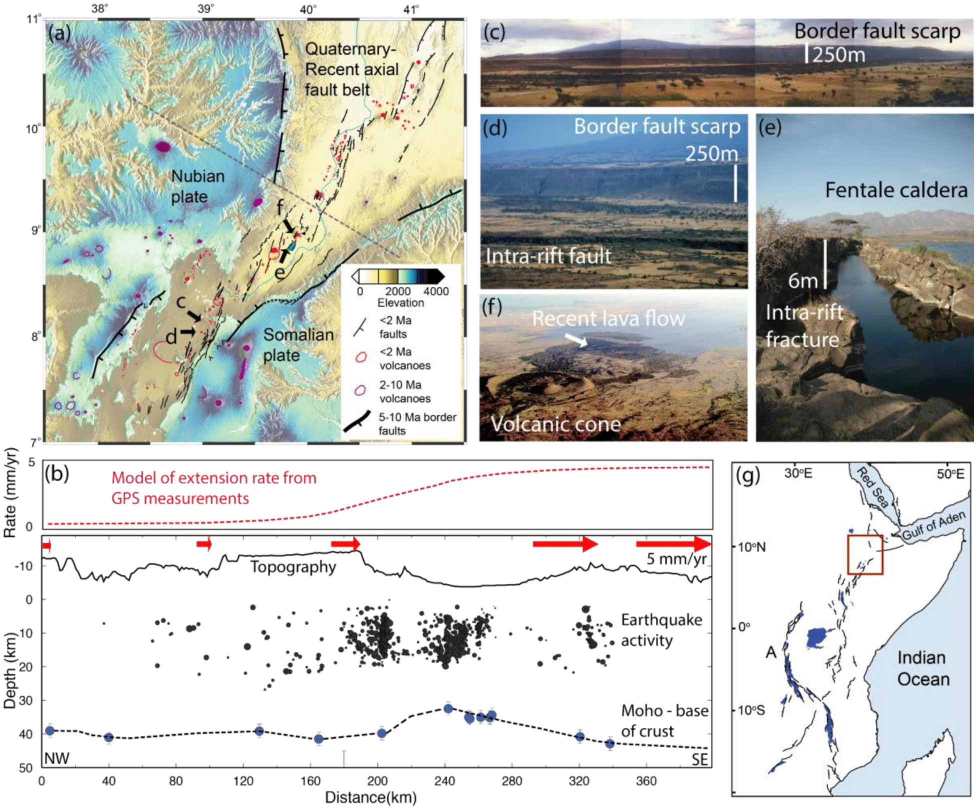


***Figure 3**: **Observations of rifts.** **(a)** Digital Elevation Model (DEM) of the Ethiopian rift showing major border and intra-rift faults in black. Active intra-rift and flank volcanic centres shown in red, with extinct rift flank volcanic centres marked in purple (modified from Maccaferri et al., 2014). **(b)** Bottom panel shows a cross section of topography, earthquake locations (Keir et al., 2006) and Moho depth (Stuart et al., 2006) on the line of section marked on the map of (a). The top panel and arrows show a model of GPS-derived surface velocities across the rift relative to a stable Nubian plate (Birhanu et al., 2016). The largest gradient in change in velocities occurs across the topographic rift valley and above where most seismicity occurs. **(c-f)** Field photographs (by Derek Keir) of faults and volcanic centres with locality and viewing direction shown with the labelled arrows in the map of (a). **(g)** The East African rift showing the location of the map in (a).*

### 2.2 The rifting process and its structural variability

The large variety of continental rift geometries has been classified in terms of first-order categories, such as rift symmetry, width, obliquity and linkage (Şengör and Natal'in, 2001). Understanding the underlying processes that cause particular rifts to fall into one or the other category has been the focus of geodynamic studies for many decades (e.g. Buck, 1991; Ziegler and Cloetingh, 2004; Sapin et al., 2021).

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


Identifying and understanding why some rifts are symmetric, but others asymmetric, spawned a long-standing issue in the rift community. The essence of this issue is whether rifts evolve in 'pure shear' stretching where lithospheric thinning, isostatic subsidence, and heat flow are distributed uniformly across the rift (McKenzie, 1978) (Fig. 4c), or whether they are governed by 'simple shear' stretching where the rift is dissected by a major inclined fault that generates laterally variable subsidence and heat flow patterns (Wernicke, 1985) (Fig. 4d). Both models have their merits and can be useful in describing the evolution of particular rifts. A single controlling fault is required for the 'simple shear' rifting models and is expressed in regions where the brittle crust is underlain by a low-viscosity crustal layer (Huismans et al., 2005). This way normal-fault activity can be balanced by lower crustal flow. Large-offset normal faults at the upper end of the major fault can rotate to a low angle, such as observed in the Basin and Range province (Wernicke, 1985). Due to its simplicity and elegant mathematical representation, the pure shear model, on the other hand, remains the default model to analyse the thermal and subsidence evolution of both rift basins and rifted margins. Pure and simple shear deformation may also both occur during rifting in a time-dependent manner such that rifts can switch between symmetric and asymmetric extension as the thermomechanical environment evolves (Huismans and Beaumont, 2003).

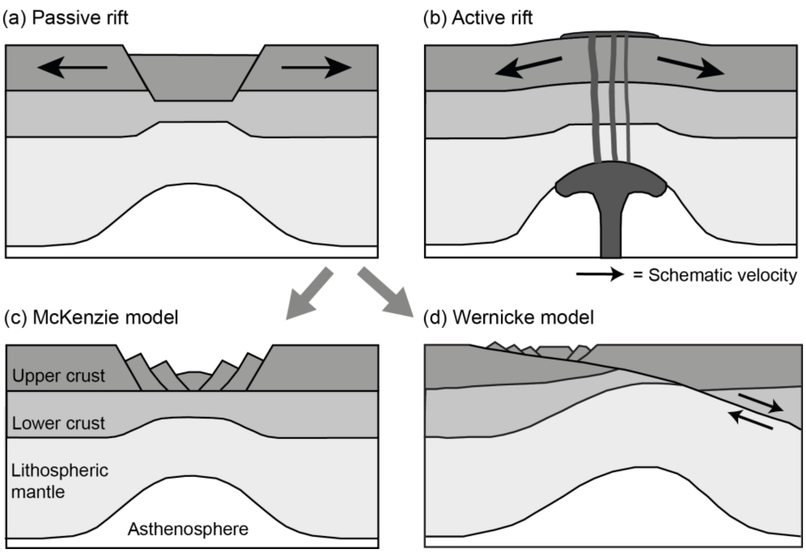


***Figure 4: Conceptual rift models***. ***(a)*** *Far-field forces related to plate tectonics (such as the pull of subducting slabs) cause continental extension in the passive rifting model. The name of the concept emphasises the passive role played by the mantle.* ***(b)*** *In active rifting, an active upwelling of warm mantle material causes volcanism and surface uplift. The plates glide gravitationally away from the uplift, thus leading to extension.* ***(c)*** *The McKenzie model (a form of passive rifting) envisages thinning of the upper crust, lower crust and lithospheric mantle in a pure shear mode (McKenzie, 1978).* ***(d)*** *In the Wernicke model (also a form of passive rifting), simple shear deformation along a low-angle detachment fault causes thinning of the upper crust that is offset from thinning of the lower crust (Wernicke, 1985).*

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


The width of present-day rift systems varies between several tens of kilometres, such as in the Baikal Rift, the Rio Grande Rift and large parts of the East African Rift (called 'narrow rifts'), to hundreds of kilometres, such as in the Aegean Rift or the Basin and Range Province ('wide rifts') (Figs 1, 2). The geodynamic factor controlling rift width is the existence of a low-viscosity crustal layer that decouples deformation within the brittle upper crust from the lithospheric mantle, as described in numerical and analogue experiments (Buck, 1991; Brun, 1999). If a thick layer of low-viscosity lower crust exists, brittle faulting is restricted to the upper crust. In that situation, lower crustal flow compensates the thinning caused by upper crustal fault activity and leads to simple-shear deformation on a crustal scale. This lower-crustal flow also impedes overall crustal thinning and the formation of a narrow rift. Such a low-viscosity crustal layer exists for comparably hot crust, which can be found in orogenic plateaus such as the Basin and Range and in collapsed orogens such as the Aegean Sea. In the opposite case where the crust is strong, deformation in crust and lithospheric mantle are tightly coupled so that faults cut deep into the lithosphere, forming a narrow rift. This setting can be found in comparably cold rifts that are marked by deep earthquake activity, like the Baikal rift or the central and southern part of the East African Rift System (Albaric et al., 2009; Craig et al., 2011).

Even though we tend to analyse rifting as a 2D process for simplification, with stretching perpendicular to a straight basin trend (e.g. Fig 4), along-strike changes in rift trends are documented in almost all rifts worldwide (Fig. 1a), often leading to variable rift axis orientations along neighbouring rift segments. Oblique rifting occurs, for example, in the Main Ethiopian Rift, the Rukwa Rift (Fig. 2a), as well as the Gulf of California, and shaped the Gulf of Aden and the Equatorial Atlantic rifted margins (Fig. 1a). A global analysis of rift activity over the last 230 million years revealed that more than 70 per cent of all major rifts exceeded an obliquity of 20 degrees (Fig. 1a; Brune et al., 2018). Analogue and numerical modelling experiments show that in the initial stages of oblique rifting, fault networks form en-echelon patterns where the fault plane dips obliquely to the far-field extension direction (Withjack and Jamison, 1986; Brune, 2014; Duclaux et al., 2020). This means that faulting is intrinsically 3D, making tectonic analysis and fault reconstruction difficult to perform via seismic and conceptual 3D cross sections. Rift axis obliquity further affects the overall width of rift systems as increased obliquity is taken up by more-or-less vertical strike-slip faults, which should lead to narrower rifts. Hence, highly oblique rifted margins are expected to be narrow, while orthogonal margins can be wide or narrow. Testing this hypothesis in a series of case studies involving rifted margins worldwide confirmed the expected correlation, but also highlighted large uncertainties in observed margin widths and inferred obliquity (Jeanniot and Buiter, 2018). Improved syn-rift plate reconstructions and fault block restorations are required to reduce uncertainties in future studies.

A further aspect of 3D rift evolution is the linkage of individual rift segments, which is preceded by a complex mechanical interaction. The ongoing linkage of the Kenyan with the Ethiopian rifts as well as the linkage between the Gulf of Aden and Red Sea rifts in Afar (Fig. 2a) generates wide domains of fault activity that are progressively focussed toward the central

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


portions of the rift (Ebinger et al., 2000; Corti et al., 2019; Pagli et al., 2019). These examples illustrate that linkage across segment boundaries involves stress rotations and fault activity that locally overprints existing structures. Numerical studies show that the strike-perpendicular offset of two segments strongly affects whether segment linkage occurs via oblique linkage, transform linkage or by microplate formation (Allken et al. 2012; Neuharth et al., 2021) and that the selected mode may dominate deformation until break-up is achieved. Natural examples for such microplate formation include the Flemish Cap at the Canadian Atlantic margin and the São Paulo Plateau offshore Brasil (Neuharth et al., 2021).

### 2.3 Force balance of rifting

The major tectonic processes driving rifting are subduction ('slab pull' caused by sinking of dense lithospheric plates into the underlying mantle, Schellart, this volume; Billen, this volume), mantle flow (exerting stresses at the base of the lithosphere), and gradients in gravitational potential energy that are caused by topography variations. The relative impact of the forces differs between individual rifts, leading to the distinction between 'active' rifts that are driven by buoyant mantle upwelling and 'passive' rifts, which are fueled by far-field forces such as slab pull (Fig. 4a,b). The negative buoyancy of subducting cold lithosphere is clearly a key driver of plate tectonics as plates connected to large subduction zones move significantly faster than others (Forsyth and Ueda, 1975; van Summeren et al., 2012). Slab pull is therefore the likely reason why the Woodlark Rift (Papua New Guinea) that is located on the downgoing side of the New Britain subduction zone is extending at a comparably high speed of up to 30 mm/yr (Petersen and Buck, 2015; Yu et al., 2022). The East African Rift on the other hand is almost entirely surrounded by mid-ocean ridges. Here, gravitational potential energy gradients resulting from dynamic topography and lateral buoyancy variations in the lithosphere are thought to provide the driving force of continental rifting (Moucha and Forte, 2011; Rajaonarison et al., 2021), which occurs at the more typical rates of less than 10 mm/yr (Birhanu et al., 2016; Brune et al., 2016).

Plate tectonic driving forces act constantly on continental interiors, but in order to initiate continental rifting, the tensile driving forces have to exceed the strength of the lithosphere over large areas. To achieve this, the forces must increase and/or the lithosphere strength decrease. Rifting often reactivates on former suture zones, where multi-scale lithospheric weaknesses exist in the form of crustal thickness variations, faults, shear zones, and foliations (Buiter and Torsvik, 2014). The impact of such tectonic inheritance has been well described in the East African Rift (Daly et al., 1989; Kolawole et al., 2018) where pre-existing Proterozoic structures have been exploited during Cenozoic extension. Another example is the Norwegian margin where collisional inheritance from the Caledonian orogeny exists in the form of thrust faults and long-term thermal weakening affected the tectonic evolution during Permo-Triassic, Jurassic and Cenozoic rifting episodes (Schiffer et al., 2020; Peron-Pinvidic et al., 2022). Notably, the North Atlantic constitutes the key example for the Wilson-cycle concept (Wilson 1966; Wilson et al., 2019), which describes the repeated reactivation of plate boundaries during orogeny and rifting. However, Wilson cycles and inheritance do not only play a role for continent-scale rift tectonics. Both the Pyrenees and the European Alps are built on previous

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


rift systems and extensional structures have been exploited during the orogeny (Mouthereau et al., 2014; Mohn et al., 2014).

Once rifting initiates, the lithospheric strength undergoes a continuous evolution that is controlled by weakening and strengthening feedbacks between several processes acting on a vast range of spatial and temporal scales. One weakening process is rheological strain localisation where the rock's yield strength is progressively reduced by accumulating damage. Strain-induced weakening can occur both in the brittle regime through gouge formation or elevated pore pressure (Mandl, 1988; Rice, 1992) as well as in the ductile regime via diffusion, dislocation or pressure solution creep. Weakening can also occur due to chemical reactions, for instance during serpentinization of the mantle, which reduces the frictional strength of the altered rocks (Escartín et al., 1997). Another weakening process is diking where vertical sheet-like magma intrusions are emplaced into the crust. These intrusions occur during relatively short-lived rifting episodes lasting between days and years (Wright et al., 2006). Strain localises within the narrow dike during intrusion, with dike-induced stress changes and heating of the surrounding rock favouring continued diking and stretching (Buck, 2006; Daniels et al., 2014). Erosion of rocks is a further weakening process as it removes material, thus reducing the pressure-dependent brittle strength of rocks, which promotes fault activity. Sedimentation is conversely a strengthening process, as the added material increases vertical stress, thus increasing brittle strength.

In addition to the above processes, the rate of rifting as well as the temperature distribution within the rifting lithosphere play major roles in its strength evolution due to the highly nonlinear dependence of viscosity on these parameters. If rifts are dominated by heat advection, hot, upwelling asthenosphere successively weakens the rift, leading to a continuous strength loss. Sediments with a low ability to conduct heat away can increase this effect by trapping heat below like a thermal blanket (Sandiford, 1999). Weakening processes may lead to a significant loss of rift strength, which may induce a run-away effect between accumulating damage and divergence rate that results in abrupt rift accelerations prior to break-up (Brune et al., 2016). However, in slow rifts which experience a large degree of conductive cooling from the surface, the velocity-reduction effect on rift strength may be offset by an increase through time when upwelling strong mantle rocks cool (Kusznir and Park, 1987; van Wijk and Cloetingh, 2002). Strengthening processes like cooling may ultimately prevent tectonic activity, thereby generating so-called failed rifts, such as the West and Central African Rift Systems, or the Mid-Continent Rift in North America (Fig. 1).

## 3. From rift to mid-ocean ridge to form a rifted margin

### 3.1. The continent-ocean boundary / transition

Continental break-up is a widely used term that designates the end of rifting and the beginning of oceanic spreading. Implicitly, it refers to a unique, instantaneous, and localised process that 'breaks' the continental lithosphere, after which new oceanic lithosphere is produced during ongoing seafloor spreading. The simplicity of the definition contributed to the term's repeated usage in plate tectonics. The advent of newer geophysical analyses and geological studies

https://doi.org/10.5194/egusphere-2022-139
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shows that the transition from continental crust to oceanic crust is however not as simple as previously theorised.

Continental rifted margins and oceanic spreading centres are governed by two very distinct geological processes, both leading to the formation of new basement: lithospheric tectonic extension and asthenospheric magmatic accretion, respectively. Break-up refers to the demarcation between these two fundamental processes in time and space. Depending on the magmatic content, the border is interpreted as a line (the 'COB' for ‘continent-ocean boundary’) or as a transition (the ‘COT’ for ‘continent-ocean transition’) (Fig. 5). However, apart from this magma-rich (COB) and magma-poor (COT) distinction, no formal definition exists in the scientific literature (Eagles et al., 2015). This means that the transition from the continental rifted margin to the oceanic domain is still largely unknown. By definition, the oceanic domain encompasses the areas of new igneous basement that are strictly oceanic in origin. Although this first-order definition sounds straightforward, the distinction with the distal margin is not simple.

From studies of slow-spreading ridges (Reston and Ranero, 2011; Sauter et al., 2013), we today recognise that oceanic crust can form by both magmatic additions (the standard three-part description, Penrose Field Conference on Ophiolites, 1972) as well as by tectonic processes (Reston, 2018; Cannat et al., 2019). Escartin et al. (2008) showed that 50% of the Mid-Atlantic Ridge system has been shaped by detachment faults and core complexes that transport deeper rocks to the Earth’s surface. Interestingly, oceanic and continental core complexes structurally resemble each other (Whitney et al., 2014). These observations question the origin and nature of the initial magmatic formation of 'oceanic crust' as opposed to tectonic processes occurring in the distal rifted margins. The existence of 'transition zones' where processes would gradually change from rifting to drifting is regularly advocated. These zones are often called 'proto-oceanic' or ‘embryonic-oceanic’, but are still poorly characterised (e.g. Gillard et al., 2015).

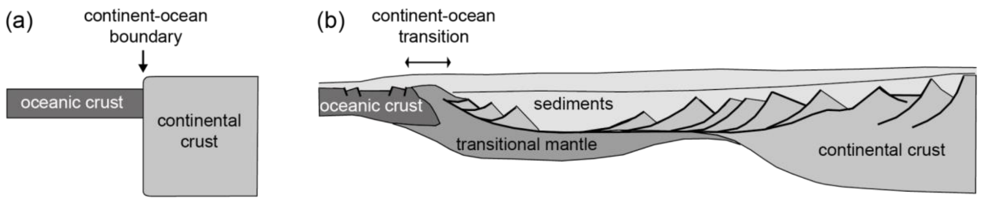



***Figure 5: Concepts of rifted margin architecture. (a)*** *Early studies depicted the transition from continent to ocean as abrupt. This view juxtaposes continental to oceanic crust along what can be mapped as a continent-ocean boundary line. Inspired by Wegener (1912).* ***(b)*** *Modern views see the transition from continent to ocean as gradual, encompassing tilted continental blocks and regions of exhumed and altered mantle. This view implies a continent-ocean transition zone, rather than a boundary. Redrawn from Peron-Pinvidic et al. (2013) with permission from Elsevier.*

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


### 3.2. Faulting and mantle exhumation

The nature of the transitional crust in the regions towards the oceanic crust can be described in different structural perspectives. Most models refer to large-scale faults in the continental crust, usually termed 'detachment faults' (Wernicke, 1985 (Fig. 4d); Lister et al., 1986; Davis and Lister, 1988). These faults are specific because of their length and the displacement they account for (usually > 20 km). Their geometry typically includes multiple parts: the steeply dipping deeper parts are the most active, whereas the shallow dipping parts are instead interpreted as segments that have been flexurally rotated during unroofing after their main phase of activity (Buck, 1988; Tucholke et al., 1998). Rolling-hinge-type detachments are often invoked as the driving mechanism for exhumation of upper crustal rocks (Lavier et al., 1999), and 'flipping detachment' models provide an efficient mechanism for exhuming important surfaces of mantle to the seafloor during final rifting and magmatic accretion at slow to ultraslow spreading centres (Gillard et al., 2015; Reston, 2018; Reston and McDermott, 2011). Based on numerical experiments of continental rifting, Naliboff et al. (2017) show that the life cycle of rift faults forms a sophisticated activity pattern with phases of fault-initiation, fault-activation, fault-linkage, fault-cross-cutting, fault-deactivation and possible fault-reactivation (Naliboff et al., 2017). Building on these experiments, Peron-Pinvidic and Naliboff (2020) propose a scenario where mantle exhumation at the final stages of rifting operates with multiple concave detachment faults that successively cut the seafloor at the rift axis, migrating off-axis and deactivating when the hanging-wall moves away. The resulting crust is an amalgamation of different lithologies, exhumed from various depths at various times, what would fit observations reported from various site studies, such as the West Iberia-Newfoundland and Norway-NE Greenland margins (Fig. 6). However, these numerical simulations do not include magma, fluid circulation and serpentinisation processes, which may well influence the deformation history of the fault system (e.g. Bickert et al., 2020).

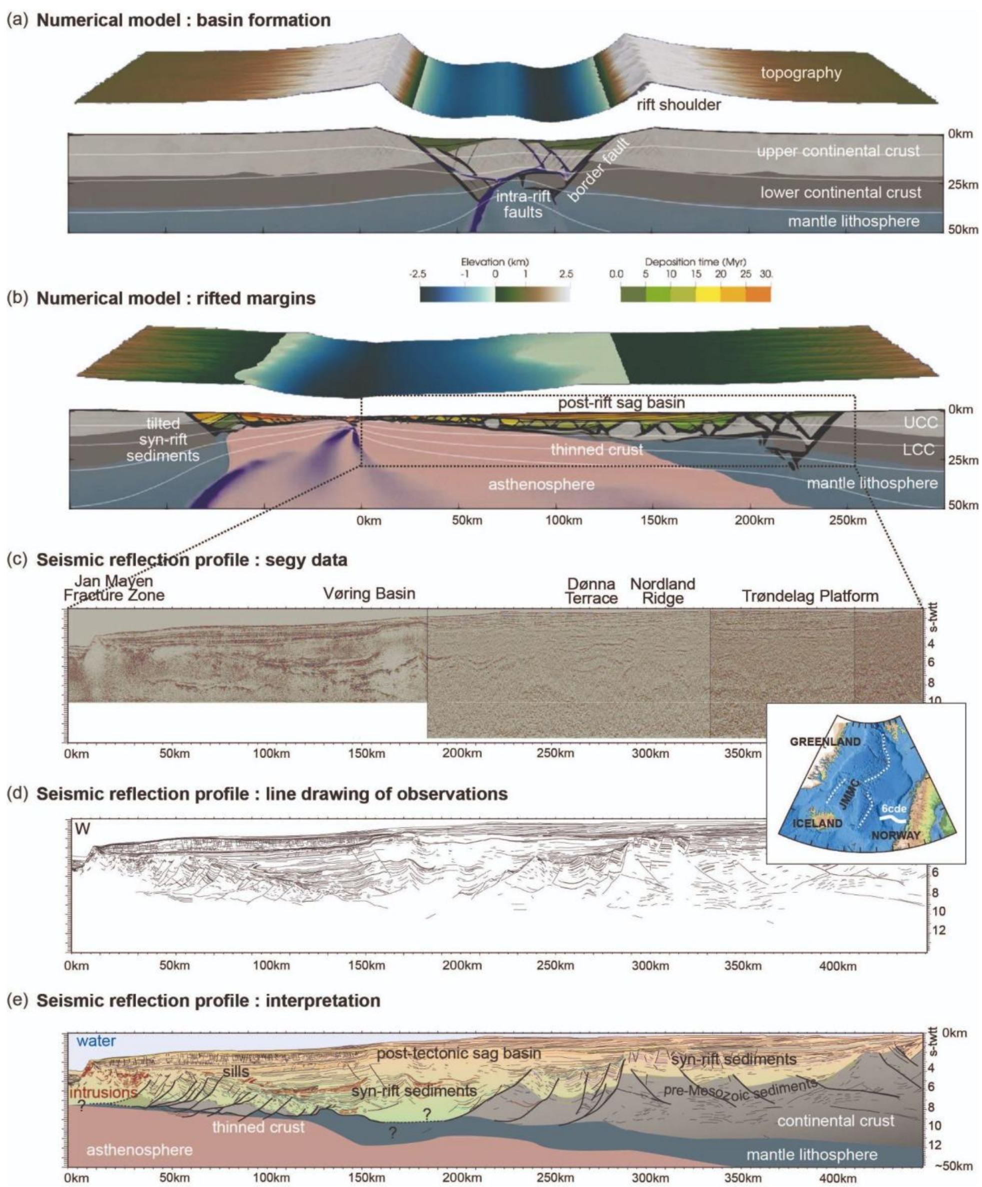
### 3.3. Break-up and post-rift evolution

The final break-up stage defines two conjugated rifted margins that are now separated by a growing ocean. In some settings the breaking of the lithosphere is accompanied by excess magmatic activity most commonly attributed to elevated mantle temperatures (White et al., 2008) from a plume (White and McKenzie, 1989) and/or vigorous mantle convection (Ligi et al, 2011). In the case of the Northeast Atlantic opening, the excessive volcanic activity led to the formation of a Large Igneous Province (LIP) including sills, lava flows, and lava deltas (e.g. Saunders et al., 1997; White et al., 2008). The progressive accumulation and seaward rotation of the thick (up to several kilometres) lava flows and intercalated sediments form seaward dipping reflectors (SDR). Such specific structures are observed and mapped in the Northeast Atlantic, from the southern Rockall Trough and Hatton Bank (west of Ireland and Scotland) up to the Lofoten margin (offshore northern Norway) and over the Faroes region (Horni et al., 2017). LIPs have been interpreted at many other rift locations, such as in the South Atlantic (the Paraná-Etendeka Flood Basalts), and in the Ethiopian Afar region (the Ethiopian Flood Basalts) (Fig. 1b).

The post-rift evolution of rifted margins is usually considered as relatively tectonically quiet. The cooling of the basement leads to a gradual subsidence of the whole margin, creating

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


accommodation space potentially filled with sediments. In some settings, the post-rift sedimentary thickness can be significant (e.g. > 15 km in the distal Mid-Norwegian margin; Straume et al., 2019; Fig. 6c-e). However, the absence of tectonic activity does not mean the rifted margins are geologically quiet. The steep bathymetric slopes generated during the margin cooling and related sedimentary accumulation can lead to slope ruptures and rock slides (Section 4).



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Preprint. Discussion started: 19 April 2022


***Figure 6**: **Numerical model of rift evolution and comparison to seismic reflection data**. **(a)** Extract of a numerical model of rift evolution, at an early rift stage. The formation of narrow rifts (less than 100 km wide) and associated sedimentary basins is achieved by border faults. Complex fault evolution dissects and thins the crust ultimately leading to break-up. Syn-tectonic sedimentation interacts with faulting while post-rift sediments form slowly subsiding sag basins. Image modified from Neuharth et al. (2022). **(b)** Extract of a numerical model of rift evolution, at breakup stage. The two conjugate rifted margins are formed with an upper plate setting (left hand margin) and a lower plate setting (right hand margin). The margins are asymmetric with the upper plate margin showing abrupt crustal thinning which operated over less than 50 km, while the lower plate margin shows a much more complex structural architecture which operated over more than 200 km. Image modified from Neuharth et al. (2022). An animation of model evolution is available at bit.ly/3CSyv3s. (cde) Seismic reflection profile from the Vøring Mid-Norwegian margin in the North Atlantic Ocean (see inset for location), selected as representative of the Atlantic-type rifted margins. **(c)** segy version without interpretation, **(d)** line drawing of all observations, **(e)** interpretation of the line drawing with a colour-code similar to Figs 6ab. Modified from Peron-Pinvidic and Osmundsen (2016). JMMC Jan Mayen Mico-Continent. UCC Upper Continental Crust. LCC Lower Continental Crust. s-twtt: second two-way-travel-time.*

## 4. Rifting and society

Rifting impacts the wider environment and resource potential of the rift region on a range of spatial and temporal scales, from geological hazards to mineral resources and climate change. In the short term and on local scales, probably the most obvious impacts of continental rifting are earthquakes and volcanic activity (Fig. 7). These are potentially hazardous to population and infrastructure, especially in the densely populated rift valleys, where thick fertile soil and fault-bound deep fresh-water lakes are found. Plate extension during continental rifting involves the steady accumulation of elastic strain in the brittle crust, which is typically released as earthquakes along rift valley faults. The long-term rate of plate motions at rifts is typically rather slow at less than 10 mm/yr (Brune et al., 2016), and therefore the earthquakes releasing this strain are generally less common in rifts than along faster moving transform and convergent plate boundaries. However, while plate motions may be slow, the fact that continental rifts can form in thick and strong continental lithosphere means that the brittle elastic layer can store a significant amount of energy prior to breaking, potentially resulting in earthquakes as large as M7-8 (Craig et al., 2011; Liu et al., 2007). This principle is demonstrated eloquently in the East African rift, where largest earthquake magnitudes are observed in regions where the rift is generally younger (<10 Myrs old), extending slower (<10 mm/yr), and cutting still thick and strong cratonic lithosphere (Craig et al., 2011; Hall et al. 2017). In contrast, the faster plate extension (~20 mm/yr) observed where rifting has just about broken the continent, such as the Red Sea and western part of the Gulf of Aden, causes more frequent but lower magnitude (M<5.5) earthquakes since the plate is thinner, hotter and weaker from 30-35 million years of rifting (Hall et al., 2017). In addition, indirect hazards, such as ground cracking and landslides associated with ground motion are in many regions, such as East Africa, more impactful than the earthquakes themselves (e.g. Asfaw, 1982) (Fig. 7c).

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


Volcano activity is also episodic and poses a major hazard to life and infrastructure as well as being a source for natural energy. In the volcanically active East African Rift, multiple basaltic lava flows have occurred during the last 2 decades that have destroyed infrastructure. Examples are the 2002 Nyiragongo eruption that flowed through the city of Goma in the Democratic Republic of Congo (Tedesco et al., 2007) and the Plinian eruption of basaltic tephra from Nabro in 2011, that led to closure of Arabian and East African airspace for several days (Goitom et al., 2015). Fortunately more explosive silicic volcanism is less frequent with large globally impactful caldera-forming eruptions only occurring at ~100 kyr intervals (Rowland et al., 2010; Siegburg et al., 2018). These types of eruptions pose a risk assessment challenge to society since they are unlikely to occur during any single human lifetime, yet the geological record contains significant evidence that several globally impactful, major caldera-forming super eruptions have occurred from rift valley volcanoes during the last few hundred thousand years (Hutchison et al., 2016). A number of these occurred in the northern East African rift and potentially drove environmental changes that have impacted the early evolution and dispersal of homo-sapiens (Hutchison et al., 2016). Rift related magmatic activity can, however, also be a positive resource such as in aiding hot fluid flow that can be exploited for geothermal energy. The majority of fluids in geothermal systems are sourced from meteoric water being heated by shallow magma-reservoirs and are focused back upwards to the surface along extensional faults in the top few kilometres of the crust (Wilkes et al, 2017) (Fig. 7a,b). A number of countries such as Iceland and Kenya use ridge/rift related geothermal power as major national sources of energy.

In the long term but at a global scale, continental rifting is an integral ingredient of plate tectonics and responsible for the ever-changing configuration of Earth's land and oceans, with associated changes in global ocean circulation, continental topographic and weathering patterns, and ice accumulation (Raymo and Ruddiman, 1992). Additionally, recent research suggests that rift-related plate thinning and associated magmatic activity can potentially affect long-term climate by transporting and releasing volatiles such as $H_2O$, $CO_2$, and $SO_2$ from the deeper Earth to the atmosphere (Fig. 7a, b). Measurements of $CO_2$ release from currently active rifts are sparse, but those that exist suggest that the volumes may significantly impact global atmospheric $CO_2$ concentrations and potentially cause major shifts in global climate (Muirhead et al., 2020; Brune et al., 2017; Lee et al., 2016). The geological record coupled with numerical models suggests this is particularly the case during rifting of thick cratonic lithosphere, in which exceptionally high concentration of $CO_2$ stored at the base of thick cratonic lithosphere can be disturbed and released (e.g., Muirhead et al., 2020).

Once rifting has broken the continent, the new rifted margins can remain geologically dynamic for tens of millions of years with implications to the environment and society. The topographic relief created by syn-rift border faulting and uplift can be several kilometres high, locally making the climate cooler, more humid and habitable. Processes such as erosion that unloads the lithosphere can cause continued uplift, flexure and earthquake activity for tens of millions of years (Gunnell and Fleitout, 1998; Redfield and Osmundsen, 2015; Silva and Sacek, 2022). Rifted margins can have high, sometimes juvenile topography, as in East Greenland and West

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


Norway. The cause of such topography in a tensile stress field, and whether the mountains represent relatively recent uplift or not, is debated (Nielsen et al., 2009; Gabrielsen et al., 2010). Ideas put forward to explain the margin orogens include glacial erosion, offshore rifted margin architecture, isostatic uplift and a long-distance finger of a mantle plume (Medvedev et al., 2013; Koptev et al., 2017; Redfield and Osmundsen, 2013). Rifted margins can also be volcanically active, such as along the Red Sea margins in Saudi Arabia and Yemen. Mantle processes such as vigorous convection created by the steeply dipping base of the rifted margin plate are thought to be responsible for the melt supply in these cases (Ebinger and Belachew, 2010).

The spatially large and deep sedimentary basins found in some continental rifts and rifted margins are globally the most common setting for the formation and accumulation of hydrocarbons, making rift-related research at the centre of this sector of the energy economy. Some basin-fill deposits such as the evaporite potash are directly a mineral resource. Veining from flow of mineral rich fluids along faults related to deep penetrating detachments, and also shallower hydrothermal systems are also a valuable resource, particularly for metals (Zappettini et al., 2017). Fortunately, the porous and permeable rock formations that make good hydrocarbon reservoirs are also capable of storing vast amounts of $CO_2$, making large-scale carbon capture and storage (CCS) a potentially important contributor to future global $CO_2$ emission reductions (IPCC, 2005).

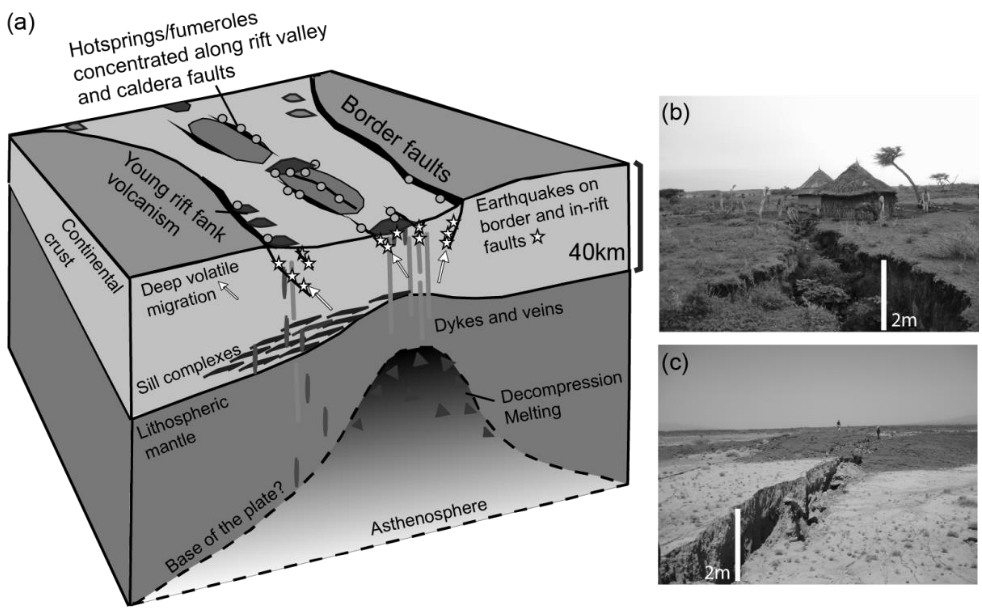


***Figure 7: Earthquakes and geothermal potential of rifts. (a)*** *Cartoon sketch of a magnetically active continental rift showing zones of surface faulting and volcanism, and the subsurface processes associated with these.* ***(b)*** *Photos of discrete and sudden fissuring and faulting events associated with rainfall induced subsidence and* ***(c)*** *earthquake swarms. Photos by Derek Keir.*

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


## 5. Summary and perspective

The combination of lithospheric and mantle driving forces that overcome lithospheric strength and stretch the continental lithosphere is expressed in spatially and temporally varying geometries of rift valleys and rifted margins. Rift systems are commonly characterised by normal faults, sedimentary basins and often by earthquakes and volcanism. But rifts differ in extension rate and direction, symmetry, width, fault patterns, as well as amounts of magma and sediments. Some rifts will evolve to break a lithospheric plate (called a success), whereas others will stall (called a failure), as determined by the interplay of the driving forces with weakening and strengthening processes. The successful rifted margins are characterised by a complex transition between continent and ocean, with an exact definition of this transition still lacking. Post-rift margins are not passive, as shown by uplift, dike intrusions, earthquakes and landslides, which is why we describe them as 'rifted margins' rather than 'passive margins'.

Earth scientists have accrued an extensive amount of information about continental rifts and rifted margins as they have been exploited for their hydrocarbon resources for many decades. This has yielded a wealth of geophysical data, and without commercial enterprises financing seismic reflection acquisition lines and borehole drilling, we would likely not have had the insight in rifts and rifted margin architecture that we have today. With the transition to sustainable energies, the exploration focus is shifting to recovery improvement, alternative energy sources (e.g. hydrogen and geothermal) and storage of $CO_2$. Whether this means a change in data acquisition remains to be seen. We express the hope that changes in exploration focus can be accompanied by increased open sharing of the geophysical and geological data that has been acquired in rift regions over the past many decades.

Current research in rifting covers a wide spectrum, as exemplified in the many topics covered in the presentations of the Rift and Rifted Margins Online Seminar (from 2020, bit.ly/37xiBQn).We expect rifts to remain a research focus for many years to come. First and foremost because of their societal impact, where earthquake and volcanic hazards as well as energy and mineral sources call for an understanding of rift forming processes. Open questions in this active research field include: Are rifts geologically safe for long-term $CO_2$ storage? Why do some rifts and rifted margins have high topography, sometimes with active normal faulting and landslide risk? How is extensional strain distributed in rifts and what are the recurrence intervals of large earthquakes and volcanic eruptions? What are the major controls on hydrothermal fluid and deeper volatile migration through the lithosphere, and how do these interact with deformation and magmatic processes?

There is also an academic interest in rifts and rifted margins, as it is scientifically fascinating how a process that is underlain by the same physical principles is expressed in such geological variety. Many questions remain open: Why are some rifts successful, but others fail? How do we define break-up? As supercontinents are thought to be underlain by a warmer mantle, are rifts forming in supercontinents different from those forming in more moderately sized continents? How did rifting proceed on a warmer, early Earth? What is exactly the relation between rifts and hotspots and do rifts propagate away from or towards hot, weak regions?

How does repeated deformation, including its effect on rheology and geochemistry, impact rifts?

Do we currently have the data and techniques to solve these (and undoubtedly many other) open questions? We would argue that we have, but that data accessibility is unfortunately not equal for all. If we were given an unlimited financial budget, we would make all seismic and drill hole data available as open access. We would contribute to Seabed 2030 (https://seabed2030.org/) to map the bathymetry of the entire ocean floor in a resolution that would approach the topographic maps of the continents. We expect that such high-resolution ocean floor maps will better delineate the transition from continent to ocean, likely including the discovery of further continental blocks offshore rifted margins such as the knolls offshore western Australia. We would also propose further drilling to establish the nature and extent of microcontinents such as Jan Mayen (east of Greenland), of ridges as the Arctic Lomonosov Ridge, and of hotspot tracks, such as the Rio Grande Rise and the Walvis Ridge, undertaken recently by the IODP (International Ocean Discovery Program 391, www.iodp.org). We would significantly increase the density of GPS measurements in active continental rifts to aid strain mapping and seismic hazard assessment. This is important as the current instrumental seismic records are short relative to earthquake repeat times and may thus underrepresent large future earthquakes. As constraints on earthquake recurrence are globally poor in rifts, far more geological dating studies of past fault slip events (paleoseismology) are required to inform the likelihood of future fault behaviour. There are many avenues that remain to be explored and that we hope will increase our understanding of rift processes and their fascinating surface expressions.

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**References**

Albaric, J., Déverchère, J., Petit, C., Perrot, J., Le Gall, B., 2009. Crustal rheology and depth distribution of earthquakes: Insights from the central and southern East African Rift System. Tectonophysics 468, 28–41. doi: 0.1016/j.tecto.2008.05.021

Allken, V., Huismans, R.S., Thieulot, C., 2012. Factors controlling the mode of rift interaction in brittle-ductile coupled systems: A 3D numerical study. Geochem. Geophys. Geosys. 13, Q05010. doi: 10.1029/2012GC004077.

Asfaw, L.M., 1982. Development of earthquake-induced fissures in the Main Ethiopian Rift, Nature 297, 393-395.

Audet, P., Bürgmann, R., 2011. Dominant role of tectonic inheritance in supercontinent cycles. Nature Geosci. 4, 184-187. doi: 10.1038/NGEO1080.

Bickert, M., Lavier, L., Cannat, M.. 2020. How do detachment faults form at ultraslow mid-ocean ridges in a thick axial lithosphere? Earth Planet. Sci. Lett. 533, 116048.

Birhanu, Y., Bendick, R., Fisseha, S., Lewi, E., Floyd, M., King, R., Reilinger, R., 2016. GPS constraints on broad scale extension in the Ethiopian Highlands and Main Ethiopian Rift, Geophys. Res. Lett. 43, 6844– 6851. doi:10.1002/2016GL069890.

Brun, J.-P., 1999. Narrow rifts versus wide rifts: inferences for the mechanics of rifting from laboratory

experiments. Phil. Trans. R. Soc. Lond. A 357, 695–712. doi: 10.1098/rsta.1999.0349.
Brune, S., 2014. Evolution of stress and fault patterns in oblique rift systems: 3-D numerical lithospheric-scale experiments from rift to breakup. Geochem. Geophys. Geosyst. 15, 3392–3415. doi: 10.1002/2014GC005446.
Brune, S., Williams, S., Butterworth, N. et al., 2016. Abrupt plate accelerations shape rifted continental margins. Nature 536, 201–204. doi: 10.1038/nature18319.
Brune, S., Williams, S.E., Müller, R.D., 2017. Potential links between continental rifting, $CO_2$ degassing and climate change through time. Nature Geosci. 10, 941–946. doi: 10.1038/s41561-017-0003-6.
Brune, S., Williams, S.E., Müller, R.D., 2018. Oblique rifting: the rule, not the exception. Solid Earth 9, 1187–1206. doi: 10.5194/se-9-1187-2018.
Brune, S., Kolawole, F., Olive, J.-A., Stamps, S., Buck, W.R., Buiter, S., 2022. Geodynamics of continental rift initiation and evolution. In review at Nature Reviews: Earth & Environment. https://eartharxiv.org/repository/view/3144/.
Bryan, S.E., Ernst, R.E., 2008. Revised definition of large igneous provinces (LIPs): Earth-Science Reviews 86 (1), 175-202. doi:10.1016/j.earscirev.2007.08.008.
Buck, W.R., 1988. Flexural rotation of normal faults. Tectonics 7, 959-973.
Buck, W.R., 1991. Modes of Continental Lithospheric Extension. J. Geophys. Res.-Solid Earth 96, 20161–20178.
Buck, W.R., 2006. The role of magma in the development of the Afro-Arabian Rift System, Geol. Soc. London Spec. Publ. 259, 43-54, doi: 10.1144/GSL.SP.2006.259.01.05.
Buiter, S.J.H., Torsvik, T.H., 2014. A review of Wilson Cycle plate margins: A role for mantle plumes in continental break-up along sutures? Gondwana Research 26, 627-653. doi: 10.1016/j.gr.2014.02.007.
Cannat, M., Sauter, D., Lavier, L., Bickert, M., Momoh, E., Leroy, S., 2019. On spreading modes and magma supply at slow and ultraslow mid-ocean ridges. Earth Planet. Sci. Lett. 519, 223-233.
Corti, G., 2009. Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. Earth-Science Reviews 96, 1–53. doi: 10.1016/j.earscirev.2009.06.005.
Corti, G., Cioni, R., Franceschini, Z., Sani, F., Scaillet, S., Molin, P., Isola, I., Mazzarini, F., Brune, S., Keir, D., Erbello, A., Muluneh, A., Illsley-Kemp, F., Glerum, A., 2019. Aborted propagation of the Ethiopian rift caused by linkage with the Kenyan rift. Nature Comm. 10, 1309. doi: 10.1038/s41467-019-09335-2.
Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events: Comptes Rendus Geoscience 335 (1), 113-140, doi:10.1016/S1631-0713(03)00006-3.
Craig, T.J., Jackson, J.A., Priestley, K., McKenzie, D., 2011. Earthquake distribution patterns in Africa: Their relationship to variations in lithospheric and geological structure, and their rheological implications. Geophys. J. Int. 185, 403–434. doi: 10.1111/j.1365-246X.2011.04950.x.
Daly, M.C., Chorowicz, J., Fairhead, J.D., 1989. Rift basin evolution in Africa: the influence of reactivated steep basement shear zones. Geol. Soc., London, Spec. Publ. 44, 309–334. doi: 10.1144/GSL.SP.1989.044.01.17
Dana, J.D., 1863. Manual of geology, 823 pp. Digital version on https://archive.org/details/bub_gb_QjwDAAAAQAAJ
Daniels, K.A., Bastow, I.D., Keir, D., Sparks, R.S.J., Menand, T., 2014. Thermal models of dyke intrusion during development of continent–ocean transition. Earth Planet. Sci. Lett. 385, 145–153. doi: 10.1016/j.epsl.2013.09.018.
Davis, G.A., Lister, G.A., 1988. Detachment faulting in continental extension; perspective from the southwestern U.S. Cordillera. In: Clark, S.P., et al. (Eds.), Processes in continental lithospheric deformation. Geol. Soc. America Spec. Paper, 133–159.
Dewey, J.F., Burke, K., 1974. Hot spots and continental break-up: implications for collisional orogeny. Geology 2, 57–60.
Dietz, R.S., 1961. Continent and ocean basin evolution by spreading of the sea floor. Nature 190, 854-857.
Duclaux, G., Huismans, R.S., May, D.A., 2020. Rotation, narrowing, and preferential reactivation of brittle structures during oblique rifting. Earth Planet. Sci. Lett. 531, 115952. doi:

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


10.1016/j.epsl.2019.115952

Ebinger, C.J., Yemane, T., Harding, D.J., Tesfaye, S., Kelley, S., Rex, D.C., 2000. Rift deflection, migration, and propagation: Linkage of the Ethiopian and Eastern rifts, Africa. GSA Bull. 112, 163–176. doi: 10.1130/0016-7606(2000)112<163:RDMAPL>2.0.CO;2.

Ebinger, C., Belachew, M., 2010. Active passive margins. Nature Geosci. 3, 670–671. https://doi.org/10.1038/ngeo972

Ebinger, C., Scholz, C.A., 2011. Continental Rift Basins: The East African Perspective. In: Busby, C., Azor, A. (Eds.), Tectonics of Sedimentary Basins. John Wiley & Sons, Ltd, Chichester, UK, pp. 183–208.

Eagles, G., Pérez-Díaz, L., Scarselli, N., 2015. Getting over continent ocean boundaries. Earth-Science Reviews. doi: 10.1016/j.earscirev.2015.10.009.

Escartín, J., Hirth, G., Evans, B., 1997. Effects of serpentinization on the lithospheric strength and the style of normal faulting at slow-spreading ridges. Earth Planet. Sci. Lett. 151, 181–189. doi: 10.1016/S0012-821X(97)81847-X.

Escartín, J., Smith, D.K., Cann, J., Schouten, H., Langmuir, C.H., Escrig, S., 2008. Central role of detachment faults in accretion of slow-spreading oceanic lithosphere. Nature 455, 790.

Faleide, J.I., Bjørlykke, K., Gabrielsen, R.H., 2010. Geology of the Norwegian Continental Shelf. In: Petroleum Geoscience, 467-499, Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-02332-3_22

Forsyth, D., Uyeda, S., 1975. On the Relative Importance of the Driving Forces of Plate Motion. Geophys. J. Royal Astr. Soc. 43, 163–200.

Gabrielsen, R.H., Faleide, J.I., Pascal, C., Braathen, A., Nystuen, J.P., Etzelmuller, B., O'Donnell, S., 2010. Latest Caledonian to Present tectonomorphological development of southern Norway. Marine Petr. Geol. 27, 709-723. doi: 10.1016/j.marpetgeo.2009.06.004.

Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins, Basin Research 12, 195-218. doi: 10.1111/j.1365-2117.2000.00121.x.

Gillard, M., Autin, J., Manatschal, G., Sauter, D., Munschy, M., 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 34(4), 753-783.

Goitom, B., Oppenheimer, C., Hammond, J. O. S., Grandin, R., Barnie, T., Donovan, A., Ogubazghi, G., Yohannes, E., Kibrom, G., Kendall, J-M., Carn, S. A., Fee, D., Sealing, C., Keir, D., Ayele, A., Blundy, J., Hamlyn, J., Wright, T., Berhe, S., 2015. First recorded eruption of Nabro volcano, Eritrea, 2011. Bulletin of Volcanology, 77(10), Art.85. doi: 10.1007/s00445-015-0966-3

Gunnell, Y., Fleitout, L. 1998. Shoulder uplift of the Western Ghats passive margin, India: a denudational model. Earth Surface Processes and Landforms 23, 391-404.

Hall, T. R., Nixon, C., Keir, D., Burton, P. W. Ayele, A., 2018. Earthquake clustering and energy release of the African–Arabian rift system. Bull. Seism. Soc. Am. 108(1), 155-162. doi: 10.1785/0120160343.

Harland, W.B., Gayer, R.A., 1972. The Arctic Caledonides and earlier oceans. Geol. Mag. 109, 289–384.

Heezen, B.C., Tharp, M., Ewing, M. 1959. The floors of the oceans: 1. The North Atlantic. Geol. Soc. Am. Spec. Papers 65. doi: 10.1130/SPE65.

Hess, H.H., 1962. History of ocean basins. In: Petrologic Studies: A volume to Honour A.F. Buddington, Geol. Soc. Am., 599-620.

Holmes, A., 1931. Radioactivity and earth movements, Trans. Geol. Soc. Glasgow 18, 559-606.

Horni, J., Hopper, J., Blischke, A., Geissler, W., Stewart, M., Mcdermott, K., Judge, M., Erlendsson, O., Arting, U., 2017. Regional Distribution of Volcanism within the North Atlantic Igneous Province. In: Peron-Pinvidic, G., Hopper, J.R., Stoker, M., Gaina, C., Funck, T., Arting, U. Doornenbal, J.C. (Eds.), The North-East Atlantic region: A reap-praisal of crustal structure, tectono-stratigraphy and magmatic evolution, Geol. Soc., London, Spec. Publ. 447.

Huismans, R.S., Beaumont, C., 2003. Symmetric and asymmetric lithospheric extension: Relative effects of frictional-plastic and viscous strain softening. J.. Geophys. Res. 108, 2496. doi: doi:10.1029/2002JB002026.

Huismans, R.S., Buiter, S.J.H., Beaumont, C., 2005. Effect of plastic-viscous layering and strain softening on mode selection during lithospheric extension. J. Geophys. Res. 110, B02406.

doi:10.1029/2004JB003114.
Hutchison, W., Fusillo, R., Pyle, D. et al., 2016. A pulse of mid-Pleistocene rift volcanism in Ethiopia at the dawn of modern humans. Nat. Comm. 7, 13192. doi: 10.1038/ncomms13192.
IPCC, 2005. Carbon Capture and Storage. In: Metz, B., Davidson, O., de Coninck, H., Loos, M., Meyer, L. (Eds.), Cambridge University Press, UK. pp 431.
Jeanniot, L., Buiter, S.J.H., 2018. A quantitative analysis of transtensional margin width. Earth Planet. Sci. Lett. 491, 95–108. doi: 10.1016/j.epsl.2018.03.003.
Johansson, L., Zahirovic, S., Müller, R.D., 2018. The interplay between the eruption and weathering of Large Igneous Provinces and the deep-time carbon cycle. Geophys. Res. Lett. 45, 5380-5389. doi:10.1029/2017GL076691.
Kämpf, H., Bräuer, K., Schumann, J., Hahne, K., Strauch, G., 2013. CO2 discharge in an active, non-volcanic continental rift area (Czech Republic): Characterisation (δ13C, 3He/4He) and quantification of diffuse and vent CO2 emissions. Chemical Geology, Frontiers in Gas Geochemistry 339, 71–83. doi: 10.1016/j.chemgeo.2012.08.005
Keir, D., Ebinger, C. J., Stuart, G. W., Daly, E., Ayele, A., 2006. Strain accommodation by magmatism and faulting as rifting proceeds to breakup: Seismicity of the northern Ethiopian rift, J. Geophys. Res. 111, B05314. doi:10.1029/2005JB003748.
Kolawole, F., Atekwana, E.A., Laó-Dávila, D.A., Abdelsalam, M.G., Chindandali, P.R., Salima, J., Kalindekafe, L., 2018. Active Deformation of Malawi Rift's North Basin Hinge Zone Modulated by Reactivation of Preexisting Precambrian Shear Zone Fabric. Tectonics 37, 683–704. doi: 10.1002/2017TC004628.
Koptev, A., Cloetingh, S., Burov, E., François, T., Gerya, T., 2017. Long-distance impact of Iceland plume on Norway's rifted margin. Scientific Reports 7. doi: 10.1038/s41598-017-07523-y.
Kusznir, N.J., Park, R.G., 1987. The extensional strength of the continental lithosphere: its dependence on geothermal gradient, and crustal composition and thickness. Geol. Soc., London, Spec. Publ. 28, 35–52.
Lavier, L.L., Buck, W.R., Poliakov, A.N.B., 1999. Self-consistent rolling-hinge model for the evolution of large-offset low-angle normal faults. Geology 27, 1127–1130. doi:10.1130/0091-7613(1999)027<1127:SCRHMF>2.3.CO;2.
Lee, H., Muirhead, J., Fischer, T. et al., 2016. Massive and prolonged deep carbon emissions associated with continental rifting. Nat. Geosci. 9, 145–149. doi:10.1038/ngeo2622.
Ligi, M., Bonatti, E., Caratori Tontini, F.,Cipriani, A., Cocchi, L., Schettino, A., Bortoluzzi, G., Ferrante, V., Khalil, S., Mitchell, N.C., Rasul, N., 2011. Initial burst of oceanic crust accretion in the Red Sea due to edge-driven mantle convection. Geology 39 (11), 1019–1022. doi:10.1130/G32243.1.
Lister, G.S., Etheridge, M.A., Symonds, P.A., 1986. Detachment faulting and the evolution of passive continental margins. Geology 14, 246-250.
Liu, M., Yang, Y., Shen, Z., Wang, S., Wang, M., Wan, Y.,. 2007. Active tectonics and intracontinental earthquakes in China: The kinematics and geodynamics. In: Stein, S., Mazzotti, S. (Eds.), Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues, Geol. Soc. Am. Spec. Paper 425, 299-318. doi:10.1130/2007.2425(19).
Maccaferri, F., Rivalta, E., Keir, D., Acocella, V., 2014. Off-rift volcanism in rift zones determined by crustal unloading. Nat. Geosci. 7, 297–300. doi:10.1038/ngeo2110.
Manatschal, G., Lavier, L., Chenin, P., 2015. The role of inheritance in structuring hyperextended rift systems: Some considerations based on observations and numerical modeling. Gondwana Research 27, 140-164. doi: 10.1016/j.gr.2014.08.006.
Mandl, G., 1988. Mechanics of Tectonic Faulting: Models and Basic Concepts. Developments in Structural Geology (Vol. 1). Elsevier, Amsterdam, 407 pp.
Mantovani, R., 1889. Les fractures de l'écorce terrestre et la théorie de Laplace, Bull. Soc. Sci. Arts Réunion, 41–53.
McKenzie, D., 1978. Some remarks on the development of sedimentary basins. Earth and Planetary Science Letters 40, 25–32. doi:10.1016/0012-821X(78)90071-7.
McQuarrie, N., Wernicke, B.P., 2005. An animated tectonic reconstruction of southwestern North America since 36 Ma. Geosphere 1, 147–172. doi:10.1130/GES00016.1
Medvedev, S., Souche, A., Hartz, E.H., 2013. Influence of ice sheet and glacial erosion on passive

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


margins of Greenland. Geomorphology 193, 36-46. doi: 10.1016/j.geomorph.2013.03.029.

Mohn, G., Manatschal, G., Beltrando, M., Haupert, I., 2014. The role of rift-inherited hyper-extension in Alpine-type orogens. Terra Nova 26, 347–353. doi:10.1111/ter.12104

Moucha, R., Forte, A.M., 2011. Changes in African topography driven by mantle convection. Nat. Geosci. 4, 707–712. doi:10.1038/ngeo1235

Moulin, M., Aslanian, D., Unternehr, P., 2010. A new starting point for the South and Equatorial Atlantic Ocean. Earth-Science Reviews 98 (1-2), 1-37.

Mouthereau, F., Filleaudeau, P.-Y., Vacherat, A., Pik, R., Lacombe, O., Fellin, M.G., Castelltort, S., Christophoul, F., Masini, E., 2014. Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence. Tectonics 33, 2283–2314. doi:10.1002/2014TC003663.

Muirhead, J.D., Fischer, T.P., Oliva, S.J. et al.. 2020. Displaced cratonic mantle concentrates deep carbon during continental rifting. Nature 582, 67–72. doi:10.1038/s41586-020-2328-3

Müller, R.D., Seton, M., Zahirovic, S., Williams, S.E., Matthews, K.J., Wright, N.M., Shephard, G., Maloney, K.T., Barnett-Moore, N., Hosseinpour, M., Bower, D.J., Cannon, J., 2016. Ocean basin evolution and global-scale plate reorganization events since Pangea breakup, Ann. Rev. Earth Planet. Sci. 44, 107-138, doi:4410.1146/annurev-earth-060115-012211.

Naliboff, J.B., Buiter, S.J.H., Peron-Pinvidic, G., Osmundsen, P.T., Tetreault, J., 2017. Complex fault interaction controls continental rifting. Nat. Comm. 8, 1179. doi:10.1038/s41467-017-00904-x.

Neuharth, D., Brune, S., Glerum, A., Heine, C., Welford, J.K., 2021. Formation of Continental Microplates Through Rift Linkage: Numerical Modeling and Its Application to the Flemish Cap and Sao Paulo Plateau. Geochem. Geophys. Geosys. 22, e2020GC009615. doi:10.1029/2020GC009615.

Neuharth, D., Brune, S., Wrona, T., Glerum, A., Braun, J., Yuan, X., 2022. Evolution of Rift Systems and Their Fault Networks in Response to Surface Processes. Tectonics 41, e2021TC007166. doi:10.1029/2021TC007166.

Nielsen, S.B., Gallagher, K., Leighton, C., Balling, N., Svenningsen, L., Jacobsen, B.H., Thomsen, E., Nielsen, O.B., Heilmann-Clausen, C., Egholm, D.L., Summerfield, M.A., Clausen, O.R., Piotrowski, J.A., Thorsen, M.R., Huuse, M., Abrahamsen, N., King. C., Lykke-Andersen, H., 2009. The evolution of western Scandinavian topography: A review of Neogene uplift versus the ICE (isostasy–climate–erosion) hypothesis. Journal of Geodynamics 47, 72-65. doi: 10.1016/j.jog.2008.09.001.

Ortelius, A., 1596. Thesaurus Geographicus. Entry Gadiricus. Digital version on https://www.digitale-sammlungen.de/en/view/bsb11055584.

Pagli, C., Yun, S-H., Ebinger, C., Keir, D., Wang, H., 2019. Strike-slip tectonics during rift linkage. Geology, 47, 31-34. doi:10.1130/G45345.1.

Penrose Field Conference on Ophiolites, 1972. Geotimes 17, 24-25.

Peron-Pinvidic, G., Manatschal, G., Osmundsen, P.T., 2013. Structural comparison of archetypal Atlantic rifted margins: A review of observations and concepts. Mar. Petr. Geol. 43, 21-47. doi: 10.1016/j.marpetgeo.2013.02.002.

Peron-Pinvidic, G., Osmundsen, P.T., Ebbing, J., 2016. Mismatch of geophysical datasets in distal rifted margins studies. Terra Nova 28(5), 340-347. doi:10.1111/ter.12226.

Peron-Pinvidic, G., Naliboff, J., 2020. The exhumation detachment factory. Geology 48(6), 635-639. doi:10.1130/G47174.1.

Peron-Pinvidic, G., Fourel, L., Buiter, S.J.H., 2022. The influence of orogenic collision inheritance on rifted margin architecture: Insights from comparing numerical experiments to the Mid-Norwegian margin. Tectonophysics 828, 229273. doi:10.1016/j.tecto.2022.229273.

Petersen, K.D., Buck, W.R., 2015. Eduction, extension, and exhumation of ultrahigh-pressure rocks in metamorphic core complexes due to subduction initiation. Geochem. Geophys. Geosyst. 16, 2564–2581. doi:10.1002/2015GC005847.

Rajaonarison, T.A., Stamps, D.S., Naliboff, J., 2021. Role of Lithospheric Buoyancy Forces in Driving Deformation in East Africa From 3D Geodynamic Modeling. Geophys. Res. Lett. 48, e2020GL090483. doi:10.1029/2020GL090483

Raymo, M., Ruddiman, W., 1992. Tectonic forcing of late Cenozoic climate. Nature 359, 117–122. doi:10.1038/359117a0.

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


Redfield, T.F., Osmundsen, P.T., 2013. The long-term topographic response of a continent adjacent to a hyperextended margin: A case study from Scandinavia. GSA Bulletin 125, 184-200. doi:10.1130/B30691.1

Redfield, T.F., Osmundsen, P.T., 2015. Some remarks on the earthquakes of Fennoscandia: A conceptual seismological model drawn from the perspective of hyperextension. Norwegian Journal of Geology 94, 233-262.

Reston, T. , 2018. Flipping detachments: The kinematics of ultraslow spreading ridges. Earth Planet. Sci. Lett. 503, 144-157. doi:10.1016/j.epsl.2018.09.032.

Reston, T.J., Mcdermott, K.G., 2011. Successive detachment faults and mantle unroofing at magma-poor rifted margins. Geology 39(11), 1071-1074. doi:10.1130/G32428.1.

Reston, T.J., Ranero, C.R., 2011. The 3-D geometry of detachment faulting at mid-ocean ridges. Geochem. Geophys. Geosys. 12(7). doi:10.1029/2011GC003666.

Rice, J.R., 1992. Chapter 20 Fault Stress States, Pore Pressure Distributions, and the Weakness of the San Andreas Fault. In: Evans, B. , Wong, T.-F. (Eds), Fault Mechanics and Transport Properties of Rocks, International Geophysics 51, 475 – 503. Academic Press.

Rooney, T.O., Herzberg, C., Bastow, I.D., 2012. Elevated mantle temperature beneath East Africa. Geology 40, 27–30. doi:10.1130/G32382.1.

Rowland, J.V., Wilson, C.J.N., Gravley, D.M., 2010. Spatial and temporal variations in magma-assisted rifting, Taupo Volcanic Zone, New Zealand, Journal of Volcanology and Geothermal Research, 190, 89-108. doi:10.1016/j.jvolgeores.2009.05.004.

Runcorn, S.K., 1965. Continental reconstructions. Phil. Trans. Royal Soc. London Series A 258, 1-11.

Ryan, W.B.F., Carbotte, S.M., Coplan, J.O., O'Hara, S., Melkonian, A., Arko, R., Weissel, R.A., Ferrini, V., Goodwillie, A., Nitsche, F., Bonczkowski, J., Zemsky, R., 2009. Global Multi-Resolution Topography synthesis. Geochem. Geophys. Geosys. 10. doi:10.1029/2008GC002332.

Sandiford, M., 1999. Mechanics of basin inversion. Tectonophysics 305, 109-120.

Sankov, V.A., Lukhnev, A.V., Miroshnitchenko, A.I., Dobrynina, A.A., Ashurkov, S.V., Byzov, L.M., Dembelov, M.G., Calais, E., Déverchère, J., 2014. Contemporary horizontal movements and seismicity of the south Baikal Basin (Baikal rift system). Izv., Phys. Solid Earth 50, 785–794. doi:10.1134/S106935131406007X

Sapin, F., Ringenbach, J.-C., Clerc, C., 2021. Rifted margins classification and forcing parameters. Sci Rep 11, 8199. doi:10.1038/s41598-021-87648-3

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., Kent, R.W., 1997. The North Atlantic Igneous Province. In: Mahoney, J.J., Coffin, M.E. (Eds.), Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism. Geophysical Monograph, 100. AGU, 45–93.

Sauter, D., Cannat, M., Roumejon, S., Andreani, M., Birot, D., Bronner, A., Brunelli, D., Carlut, J., Delacour, A., Guyader, V., Macleod, C.J., Manatschal, G., Mendel, V., Menez, B., Pasini, V., Ruellan, E., Searle, R., 2013. Continuous exhumation of mantle-derived rocks at the Southwest Indian Ridge for 11 million years. Nature Geosci. 6(4), 314-320. doi:10.1038/ngeo1771.

Schiffer, C., Doré, A.G., Foulger, G.R., Franke, D., Geoffroy, L., Gernigon, L., Holdsworth, B., Kusznir, N., Lundin, E., McCaffrey, K., Peace, A.L., Petersen, K.D., Phillips, T.B., Stephenson, R., Stoker, M.S., Welford, J.K., 2020. Structural inheritance in the North Atlantic. Earth-Science Reviews, A new paradigm for the North Atlantic Realm 206, 102975. doi:10.1016/j.earscirev.2019.102975.

Scholz, C.H., 2019. The Mechanics of Earthquakes and Faulting. Cambridge University Press. ISBN 978-1-107-16348-5.

Sembroni, A., Faccenna, C., Becker, T.W., Molin, P., Abebe, B., 2016. Long-term, deep-mantle support of the Ethiopia-Yemen Plateau. Tectonics 35, 469–488. doi:10.1002/2015TC004000.

Şengör, A.M.C., Natal'in, B.A., 2001. Rifts of the World. Geological Society of America Special Papers 352, 389–482. doi:10.1130/0-8137-2352-3.389.

Siegburg, M., Gernon, T. M., Bull, J. M., Keir, D., Barfod, D. N., Taylor, R. N., Abebe, B., Ayele, A., 2018. Geological evolution of the Boset-Bericha Volcanic Complex, Main Ethiopian Rift: 40Ar/39Ar evidence for episodic Pleistocene to Holocene volcanism. J. Volc. Geothermal Res. 351, 115-133. doi:10.1016/j.jvolgeores.2017.12.014.

Silva, R. M., Sacek, V., 2022. Influence of surface processes on postrift faulting during divergent margins evolution. Tectonics 41, e2021TC006808. doi:10.1029/2021TC006808.

https://doi.org/10.5194/egusphere-2022-139
Preprint. Discussion started: 19 April 2022


Snider-Pellegrini, A., 1858. La Création et ses mystères dévoilés.

Stamps, D.S., Saria, E., Kreemer, C., 2018. A Geodetic Strain Rate Model for the East African Rift System. Scientific Reports 8, 732. doi:10.1038/s41598-017-19097-w

Straume, E.O., Gaina, C., Medvedev, S., Hochmuth, K., Gohl, K., Whittaker, J.M., Abdul Fattah, R., Doornenbal, J.C., Hopper, J.R., 2019. GlobSed: Updated Total Sediment Thickness in the World's Oceans. Geochem. Geophys. Geosys. 20, 1756–1772. doi: 10.1029/2018GC008115.

Stuart G.W., Bastow I.D., Ebinger C.J., 2006. Crustal structure of the Northern Main Ethiopian rift from receiver function studies. Geol. Soc. London Spec. Publ. 259, 253–267.

Styron, R., Pagani, M., 2020. The GEM Global Active Faults Database. Earthquake Spectra 36, 160–180. doi:10.1177/8755293020944182.

Suess, E., 1885. Das Antlitz der Erde 1. 779 pp.

Tedesco, D., Vaselli, O., Papale, P., Carn, S. A., Voltaggio, M., Sawyer, G. M., Durieux, J., Kasereka, M., Tassi, F., 2007. January 2002 volcano-tectonic eruption of Nyiragongo volcano, Democratic Republic of Congo, J. Geophys. Res., 112, B09202. doi:10.1029/2006JB004762.

Torsvik, T.H., Cocks, L.M.R., 2005. Norway in space and time: a centennial cavalcade. Norw. J. Geol. 85, 73–86.

Tucholke, B.E., Lin, J., Kleinrock, M.C., 1998. Megamullions and mullion structure defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge. J. Geophys. Res. 103, 9857-9866.

van Summeren, J., Conrad, C.P., Lithgow-Bertelloni, C., 2012. The importance of slab pull and a global asthenosphere to plate motions. Geochem. Geophys. Geosys. 13. doi:10.1029/2011GC003873.

van Wijk, J.W., Cloetingh, S.A.P.L., 2002. Basin migration caused by slow lithospheric extension. Earth Planet. Sci. Lett. 198, 275–288. doi:10.1016/S0012-821X(02)00560-5.

Vine, F.J., Matthews, D.H., 1963. Magnetic anomalies over oceanic ridges. Nature 199, 947-949.

Wegener, A., 1912. Die Entstehung der Kontinente. Geol. Rundschau 3, 276–292. doi: 10.1007/BF02202896.

Wernicke, B., 1985. Uniform-sense normal simple shear of the continental lithosphere. Can. J. Earth Sci. 22, 108–125. doi:10.1139/e85-009

White, R., Smith, L., Roberts, A. et al., 2008. Lower-crustal intrusion on the North Atlantic continental margin, Nature 452, 460–464. doi:10.1038/nature06687

White, R., McKenzie, D.,1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts, J. Geophys. Res., 94(B6), 7685–7729. doi:10.1029/JB094iB06p07685.

Wilkes, M., Kendall, J-M., Nowacki, A., Biggs, J., Wookey, J., Birhanu, Y., Ayele, A., Bedada, T., 2017. Seismicity associated with magmatism, faulting and hydrothermal circulation at Aluto Volcano, Main Ethiopian Rift. J. Volc. Geothermal Res. 340, 52-67. doi:10.1016/j.jvolgeores.2017.04.003.

Wilson, J.T., 1966. Did the Atlantic close and then re-open? Nature 211, 676–681.

Wilson, R.W., Houseman, G.A., Buiter, S.J.H., McCaffrey, K.J.W., Doré, A.G., 2019. Fifty years of the Wilson Cycle Concept in Plate Tectonics: An Overview. Geol. Soc., London, Spec. Publ. 470. doi:10.1144/SP470-2019-58.

Withjack, M.O., Jamison, W.R., 1986. Deformation produced by oblique rifting. Tectonophysics 126, 99–124. doi:10.1016/0040-1951(86)90222-2.

Whitney, D.L., Teyssier, C., Rey, P., Buck, R., 2014. Continental and oceanic core complexes. Geol. Soc. Am. Bull. 125(3/4), 273–298. doi:10.1130/B30754.1.

Wright, T. J., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D., Stork, A., 2006. Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. Nature, 442(7100), 291-294. doi:10.1038/nature04978.

Yu, Y., Tilmann, F., Zhao, D., Gao, S.S., Liu, K.H., 2022. Continental break-up under a convergent setting: Insights from P wave radial anisotropy tomography of the Woodlark rift in Papua New Guinea. Geophys. Res. Lett. 49, e2022GL098086. doi:10.1029/2022GL098086

Zappettini, E.O., Rubinstein, N., Crosta, S., Segal, S.J., (2017). Intracontinental rift-related deposits: A review of key models. Ore Geology Reviews, 89, 594-608, https://doi.org/10.1016/j.oregeorev.2017.06.019.

Ziegler, P.A., Cloetingh, S., 2004. Dynamic processes controlling evolution of rifted basins. Earth-Science Reviews 64, 1–50. doi:10.1016/S0012-8252(03)00041-2.