---

# Analogue modelling of continental rifting: an overview

Frank Zwaan[a], Guido Schreurs[a]

(a) University of Bern, Baltzerstrasse 1+3, 3012 Switzerland
email: frank.zwaan@geo.unibe.ch

Keywords: Continental rifting, analogue modelling, extension, experimental modelling, analysis techniques, rift propagation, rift interaction, oblique extension

## 1. Introduction

When studying rifts and rifted margins, geologists have to face various challenges. Such tectonic systems cover large parts of the globe, making it hard to chart them in detail. Furthermore, large parts of these systems are buried under thick layers of sediment or covered by water, strongly reducing their accessibility. These problems have been mitigated to a degree by the use of geophysical techniques, in particular reflection seismics, and deep borehole drilling. Yet perhaps the greatest obstacle on the path to a thorough understanding of rift processes is posed by the timescale on which the latter operate. It is simply not possible to directly observe the development of a rift system that takes millions of years, and the processes and kinematics involved remain obscure.

Recognizing these challenges, geologists have long since turned to analogue models. By choosing the correct materials and experimental set-up, it is possible to simulate tectonic processes stretching over vast spatial and temporal scales within a couple of hours or days in the laboratory. This approach provides an easy and relatively cheap method to test various parameters that may affect tectonic systems, providing unique insights in associated dynamics and kinematics that are not readily deduced from static field examples, which is especially relevant for petroleum geologists (e.g. Naylor et al. 1994; Brun & Fort 2004). The first such analogue model (or experiment), simulating tectonic folding, was published by Sir James Hall in 1815 (Hall, 1815). In the 200 years since these first experiments, a wide variety of methods have been used to simulate a vast spectrum of tectonic processes (e.g. Graveleau et al. 2012; Koyi 1997). It must however be stressed that analogue modelling applications are not restricted to tectonics, but have also been applied to study, for instance, sedimentary processes, magmatic events, slope collapse and tsunami hazards (e.g. Donnadieu et al. 2003; Wang et al. 2014; McFall & Fritz 2016; Poppe et al. 2019). Meanwhile, a broad arsenal of methods has been developed to not only observe, but also quantify external and internal model deformation, so that the analogue modelling community remains at the forefront of geological innovation.

Although the first models were conducted to simulate compressional tectonics, numerous experimental studies have addressed extensional tectonics over the years. Ample references to these studies can be found in the reviews and overview papers by Vendeville et al. (1987), McClay (1990), Allemand & Brun (1991), Beslier (1991), Naylor et al. (1994), McClay et al. (1996), Koyi (1997), Brun (1999), Michon & Merle (2000, 2003), Corti et al. (2003), Bahroudi et al. (2003), Corti (2012), and Zwaan et al. (2019). The aim of this text is therefore not to present an exhaustive review of all preceding publications, but to provide an overview of analogue modelling of rift tectonics, describing the general methodology (materials and scaling, set-ups and state-of the art analysis techniques), and to illustrate how these can be applied for studying a variety of aspects of rifts and rifted margins. We also describe the current challenges and opportunities in the field, which revolve around key topics such as rheology, structural inheritance and kinematics, and hope that this work may serve as a guide and inspiration for future analogue modelling studies.

## 2. Methodology

Before running an experiment, analogue modellers need to carefully consider factors such as scaling, model materials and set-up, in order to ensure that the model simulates the chosen natural tectonic setting as best as possible.

### 2.1. Scaling principles

When using analogue modelling techniques, proper scaling is necessary to guarantee (1) the geometrical, (2) the kinematic and (3) the dynamic similarity between a model and its natural equivalent. These similarities can be expressed by means of simple scaling equations (Hubbert 1937, Ramberg 1981; Le Calvez 2002; Corti et al. 2003 and references therein). Geometrical similarity implies that all dimensions (length, width, height, layer thickness, fault angles) in the analogue model have the same proportions as in the natural prototype (i.e. the model looks the same). Kinematic similarity signifies that the model and the natural example maintain geometric similarity during their deformation without developing any temporal distortions along the way (i.e. structures develop at the correct moment in time). Finally dynamic similarity is established when all forces, stresses and the rheology of the materials are properly translated from the natural example to the model scale (i.e. all forces maintain the same relative proportions as in nature). Although it is practically impossible to incorporate all detailed complexities that characterize natural geological settings into a small laboratory experiment, a correct scaling of the dominant factors controlling deformation will allow the scaling criteria to be fulfilled. In order to achieve this, it is important to select the proper analogue materials that reproduce the behaviour of the lithosphere, and to choose an experimental set-up, model dimensions, as well as a deformation rate appropriate for simulating a specific tectonic setting (e.g. Bahroudi et al. 2003; Zwaan et al. 2019).

### 2.2. Materials

For modelling the brittle parts of the lithosphere, granular materials such as fine quartz sand are commonly used, but other materials such as wet clay or wheat flour are also applied (e.g. Schellart & Strak 2016; Reber et al. 2020). These materials, of which the rheological properties can be tested with a ring-shear tester (e.g. Panien et al. 2006a) (or with a rheometer in the case of wet clay, Eisenstadt & Sims 2005), have angles of internal friction similar to those of materials in the brittle upper crust or upper lithospheric mantle (Panien et al. 2006a; Ritter et al. 2016; Klinkmüller et al. 2016), meaning that they develop similar structures as their natural counterpart when subject to deformation (Fig. 1a). If necessary, it is possible to mix granular materials or to wet them to adjust their properties (e.g. cohesion) (Van Mechelen, 2004; Abdelmalak et al. 2016; Montanari et al. 2017). Some granular materials (e.g. glass beads) have a lower angle of internal friction and can serve to represent structural weaknesses such as detachment layers. Since deformation of these materials is strain rate-independent, experimental deformation rates can be selected at will.

For the modelling of ductile parts of the lithosphere such as the lower crust, lower lithospheric mantle or crustal décollements (e.g. shales or salt), a wide variety of viscous materials can be used. Silicones are a common choice, but an overview of alternatives can be found in for example Schellart & Strak (2016) and Reber et al. (2020). Often substances are mixed to obtain a viscous material with the correct density and properties. These viscous materials can have various rheologies, from Newtonian (linear) to power-law types, which can be tested using a rheometer (e.g. Rudolf et al. 2016). Yet, they have in common that their behavior is strain rate-dependent (generally strengthening with increasing strain rates, Brun 1999, 2002). Therefore, it is very important to properly scale deformation rates when applying viscous materials. When simulating the whole lithosphere, a low-viscosity material such as honey or glucose syrup is often used to incorporate the isostatic effects of the underlying (asthenospheric) mantle (Fig. 1d). It is however important to note that analogue materials do generally not incorporate the effects of temperature variations in the lithosphere (e.g. melting and phase changes), which poses some limitations to their application. For more information on (viscous) materials, see Schellart & Strak (2016), Rudolf et al. (2016), Reber et al. (2020) and references therein.

## 2.3. Experimental set-ups and boundary conditions

Set-ups for experimental modelling concern the method of imposing deformation on the model (boundary conditions), and a first-order distinction can be made on the base of the gravity field that is applied. In the past, numerous researchers have used a centrifuge set-up that allows enhanced-gravity experiments (e.g. Koyi 1997 and references therein). This method, in which an enhanced gravitational force (up to 200 g, Corti et al. 2003) is used to collapse the model layers to create extension, allows the application of relatively stiff viscous materials while respecting scaling laws, simplifying model construction. Drawbacks include the small size of the model and the challenges of observing the rotating model within the closed centrifuge. Yet the centrifuge method is still being used today, yielding highly relevant results in the field of rift tectonics (e.g. Corti et al 2003; Agostini et al. 2009; Corti (2012); Philippon et al. 2015).

Running analogue experiments under normal gravity conditions is generally easier than the centrifuge approach. Nowadays it is the most popular option, and therefore the focus of this book chapter. As described by e.g. Vendeville et al. (1987), Allemand & Brun (1991) and Zwaan et al. (2019) there are various set-ups to model extensional tectonics under normal gravity conditions, depending on the model scale (upper crustal to lithospheric), tectonic setting and inferred lithospheric strength profile (Fig. 1). An important difference between these and centrifuge models is that deformation in normal gravity models is generally driven by the mobile model base and/or sidewalls, i.e. by an imposed extension velocity boundary condition, rather than by gravitational forces.

When studying deformation in the brittle upper parts of the lithosphere, from basin- to upper crustal scale, modellers have often used a so-called plate base or conveyer base set-up, on top of which the brittle model layers are sitting (Fig 1a). By moving the base plate apart with the use of precise (stepper) motors, its edge forms a so-called velocity discontinuity (VD), which is meant to simulate a fault in the basement that causes the brittle cover to deform locally (as both are directly “coupled”, i.e. the base directly influences the brittle cover). A problem with this set-up is that the “basement fault” does not allow vertical motion, which can be solved with a basement block set-up (see section 3.1.1). Another basal boundary condition can be applied with a compressed foam base underlying a sand layer (Fig. 1b, e.g. Schlagenhauf et al. 2008; Zwaan et al. 2019). This set-up may simulate a ductile lower crust directly coupled to the brittle crust. Here distributed deformation is transmitted to the brittle layer as the model sidewalls move apart and the foam expands, leading to widespread faulting. A rubber base can create a similar type of deformation (e.g. Bahroudi et al. 2003), but may also cause strong boundary effects due to the fact that rubber, when stretched, tends to contract perpendicularly with respect to the stretching direction (see e.g. Zwaan et al. 2019).

A standard model set-up for brittle-ductile settings involves a base plate system with a viscous layer representing the ductile lower crust and an overlying brittle layer simulating the upper crust (Fig. 1c, e.g. Tron & Brun 1991, Allemand et al. 1989; Michon & Merle 2000, 2003). Note that one could also use such a layering for simulating a detachment (e.g. salt) within the brittle crust (see also section 3.1.1.). Here the velocity discontinuity underlying the model materials represents a fault in the brittle mantle, localizing deformation. Importantly, the viscous material, if sufficiently weak, can act as a detachment layer, decoupling the brittle cover from the model base, so that the latter can to a degree deform independently. Depending on numerous factors, a single, double or no rift at all may develop (see also section 3.1.2).

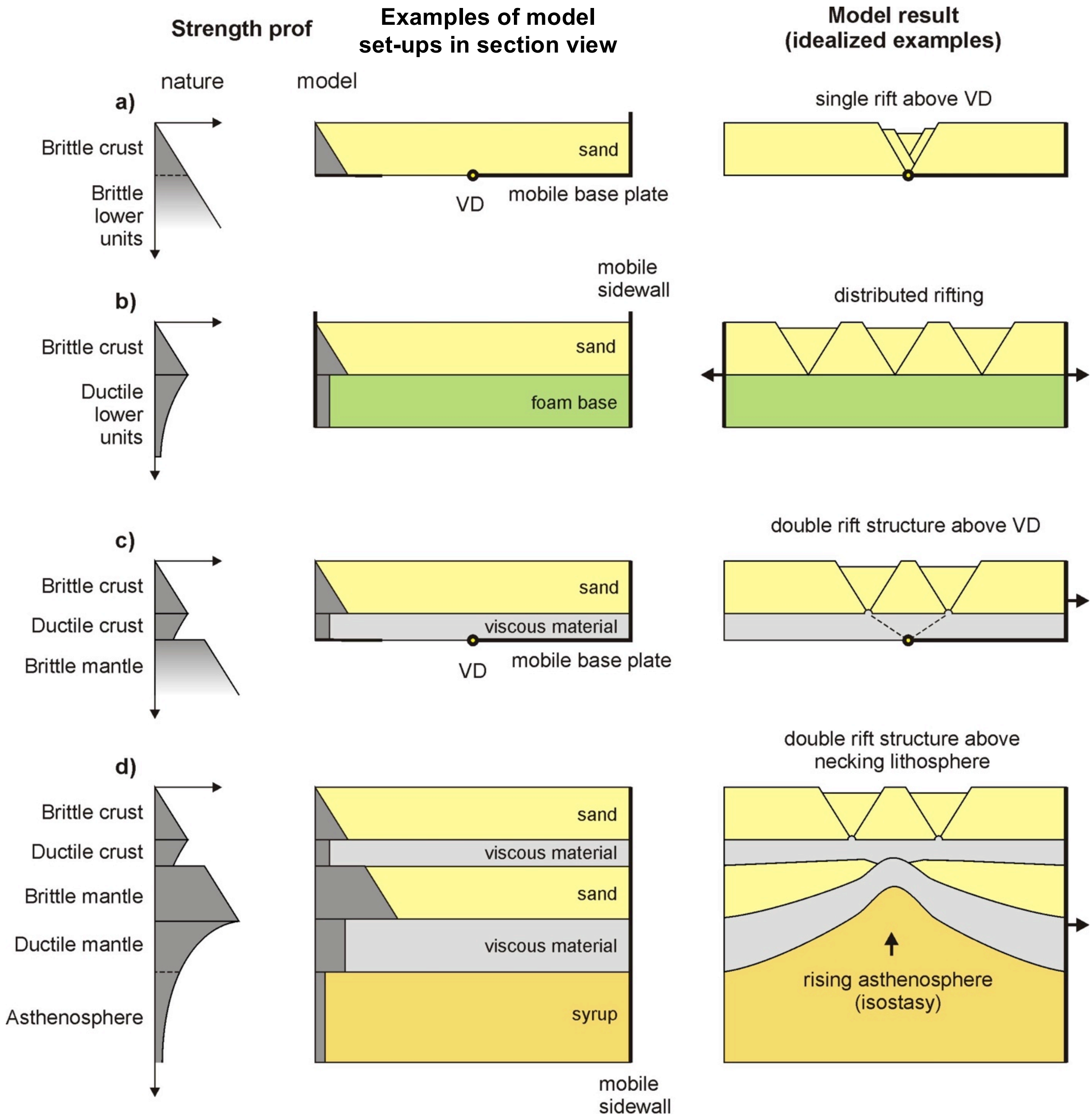


**Fig. 1.** Schematic section-view examples of normal-gravity experimental set-ups for simulating rifting at different scales, and examples of idealized results (without sedimentation). Note that slight variations in boundary conditions may have important effects on model evolution (see Figs. 4, 5). (a) Base plate set-up with brittle cover, representing a brittle-only system, develops a graben at the edge of the basal plate, where a velocity discontinuity (VD) occurs. (b) Foam base set-up, representing a brittle cover overlying a (ductile) deeper layer that evenly distributes faulting. (c) Brittle-viscous base plate model, representing a brittle-ductile crust overlying a very strong brittle mantle with a single fault (VD). Depending on various factors, a double rift may develop above the VD. (d) Four-layer Lithospheric-scale experiment on top of syrup representing the asthenosphere, allowing isostatic compensation. Deformation is induced by moving the model sidewall. Compare with (c). Modified after Allemand & Brun (1991), Brun (1999, 2002) and Zwaan et al. (2019).

Finally, when simulating rifting of the entire lithosphere, modellers need to include the mantle lithosphere and the underlying asthenosphere, which allows for isostatic compensation (Fig. 1d). In this case, four-layer models representing the brittle and viscous parts of the lithosphere are mostly used, although modellers have also worked with three-layer systems (e.g. Allemand et al. 1989). A very weak viscous layer such as honey or glucose syrup is used as an analogue for the asthenosphere. By moving the sidewalls apart, the layers are stretched. Also in these models, numerous factors, especially the coupling between the various layers (itself a function of viscosity and strain rate), may affect the style of rifting (see section 3.1.3).

When applying analogue models, their layering translates to a strength profile that should be similar between model and nature (e.g. Zwaan et al. 2019; Fig. 1). Whereas the brittle part of the profiles are mostly matched fairly well, the depth-dependent strength decrease in the ductile domain often remains an approximation since the effects of increased heating and pressure are challenging to incorporate. Also, various other lithospheric strength profiles may occur in nature, which can be replicated with different materials and layer thicknesses.

Furthermore, it may be necessary to control where deformation occurs in a model to ensure reproducibility, or to simulate pre-existing structures that reactivate. In the case of direct coupling, faulting will be directly affected by the model base (1a, b). Yet when viscous layers decouple the model components, modellers can for instance apply “seeds” (rods of viscous material) at the base of the brittle cover to weaken it locally (e.g. Le Calvez & Vendeville, 2002, Zwaan et al. 2016; Molnar et al. 2019) or create pre-cut faults within the brittle layer (e.g. McClay et al. 2002; Bellahsen & Daniel 2005), to localize deformation. On a lithospheric scale, modellers have also used weak zones within the upper mantle analogue to focus deformation (Molnar et al. 2017).

The examples of model set-ups in Fig. 1 are shown in section view, and analogue models have often been depicted and analysed as such. This is permissible if the section is parallel to the deformation direction, and if no variations along the rift axis are included, so that deformation can be assumed to have occurred in plane. Yet it is important to emphasize that any analogue model experiment is 3D, and that numerous models incorporate processes that act in the third dimension. For these experiments, analysis cannot be limited to a single 2D section.

### 2.4. Model analysis techniques

Researchers have been using increasingly sophisticated techniques to capture deformation in their analogue experiments. The most basic option, used since the early days of modelling, is photography (Fig 2a). Top view images are a great help for visualizing model evolution and are part of the standard toolkit of any analogue model laboratory. Automated time-lapse photography allows modellers to follow deformation in great detail. Moreover, if the model set-up includes a transparent sidewall, side view photographs provide valuable insights in how the model is deforming internally, although researchers must be aware of potential boundary effects due to sidewall friction. A very common alternative is to make cross-sections of the experiment. Yet in order to do so, the model must be stabilized (e.g. wetted, frozen, or impregnated with gelatine) and physically cut. Although several labs have elevated such techniques to an art-form, cutting very fine sections, of which the photographs can be imported in structural interpretation software for detailed analysis (e.g., Wu et al. 2009; Withjack et al. 2017; Dooley & Hudec 2020), it means that the model must be destroyed and the resulting information only represents the final model state. Still such sections provide instructive insights in model structures and form the basis of several figures presented in this book chapter.

Researchers commonly add surface markers (e.g. a grid) or differently colored sand layers to visualize deformation in map view and side view/cross-section photographs, allowing a semi-quantitative assessment of deformation (Fig. 2e). More precise analysis of such data can be achieved by means of particle image velocimetry (PIV) or digital image correlation (DIC) of time-lapse series (e.g. Adam et al., 2005; Boutelier et al. 2019). These techniques compare photographs from different time steps tracing and displaying 2D displacement (Fig. 2f). The now fully quantified 2D displacement patterns furthermore allow detailed strain analysis (e.g. e.g. Boutelier & Oncken 2011).

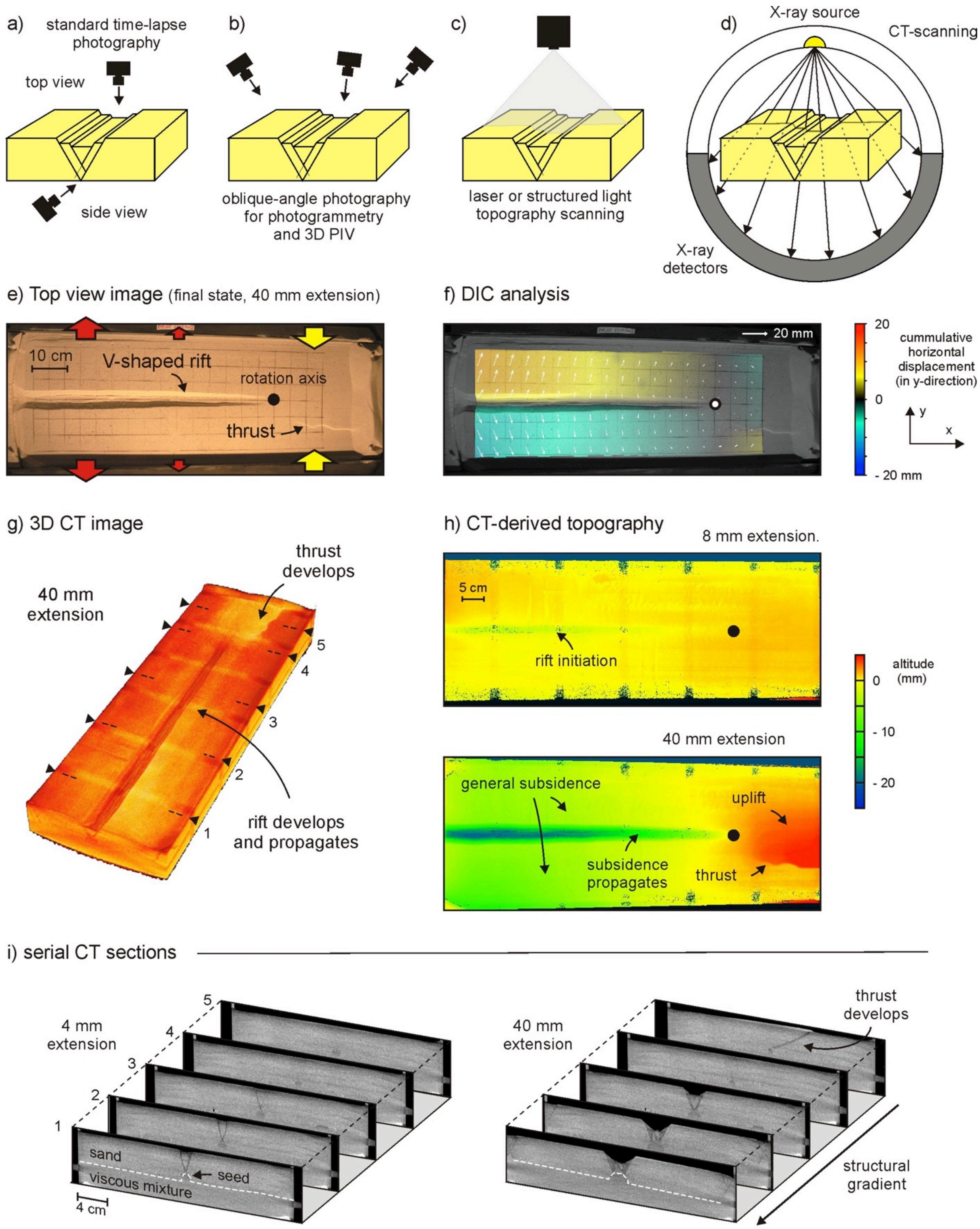


**Fig. 2.** Experimental monitoring techniques. (a) Top- and side-view photography, for 2D PIV/DIC analysis. (b) Oblique-angle photography for topographic and 3D PIV/DIC analysis. (c) Surface scanning for topographic evolution monitoring. (d) X-Ray CT-scanning allowing non-destructive inspection of internal model evolution, as well as internal PIV/DIC and DVC analysis. (e-i) Application of various analysis techniques on a rotational extension experiment from Zwaan et al. (2020). (e) Top view of final model state. (f) Quantification of cumulative horizontal displacement through DIC analysis. (g) 3D CT imagery of the final deformation stage. (h) CT-derived topography maps. (i) Serial CT sections of internal structures over time, showing the structural gradient in the early and final stages of the model run. Note the structural weakness (seed) that localizes deformation. Section locations are indicated in (g).

Nevertheless these results represent only 2D insights, whereas the processes in models and in nature are three-dimensional. By using stereoscopic camera configurations or laser/structured light scanners, it is possible to capture 3D surface deformation (e.g. Donnadieu et al. 2003; Michon & Sokoutis 2005; Schlagenhauf et al. 2008; Nestola et al. 2015). Photogrammetry software can reconstruct detailed digital elevation models that allow researchers to quantify vertical displacement. Yet more sophisticated is 3D surface analyses by means of PIV software. Similar to normal photogrammetry software, this 3D PIV technique reconstructs the surface of the model, and goes a step further than 2D PIV methods by tracing vertical displacements as well (e.g. Adam et al. 2005; Molnar et al. 2017, Ge et al. 2019). As a result, this technique allows a unique and fully quantified 3D analysis of surface deformation.

However, these techniques do not provide a complete insight into internal model deformation. This can so far only be achieved by means of X-ray CT-scanning, during which the model is not physically disturbed (e.g. Naylor et al. 1994; Colletta et al. 1991; Schreurs et al. 2003), in contrast to cutting it to obtain cross-sections. The method has some limitations in that both the set-up and experimental materials need to be X-ray transparent, and the complete experiment needs to fit into a (medical) CT scanner. CT-scanning however provides unrivalled potential for model analysis. The model can be visualized in 3D (Fig. 2g) and it allows the extraction of detailed digital topography maps, much like photogrammetry or surface scanning (Fig. 2h). Furthermore the 3D CT volume allows modellers to make cross-sections in any direction they desire, for every time step at which the model was scanned. This provides detailed insights into internal model development (e.g. Zwaan et al. 2020, Fig. 2i), and also allows 4D analyses when imported into structural interpretation software (e.g. Chauvel et al. 2018; Fedorik et al. 2019). Yet also these insights remain semi-quantitative. The final step is to apply PIV or DIC techniques on CT data, which can be done on 2D sections from different time intervals, yielding unique quantitative information (Zwaan et al. 2020), but also on successive 3D volumetric CT-data sets produced at different time steps during the evolution of one particular experiment. This so-called digital volume correlation (DVC) technique (Adam et al. 2013) uniquely allow the tracing of displacements and the quantification of strain throughout the complete model, clearly illustrating that rifting is a 3D process (e.g. Zwaan et al. 2018, Fig. 2j).

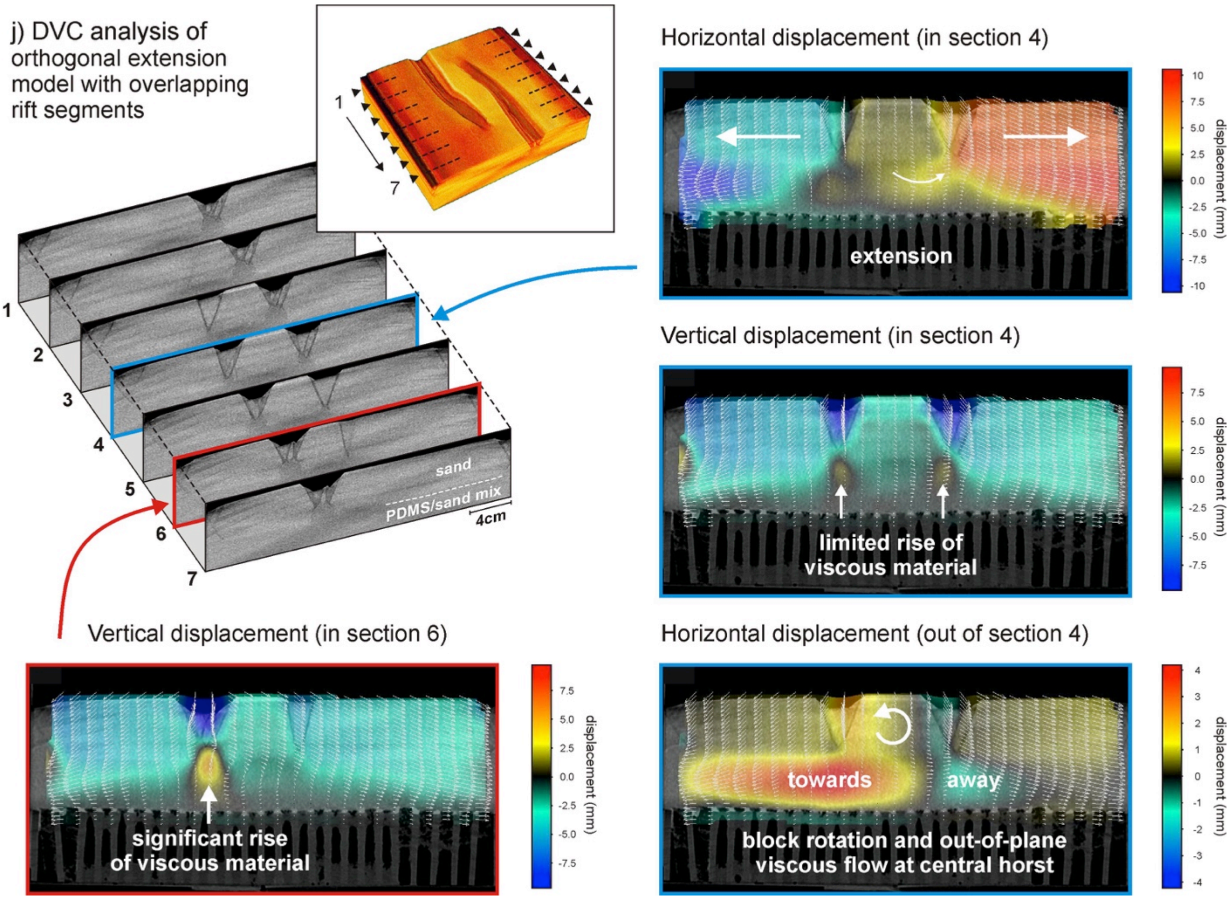


**Fig. 2. (continued**) (j) Example of digital volume correlation (DVC) analysis on CT data from a model with interacting rift segments under orthogonal extension, illustrating internal displacement patterns. Note the differences in vertical displacement at different places, as well as out-of-plane displacement of both brittle and viscous material, highlighting the 3D character of the system (compare vertical displacements in sections 4 and 6). Modified after Zwaan et al. (2018).

## 3. Model application

As described in section 2, different set-ups and materials are used to study diverse aspects of rifting on different scales. In the following, we shall provide an overview of various examples, ranging from quasi-2D models of crustal and lithospheric scale models, to experiments involving 3D rift processes such as oblique extension, rift segment interaction and rotational rifting. As emphasized in section 2.3, all analogue models are by definition 3D objects. However, rift models are often analysed in section parallel to the extension direction, which provides quasi-2D insights.

### 3.1. A 2D perspective on rifting

#### 3.1.1. Normal fault development in the upper crust

Various authors have simulated the development of normal faulting in the upper (parts of the) crust (Fig. 3). For instance the CT-scanned experiments by Panien et al. (2006a) reveal that in a brittle base plate set-up, normal faulting in the shape of a graben initiates at the basal velocity discontinuity (VD), and subsequently propagates towards the model surface (Fig 3a). Furthermore, the authors show that due to stress deflection, these initial faults may overturn towards the surface, becoming reverse faults in the upper few mm of the model (Fig. 3a).

Later on, the lower part of the normal fault is reactivated and continues upward in the footwall with the initial subvertical and reverse segments being abandoned. Such features are also found in nature (Trippanera et al. 2014), most spectacularly at the rims of collapsed calderas (Martí et al. 2008). When extension is asymmetric, the resulting fault pattern will also be asymmetric, as new faults develop above the edge of the moving base plate (e.g. McClay 1990; Beslier 1991; Allemand & Brun 1991, Fig. 3b).

Other researchers have studied the effects of basement block subsidence on fault development in the sedimentary cover. Naylor et al. (1994) show how vertical basement faults can cause reverse faulting in the overburden (Fig. 3c), in a process similar to the reverse faults described by Panien et al. (2006a) (Fig. 3a). By contrast, models with low-angle basement faults create a graben structure above the fault (Naylor et al. 1994; Holland et al. 2006) (Fig. 3d). Furthermore, if the basement fault is listric, a roll-over structure forms, and if syn-rift sedimentation is applied by stepwise filling up the generated accommodation space, a series of small grabens will develop in the accumulating hanging wall strata (e.g. McClay 1990, Fig. 3e).

Moreover, adding a layer of relatively weak viscous material to simulate salt or shale detachments can decouple the brittle cover from the model basement (e.g. Vendeville et al. 1995; Dooley et al. 2003, Fig. 3f). As a result, flexure can develop as the viscous material flows, and normal faulting in the brittle layer can be displaced sideways with respect to the underlying basement fault (Fig. 3f).

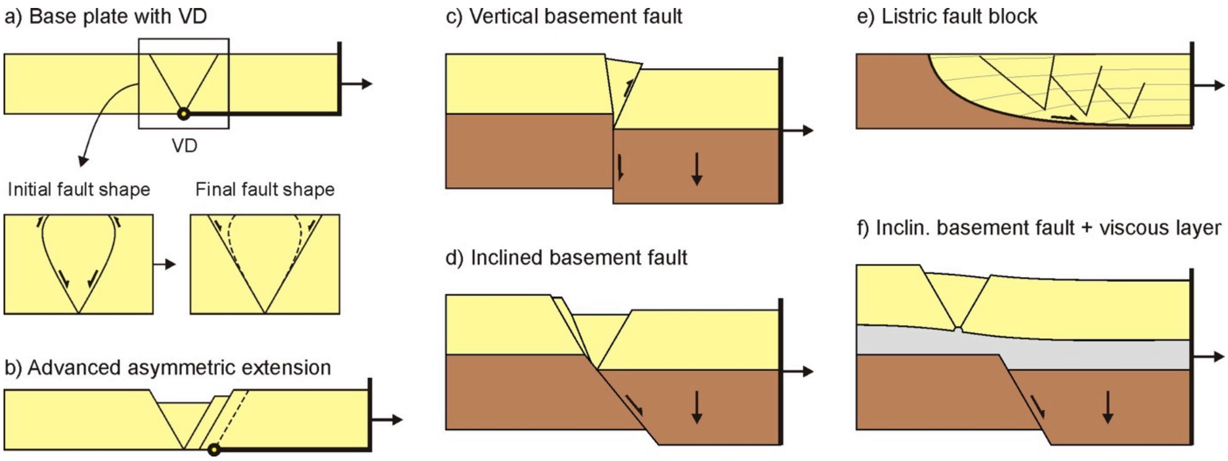


**Fig. 3.** Schematic examples of upper crustal scale models to study normal faulting. (a) Base plate creating a graben in the brittle material above the velocity discontinuity (VD) at its plate edge (top). Initial fault may be curved, leading to local reverse kinematics (bottom left). Later on, full normal faulting is established (bottom right). (b) When extension is asymmetric, an asymmetric graben will form after advanced deformation. Modified after Allemand et al. (1989), Panien et al. (2006a). (c) Vertical (high angle) basement fault causing reverse faulting in the brittle cover. Modified after Naylor et al. (1994). (d) Inclined (low angle) basement fault inducing normal faulting and graben formation in brittle cover. Modified after Naylor et al. (1994). (e) Listric fault model developing a roll-over anticline with internal grabens. Modified after McClay (1990). (f) Effect of a decoupling viscous layer on faulting in the brittle cover above a basement fault. Compare with (d). Modified after Dooley et al. (2003).

### 3.1.2. Brittle-viscous crustal scale models

When zooming out to full-crustal scale, applying brittle-viscous layers representing the entire brittle-ductile crust, researchers have found various influences of lithospheric strength (i.e. layer thicknesses and extension rates) as well as model boundary conditions on the mode of rifting (Brun 1999; Corti et al. 2003; Zwaan et al. 2019 and references therein). A very thick viscous layer, representing for instance the effect of crustal thickening and radioactive heating in an orogen, creates a very weak crust (Fig. 4a). As a result, the brittle cover is very much decoupled from the model base, which induces detachment faulting and the formation of exhumation structures analogue to metamorphic core complexes (Brun et al. 1994, Fig. 4a).

By contrast, a thinner viscous layer (low brittle-to-viscous thickness ratio), representing a colder crust, leads to localized rifting when extension rates are low (Fig. 4b). However, when applying high extension rates, the viscous layer is stronger and coupling between the viscous and brittle layers is enhanced so that they start deforming together, causing distributed faulting ("wide rift mode", Brun 1999) (Fig. 4c).

When the viscous layer is even thinner as may be the case in an older, cold crust, the basal boundary condition starts to affect the style of rifting (Fig 4d-f). This boundary condition was not particularly important in the previous cases due to a high degree of decoupling between model base and brittle layer (Fig. 4a-c). However, increased coupling between the base and brittle cover rifting causes the materials to deform in a similar way as in the models without a viscous layer (Figs 1a, b, 3a-d, 4d-f). A foam base (simulating a ductile/weak mantle) causes distributed extension throughout the brittle cover (Fig. 4d), whereas a plate base (simulating a strong/brittle mantle) causes more localized deformation (Zwaan et al. 2019, Fig. 4e). Whether a single or double rift develops in the latter depends on the extension rate (Michon & Merle 2000).

Further influences on the evolution of brittle-viscous rift systems are caused by the application of asymmetric extension and sedimentation. Simply put, symmetric rifting will lead to symmetric rift structures, whereas asymmetric rifting, if coupling between the base and brittle cover is significant enough, may cause the rift to focus on the moving plate, away from the basal velocity discontinuity (Allemand & Brun 1991, Fig. 4f). Moreover, syn-rift sedimentation can not only prevent the brittle layer from breaking up so that deformation remains focused along a few large normal faults (Fig. 4h), but the weight of the sediment infill also prevents viscous material from rising below an otherwise thinned rift wedge (Zwaan et al. 2018, Fig. 4g, h). Such flow of viscous material below the rift basin can be clearly visualized by means of displacement analysis on CT data (Zwaan et al. 2018, 2020, Fig. 2j).

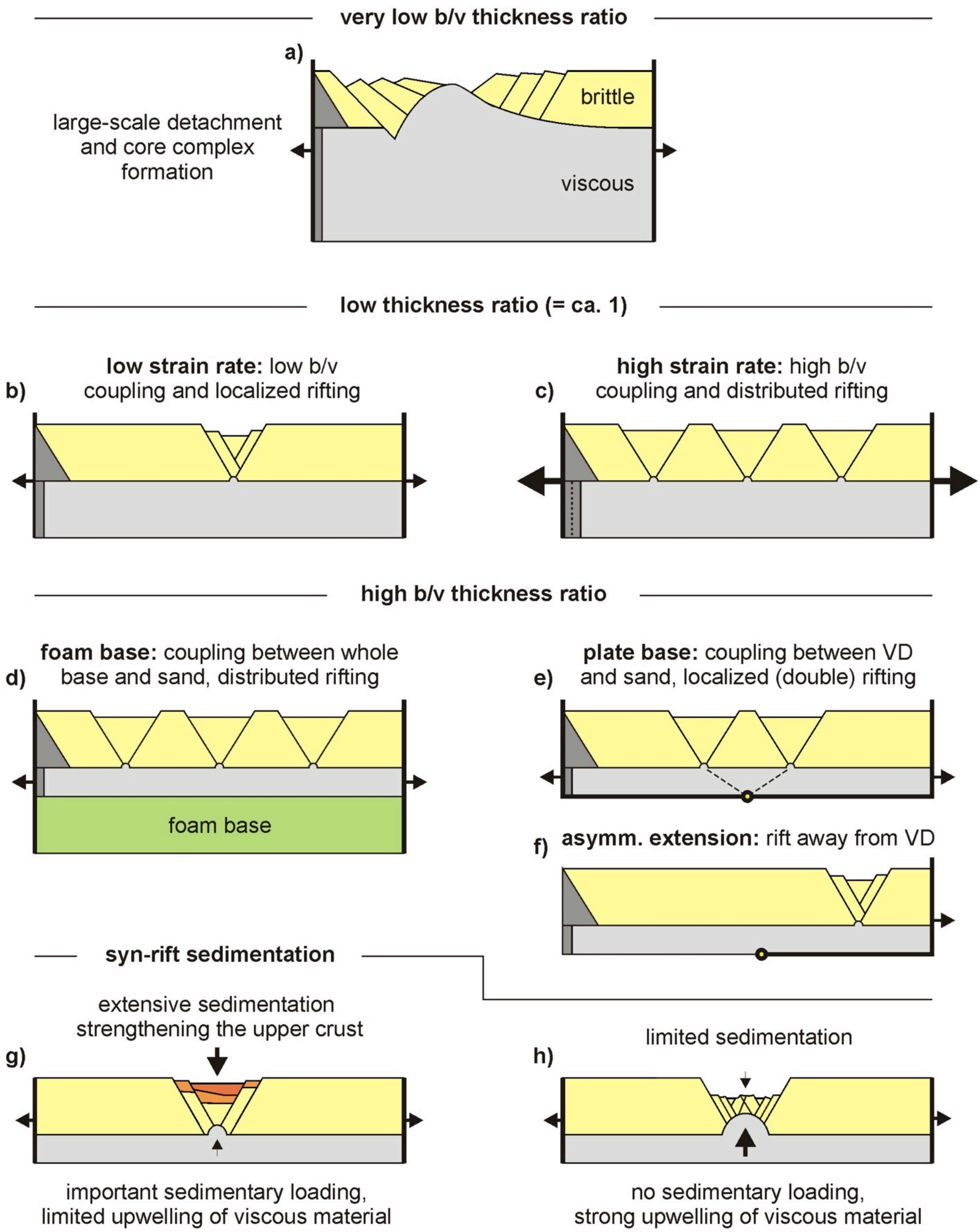
very low b/v thickness ratio
a)
large-scale detachment and core complex formation
brittle
viscous
low thickness ratio (= ca. 1)
b)
low strain rate: low b/v coupling and localized rifting
c)
high strain rate: high b/v coupling and distributed rifting
high b/v thickness ratio
d)
foam base: coupling between whole base and sand, distributed rifting
foam base
e)
plate base: coupling between VD and sand, localized (double) rifting
f)
asymm. extension: rift away from VD
syn-rift sedimentation
g)
extensive sedimentation strengthening the upper crust
important sedimentary loading, limited upwelling of viscous material
h)
limited sedimentation
no sedimentary loading, strong upwelling of viscous material

**Fig. 4.** Schematic examples of parameters affecting brittle-viscous experiments. (a) Very low brittle-to-viscous (b/v) thickness ratios (i.e. very low strength) decouple the brittle layer from the base, leading to core complex formation. Modified after Brun et al. (1994). (b-c) Low b/v thickness ratios still decouple the brittle layer from the base, yet high strain rates cause distributed faulting (wide rifting mode), whereas low strain rates localize deformation (narrow rifting mode). Modified after Brun (1999) and Zwaan et al. (2019). (d-f) A thin viscous layer leads to coupling between base and brittle cover. For foam base set-ups, the foam's distributed deformation transfers to the brittle cover, which develops widespread faulting. A base plate set-up causes localized deformation above the velocity discontinuity (VD), yet depending on strain rate a single or double rift may develop. Modified after Michon & Merle (2000, 2003). Furthermore, asymmetric extension may (in some cases) deflect deformation away from the VD (Allemand et al. 1989). (g-h) Effects of sedimentation on rift development. Sedimentary infill causes strengthening of the brittle layer, focusing fault activity along a few faults, and suppressing upwelling of viscous material. Absence of sedimentation causes the rift wedge to split along numerous faults while the viscous layer rises. Modified after Zwaan et al. (2018). Note that the dark grey on the left of the images represents the strength profile.

### 3.1.3. Lithospheric scale models

For crustal-scale models, it is not always necessary to incorporate the (isostatic) effects of the deeper mantle layers. But as plate tectonics involves the entire lithosphere, which is in isostatic equilibrium with the asthenosphere, both are included in various large-scale model studies of rifting (e.g. Allemand et al. 1989; Brun & Beslier 1996; Nestola et al. 2015; Molnar et al. 2017; Beniest et al. 2018). These experiments show that the presence of a competent upper mantle layer is of great importance (Corti et al. 2003). When such a layer is absent, the strength of the lithosphere is dominated by the upper crust, leading to localized rifting (Fig. 5a, similar to Fig. 4b). When present, this competent upper mantle controls the strength of the lithosphere and its rupture creates either a single or double rift in the brittle upper crustal layer (Fig. 5b, c, compare with Figs. 1c, 4e).

In such four-layer lithospheric models, (de)coupling between brittle and viscous layers is highly important. When coupling is low, either due to low strain rates or low viscosities in the ductile domain (Brun 1999; 2002), deformation is localized in both the brittle mantle and crust, which may represent natural rift settings like in the Upper Rhine Graben (Beslier 1991, Brun 1999, Fig. 5c). By contrast, enhanced (intermediate) brittle-viscous coupling causes a more distributed style of rifting and may lead to exhumation of the model mantle as observed in nature along the Atlantic margin of Iberia (Fig. 5d, Brun & Beslier 1996). On the other hand, extension of models with high coupling between its viscous and brittle components may cause widespread deformation (Beslier 1991, Fig. 5e, compare with Fig. 4c and d).

The models in Fig. 5 do however not consider structural inheritance. Other researchers have included crustal and mantle weaknesses to localize deformation (e.g. Agostini et al. 2009). Beniest et al. (2018) have studied lateral strength variations and show how rifting predominantly localizes in the weaker part of the lithosphere (i.e. away from competent areas such as cratons). Corti et al. (2003) include low-viscosity patches to represent melts and provide a schematic overview of the relative relations between various parameters and rift styles (their Fig. 36). But although these models yield valuable insights in rift processes, including mantle exhumation (Brun & Beslier 1996, Fig. 5d), analogue models are limited to the continental rifting phase, given that commonly applied materials do not allow the creation of new oceanic lithosphere.

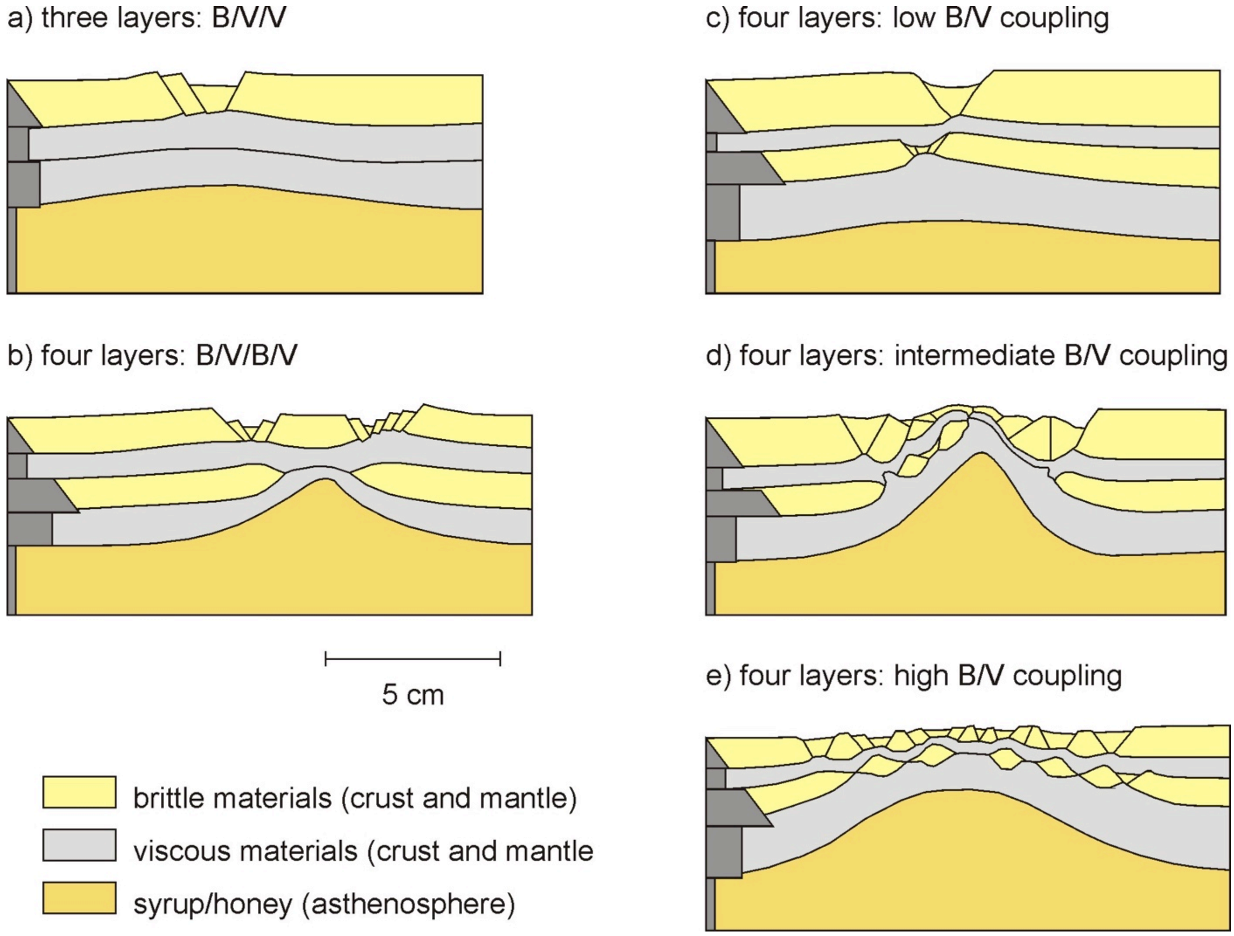


**Fig. 5.** Schematic examples of lithospheric-scale rift model results as a function of (a, b) lithospheric layering (three vs. four layers) and (c-e) degree of coupling between the brittle and viscous materials (B/V coupling) in four-layer models. B: brittle, V: viscous (ductile). Modified after Allemand et al. (1989), Beslier (1991), Brun & Beslier (1996) and Brun (2002).

### 3.2. Exploring 3D rift processes

Although many studies have approached lithospheric extension as a 2D phenomenon and analysed it accordingly, various authors have explored the third dimension as well. Their results show the importance of understanding the 3D aspects of rift processes, resulting from e.g., oblique extension, the interaction between individual rift segments, rotational rifting or rift propagation.

#### 3.2.1. Oblique extension

Most extensional systems experience some form of oblique extension during their life-time (Brune et al. 2018) and researchers have extensively used analogue models in order to understand the significance of this parameter, (e.g. Withjack & Jamison 1986; Tron & Brun 1991; McClay & White 1995; Clifton et al. 2000; Agostini et al. 2009; Autin et al. 2010, 2013). These studies show that under orthogonal extension settings, large normal faults strike perpendicularly to the extension direction and thus parallel to the rift axis (Fig. 6a). Yet when extension is oblique, the faults strike at an angle to the rift axis (although not perpendicular to the extension direction, see Withjack & Jamison 1986), and the resulting rift zone is bordered by en echelon boundary faults (Fig. 6b). Although the boundary faults are oriented obliquely to the rift axis, their kinematics remain dominantly normal (Philippon et al. 2015). With increasing obliquity towards the strike-slip domain, however, normal faults will give way to strike-slip faults. Typical for such models is the development of initial Riedel shears above the rift axis, which subsequently link up to form a continuous strike-slip fault (e.g. Naylor et al. 1986; Dooley & Schreurs 2012 and references therein, Fig. 6c).

Furthermore, Keep & McClay (1997), Bonini et al. (1997) and others explore the effects of multiphase oblique extension and show how structures formed during the initial phases are often reactivated to dominate subsequent extension phases. However, the reactivation of pre-existing structural weaknesses in the crust or mantle under (oblique) extension only localizes deformation when oriented favorably to the regional (oblique) extension direction (Zwaan & Schreurs 2017; Molnar et al. 2019). On a lithospheric scale, Autin et al. (2010) describe how their models suggest that oblique extension may protract break-up.

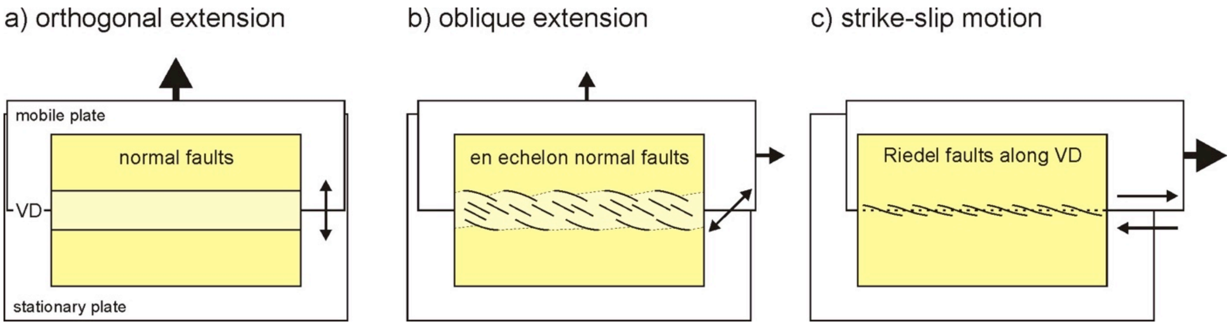


**Fig. 6.** Schematic map view examples of fault patterns related to different extension directions as observed in experiments. (a) orthogonal extension leads to long, velocity discontinuity (VD)-parallel normal faults. (b) when extension is oblique, en echelon normal faults develop along the VD, but their strike is not perfectly perpendicular to the extension direction (Withjack & Jamison 1986). (c) Under strike-slip conditions, a series of Riedel shears appear above the VD, which in later stages connects to form a continuous strike-slip fault. Modified after Tron & Brun (1991). Note that in the set-ups shown in (a) and (b) the diverging base plates are generally connected by a rubber sheet or partly overlain by a patch of viscous material.

### 3.2.2. Rift segment interaction

When the lithosphere is stretched, deformation often localizes along pre-existing structural weaknesses to form individual rift segments. In order to develop into a full-scale rift system, these segments need to interact, propagate and connect. Analogue studies show that such rift interaction structures are affected by the horizontal distance (offset), the amount of underlap or overlap between rift segments, and the presence of secondary pre-existing weaknesses linking the segments and oblique extension (e.g. Acocella et al. 1999; Le Calvez & Vendeville 2002; Tentler 2003a, b; Molnar et al. 2019). The effect of the latter is well visible if the offset between rift segments is sufficiently large (Fig. 7a-c). Since normal faults tend to develop at high angles to the regional extension direction (see section 3.2.1), rift segments propagate either away from, parallel to, or toward each other. In the latter case, the central block may become isolated (rift pass structure) and can start rotating due to the interaction between the overlapping rift axes (Zwaan et al. 2018, Figs. 7c, 2j), a process currently observed at the Victoria Plate in the East African Rift (Glerum et al. 2020). In situations with small offsets, these effects will not occur as the rift segments readily grow into each other (Fig. 7d). Furthermore, when the rift segments underlap, a series of minor en echelon grabens may develop (e.g. Tentler 2003a, b, Fig. 7e). Some models show that secondary pre-existing weaknesses may help to connect rift segments, but only if these are oriented favorably to the extension direction; if they are aligned (sub-)parallel to the extension direction they will not activate (Zwaan & Schreurs 2017; Molnar et al. 2019). Yet when applying strongly controlling basal boundary conditions with a plate base set-up, it is possible to force the development of transform fault-like structures along the edge of the plate, even if this velocity discontinuity is aligned with the extension direction (e.g. Acocella et al. 1999; Dauteuil et al. 2002, Fig. 7f).

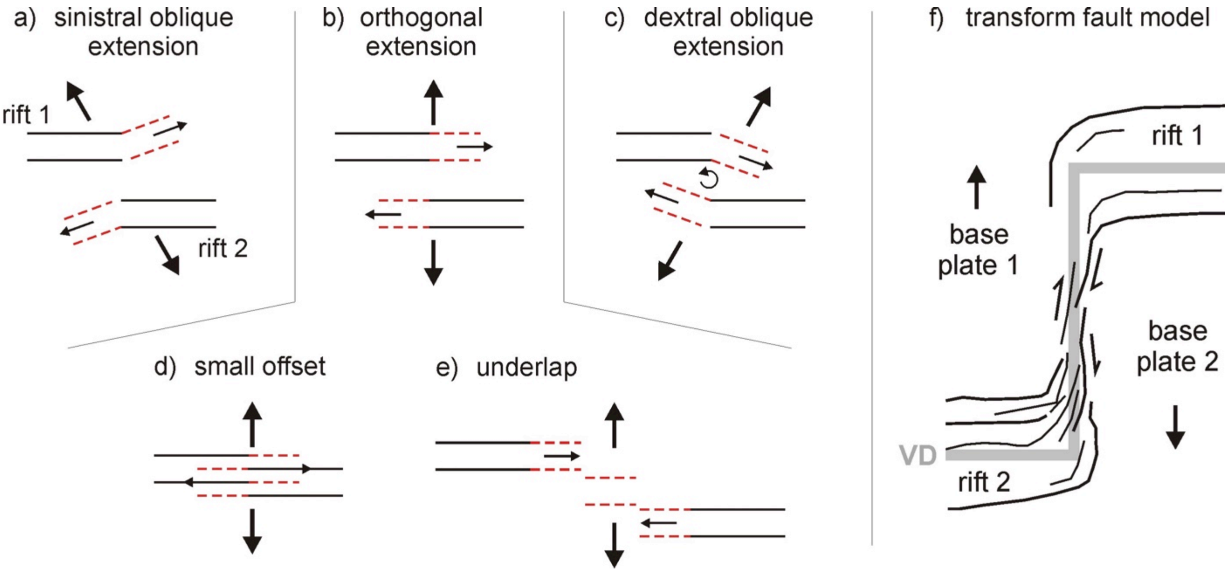


**Fig. 7.** Schematic examples of modelled rift interaction between right-stepping rift segments, depending on extension direction. Since the strike of new normal faulting tends to be at high angles with respect to the extension direction (Withjack & Jamison 1986), (a) sinistral oblique extension causes the rifts to diverge, (b) orthogonal extension has the rifts grow in a parallel fashion and (c) dextral oblique extension lets the rifts grow together. The block in between the rifts in (c) can start rotating and even form a continental sliver or microcontinent. Note that the relations between rift development and extension direction as shown in this figure are opposite when the rift segments are arranged in a left-stepping fashion. (d) Rifts directly grow into each other when their offset is small. (e) Rifts may create en echelon interaction zones when underlap and offset are sufficiently large. (f) Transform fault modelled by a plate base set-up. VD: velocity discontinuity. Modified after Dauteuil et al (2002); Tentler (2003a, b), Zwaan et al. (2016) and Zwaan & Schreurs (2017).

### 3.2.3. Rotational rifting and rift propagation

When running rifting experiments, modellers generally apply constant extension rates along the length of their models (Figs. 6, 8a). Yet plate tectonics on a globe demands rotational motion about an Euler pole, whereas various cases of smaller-scale plate rotations are recorded around the world (Zwaan et al. 2020, Fig. 8a). A few analogue modellers have explored the implications of rotational boundary conditions (e.g. Souriot & Brun 1992; Benes & Scott 1996; Sun et al. 2009; Molnar et al. 2017). These models invariably show that rift development in rotational settings causes structural gradients, rift propagation and the formation of V-shaped basins, whereas constant along-strike extension rates lead to cylindrical structures (Figs. 2e-j, 6, 8). In addition, pressure gradients in such models cause not only across-strike displacements (Fig. 2j), but also along-strike flow of viscous material, highlighting the importance of a 3D mindset when studying rifting processes (Zwaan et al. 2018, 2020). DVC analysis of CT data clearly shows the interaction between deep-seated viscous deformation and surface deformation (Fig. 2j).

The models depicted in Fig. 8a and b concern a homogeneous layer cake. Molnar et al. (2017, 2018, 2019) describe how structural weaknesses of various types and orientations can (partially) reorient propagating rift systems. Benes & Scott (1996) test how such propagating rifts interact when encountering a competent domain, and describe how the rift has trouble penetrating the latter (Fig. 8c). When the rheological contrast is perpendicular to the extension direction, the well-defined propagating rift spreads out over various faults. Yet if the rheological contrast is obliquely oriented, part of the deformation is deflected along it (Fig. 8d). A similar result is obtained by Brune et al. (2017), who use both analogue and numerical models to study how an oblique weak zone affects rift interaction, although the authors use constant-along strike strain rates (Fig. 8e).

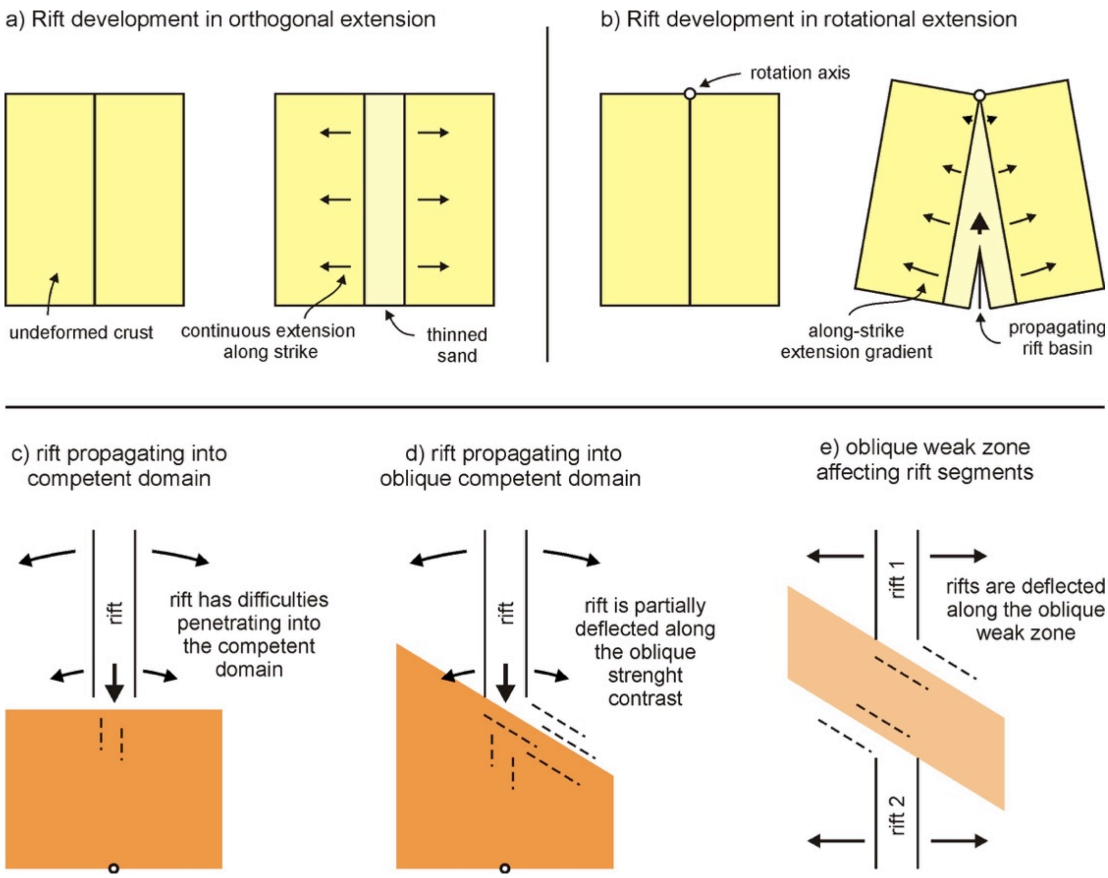

**Fig. 8.** Schematic examples of rift development and propagation under different boundary conditions. (a) Orthogonal extension causes synchronous rift development along its axis. Oblique extension boundary conditions produce similar results (Fig. 6). (b) Rotational rifting, inducing a strain rate and structural gradient, as well as rift propagation toward the rotation pole. Compare with Fig. 2e-i. (c) Rift propagating into a competent domain orthogonal to the rift axes. (d) Rift propagating into a competent domain oblique to the rift axes. (e) Rift deflection along a zone of different rheological competence. Modified after Vink (1980) and Martin (1984), Benes & Scott (1996) and Brune et al. (2017).

## 4. Summary, challenges and future opportunities

In the above pages, we have described how analogue modelling techniques have been used to study a wide variety of aspects associated with rifting processes, from normal fault development to lithospheric necking. The variety of analogue modelling methods and advanced analysis techniques provides researchers with a handy and highly versatile toolkit to explore factors that may affect rifting, yielding invaluable insights into the dynamic evolution and associated kinematics. A key message should be that although various models have focussed on the 2D aspects of rifting processes, it is evident that the third dimension needs to be taken into account for a proper understanding of rifting. Analogue models thus provide crucial insights, but it should be highlighted that there is still plenty of potential for improvements and future applications.

Recently, Peron-Pinvidic et al. (2019) listed six main focus points for rift and passive margin research efforts: rheology, structural inheritance, faulting, stratigraphy, kinematics and the influence of the mantle, between which various links exist. Analogue modelling work could contribute significantly to a better understanding of the role of these parameters during rifting.

(1) The influence of rheology can be addressed through analogue modelling materials as researchers are constantly looking for new, adequate materials to improve model performance (e.g. Schellart & Strak 2016, Reber et al. 2020). A common limitation in analogue models is for instance that model material cannot undergo phase changes due to thermal effects or hydration of minerals. Yet modellers have for instance used materials such as paraffin wax, which melts and solidifies when changing temperature (e.g. Oldenburg & Brune 1972; Brune & Ellis 1997; Katz et al. 2005), water representing the asthenosphere (Chemenda et al. 2002) and gelatine to simulate earthquakes (Corbi et al. 2013), although these materials often require very specialized set-ups. A major breakthrough would be the development of convenient analogue materials that would allow the simulation of both continental rifting until break-up and the subsequent creation of oceanic lithosphere (see section 3.1.3).

(2) The role of structural inheritance (compositional, structural or thermal) can be addressed in a variety of ways. Differences in lithospheric composition can be simulated by using different model materials, and is strongly related to the topic of rheology. Structural inheritance includes discrete weaknesses (linear seeds, pre-cut faults), but it may also be possible to induce pervasive features such as a regional foliation (Chattopadhyay & Chakra 2012). Furthermore, the application of multiphase deformation can be of great value. Various experimental studies focus on multiphase rifting (e.g. Keep & McClay 1997, Bonini et al. 1997), or inversion of rift basins (e.g. Brun & Nalpas 1996, Panien et al. 2005, Mattioni et al. 2007, Cerca et al. 2010) and show how pre-exiting faults may, or may not, play a role during subsequent tectonic phases. Vice versa, one could model another part of the Wilson cycle by simulating a compressional phase that is followed by rifting.

(3) Analogue models are excellent for studying faulting, but how faults develop in 3D space remains poorly constrained (Jackson et al. 2017). In order to get a more detailed grasp of fault development during rifting, analysis techniques should be optimized. Key is to fully capture model surface deformation by means of (3D) PIV/DIC methods. Also detailed 3D analysis of fault populations over time by importing 3D CT data in structural analysis software (e.g. Fedorik et al. 2019) will provide crucial insights. Such data can also be used to create (3D) synthetic seismics, that can be compared with seismic surveys from natural rift zones (Lindanger et al. 2004). Another intriguing application in this line is the use of CT-scanned models to test the validity of methods commonly used for tectonic restorations (Chauvin et al. 2018). The latter would allow the application of numerical analysis techniques and machine learning algorithms on analogue models (e.g. Corbi et al. 2019). Especially combining analogue and numerical methods to tackle a specific topic calibrates modelling results and strengthens their reliability (e.g. Bellahsen et al. 2003; Buiter et al. 2006; Panien et al. 2006b; Corti et al. 2007; Quirk et al. 2012; Zwaan et al. 2016; Brune et al. 2017; Hughes et al. 2020). Also collaboration between analogue modelling laboratories improves research quality and output. In order to promote such cooperation EPOS has created a network of labs (Multi-scale Laboratories) allowing knowledge exchange and resource sharing (https://www.epos-ip.org/tcs/multi-scale-laboratories).

(4) The development of stratigraphy in rift and passive margin settings is strongly affected by faulting, but sedimentary infill, if thick enough, can itself also affect the tectonic framework (Zwaan et al. 2018). The application of sedimentation processes in analogue models is often rather coarse: often the basin is simply filled up to the brim. Hughes et al. (2020) recently developed a device that allows localized deposition of sedimentary units, opening the way to including detailed sedimentation patterns in analogue models. Another way in which sedimentation can affect a rift system is by the formation of layers with different properties, creating rheological variations and compositional inheritances. The most extreme case is the formation of thick salt deposits, which can decouple the sedimentary cover from the underlying basement, as modelled by many researchers (e.g. McClay et al. 1998, Brun & Fort 2004, Fort et al. 2004, Vendeville 2005; Adam & Krezsek 2012, Ge et al. 2019, Fig. 3e). It may be noted that such work is of great interest for hydrocarbon exploration.

(5) The kinematics of rifting concern factors as extension directions, deformation rates, but also changes in general deformation style on the path from incipient rifting to continental break-up. Analogue models are well-suited for studying these topics, especially when addressing their 3D aspects (Figs. 4-8). An interesting challenge may concern extension boundary conditions since extension rates are also known to change over time, especially before the moment of break-up, as shown by Brune et al. (2016). The authors attribute this effect to the fact that the forces that act on a rifting plate are rather constant, but that the dwindling strength of the lithosphere towards break-up translates in a rapid acceleration of extension. Analogue modellers should attempt to incorporate such changing strain rates, at least when modelling large-scale rift systems. This could be done by either programming different extension velocities over time, or perhaps more elegantly, by applying some sort of force boundary condition by means of a weight-and-pulley system. Also here, a link with numerical models may help to explore kinematic links with the deep earth and large-scale driving forces.

(6) Finally, the influence of the mantle, which is considered a dominant factor during rifting and continental break-up should be further explored. This topic is strongly associated with rheology and kinematics, and various analogue modellers have included the mantle in their lithospheric-scale experiments (e.g. Fig. 5, Corti et al. 2003 and references therein). For these models, the inclusion of convenient analogue materials that can mimic temperature-dependent rheological changes during rifting should be a major objective. Furthermore, most lithospheric-scale models have focused on the 2D

aspects of rifting. Fully 3D efforts including oblique or rotational rifting such as applied in the works by Agostini et al. (2009), Philippon et al. (2015), and Molnar et al. (2017) will yield important insights on mantle influence within rift systems. Especially the application of advanced methods like CT-scanning and DVC analysis would greatly help to unravel the complex internal deformation of the lithosphere and the interactions between the (different components of the) crust, lithospheric mantle and the asthenosphere below.

In addition to the research focus points listed above, we must stress that considerable opportunities lie in rerunning models from previous studies. In a first step this would allow to evaluate experimental reproducibility, although this might be challenging as older publications often lack the necessary background information on rheology, set-up and the practicalities surrounding model construction. It is therefore of great importance to provide all relevant information when publishing modelling work (Zwaan et al. 2019) and to make extensive supplementary material public available via online repositories (e.g. at GFZ Data Services, which is part of the EPOS network: http://dataservices.gfz-potsdam.de). In a second step, rerunning previously published models would help to obtain more detailed and quantified insights, especially on the evolution of internal model deformation. In fact, models analysed with state-of-the-art PIV, DIC and DVC methods provide a wealth of data, revealing processes and details, as well as boundary effects that may have gone previously unnoticed (e.g. Adam & Krezsec 2012; Molnar et al. 2017; Zwaan et al. 2018, 2020). It is especially this kind of detailed observations made possible by the latest technical developments that constantly help us to revise and improve our interpretations of the natural world.

**Acknowledgements**

We thank the members of the Tectonics research group of the University of Bern's Institute of Geological Sciences, in particular Marco Herwegh, Veronica Peverelli, Timothy Schmid, Renata Schmitt, James Gilgannon, Vénice Akker and Ferdinado Musso Piantelli, for providing valuable and constructive feedback that greatly helped to improve the text.

## References


Abdelmalak, M.M., Bulois, C., Mourges, R., Galland, O., Legland, J.-B., Gruber, C. 2016. Description of new dry granular materials of variable cohesion and friction coefficient: Implications for laboratory modeling of the brittle crust. Tectonophysics 684, 39-51. https://doi.org/10.1016/j.tecto.2016.03.003

Acocella, V., Faccenna, C., Funiciello, R., Rossetti, F. 1999. Sand-box modelling of basement-controlled transfer zones in extensional domains. Terra Nova 11, 149–156. https://doi.org/10.1046/j.1365-3121.1999.00238.x

Agostini, A., Corti, G., Zeoli, A., Mulugeta, G. 2009. Evolution, pattern, and partitioning of deformation during oblique continental rifting: Inferences from lithospheric-scale centrifuge models. Geochemistry, Geophysics, Geosystems 10, Q11015. https://doi.org/10.1029/2009GC002676

Adam, J., Urai, J.L., Wieneke, B., Oncken, O., Pfeiffer, K., Kukowski, N., Lohrmann, J., Hoth, S., van der Zee, W., Schmatz, J. 2005. Shear localisation and strain distribution during tectonic faulting – new insights from granular-flow experiments and high-resolution optical image correlation techniques. Journal of Structural Geology, 27, 283-301. https://doi.org/10.1016/j.jsg.2004.08.008

Adam, J., Krezsec, C. 2012. Basin-scale salt tectonic processes of the Laurentian Basin, Eastern Canada: insights from integrated regional 2D seismic interpretation and 4D physical experiments. In: Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T., Hodgkinson, R. (eds) Salt Tectonics, Sediments and Prospectivity. Geological Society, London, Special Publications, 363, 331-360. http://dx.doi.org/10.1144/SP363.15

Adam, J., Klinkmüller, M., Schreurs, G., Wieneke, B. 2013. Quantitative 3D strain analysis in analogue experiments simulating tectonic deformation: Integration of X-ray computed tomography and digital volume correlation techniques. Journal of Structural Geology 55, 127-149. https://doi.org/10.1016/j.jsg.2013.07.011

Allemand, P., Brun, J.-P., Davy, P., Van der Driessche, J. 1989. Symétrie et asymétrie des rifts et mécanismes d'amincissement de la lithopsphère. Bulletin de la Société Géologique de France 8, 445–451. https://doi.org/10.2113/gssgfbull.V.3.445

Allemand, P., Brun, J-.P. 1991. Width of continental rifts and rheological layering of the lithosphere. Tectonophysics 188, 63-69. https://doi.org/10.1016/0040-1951(91)90314-I

Autin, J., Bellahsen, N., Husson, L., Beslier, M.-O. Leroy, S., d'Acremont, E. 2010. Analog models of oblique rifting in a cold lithosphere. Tectonics 29, TC6016. https://doi.org/10.1029/2010TC002671

Autin, J., Bellahsen. N., Leroy, S., Husson, L., Beslier, M.-O., d'Acremont, E. 2013. The role of structural inheritance in oblique rifting: Insights from analogue models and application to the Gulf of Aden. Tectonophysics 607, 51-64. http://dx.doi.org/10.1016/j.tecto.2013.05.041

Bahroudi, A., Koyi, H. A., Talbot, C. J. 2003. Effect of ductile and frictional décollements on style of extension. Journal of Structural Geology 25, 1401–1423. https://doi.org/10.1016/S0191-8141(02)00201-8

Benes, V., Scott, S.D. 1996. Oblique Rifting in the Havre Trough and Its Propagation into the Continental Margin of New Zealand: Comparison with Analogue Experiments. Marine Geophysical Researches 18, 189-201.
https://doi.org/10.1007/BF00286077

Beniest, A., Willingshofer, E, Sokoutis, D., Sassi, W. 2018. Extending Continental Lithosphere With Lateral Strength Variations: Effects on Deformation Localization and Margin Geometries. Frontiers in Earth Science 6, 148.
https://doi.org/10.3389/feart.2018.00148

Bellahsen, N., Daniel, J.-M., Bollinger, L., Burov, E. 2003. Influence of viscous layers on the growth of normal faults: insights from experimental and numerical models. Journal of Structural Geology 25, 1471-1485.
https://doi.org/10.1016/S0191-8141(02)00185-2

Bellahsen, N., Daniel, J.M. 2005. Fault reactivation control on normal fault growth: an experimental study. Journal of Structural Geology 27, 769-780.
https://doi.org/10.1016/j.jsg.2004.12.003

Beslier, M.-O. 1991. Formation des marges passives et remontée du manteau: modelisation experimentale et exemple de la marge de la Galice. Mémoires de Géosciences Rennes, 45.
https://tel.archives-ouvertes.fr/tel-00594598

Bonini, M. Souriot, T., Boccaletti, M., Brun, J.P. 1997. Successive orthogonal and oblique extension episodes in a rift zone: Laboratory experiments with application to the Ethiopian Rift. Tectonics, 16, 347– 362.
https://doi.org/10.1029/96TC03935

Boutelier, D., Oncken, O. 2011. 3-D thermo-mechanical laboratory modeling of plate-tectonics: modeling scheme, technique and first experiments. Solid Earth 2, 35–51.
https://doi.org/10.5194/se-2-35-2011

Boutelier, D., Schrank, C., Regenauer-Lieb, K. 2019. 2-D finite displacements and strain from particle imaging velocimetry (PIV) analysis of tectonic analogue models with TecPIV. Solid Earth 10, 1123–1139.
https://doi.org/10.5194/se-10-1123-2019

Brun, J.-P., Sokoutis, D., Van Den Driessche, J. 1994. Analogue modeling of detachment fault systems and core complexes. Geology 22, 319-322.
https://doi.org/10.1130/0091-7613(1994)022<0319:AMODFS>2.3.CO;2

Brun, J.-P., Beslier, M.O. 1996. Mantle exhumation at passive margins. Earth and Planetary Science Letters 142, 161-173.
https://doi.org/10.1051/bsgf/2019007

Brun, J.-P , Nalpas, T . 1996. Graben inversion in nature and experiments. Tectonics 15 (2), 677-687.
https://doi.org/10.1029/95TC03853

Brun, J.-P. 1999. Narrow rifts versus wide rifts: inferences for the mechanics of rifting from laboratory experiments. Philosophical Transactions of the Royal Society of London, A 357, 695-710.
https://doi.org/10.1098/rsta.1999.0349

Brun, J.-P. 2002. Deformation of the continental lithosphere: Insights from brittle-ductile models. In: De Meer, S., Drury, M.R., De Bresser, J.H.P., Pennoch, G.M. (eds) Deformation

Mechanisms, Rheology and Tectonics. Current Status and Future Perspectives. Geological Society, London, Special Publications, 200, 355-370. https://doi.org/10.1144/GSL.SP.2001.200.01.20

Brun, J.-P., Fort, X. 2004. Compressional salt tectonics (Angolan margin). Tectonophysics 382, 129-150. https://doi.org/10.1016/j.tecto.2003.11.014

Brune, J.N., Ellis, M.A. 1997. Structural features in a brittle–ductile wax model of continental extension. Nature 387, 67–70. https://doi.org/10.1038/387067a0

Brune, S., Williams, S., Butterworth, N., Müller, D. 2016. Abrupt plate accelerations shape rifted continental margins. Nature 536, 201–204. https://doi.org/10.1038/nature18319

Brune, S., Corti, G., Ranalli, G. 2017. Controls of inherited lithospheric heterogeneity on rift linkage: Numerical and analogue models of interaction between the Kenyan and Ethiopian rifts across the Turkana depression. Tectonics 36, 1767-1786. https://doi.org/10.1002/2017TC004739

Brune, S., Williams, S.E., Müller, R.D. 2018. Oblique rifting: the rule, not the exception. Solid Earth 9, 1187-1206. https://doi.org/10.5194/se-9-1187-2018

Buiter, S.J.H., Babeyko, A.Y., Ellis, S., Gerya, T.V., Kaus, B.J.P., Kellner, A., Schreurs, G., Yamada, Y. 2006. The numerical sandbox: comparison of model results for a shortening and an extension experiment. In: Buiter, S.J.H., Schreurs, G. (eds) Analogue and Numerical Modelling of Crustal-Scale Processes. Geological Society, London, Special Publications 253, 29–64. https://doi.org/10.1144/GSL.SP.2006.253.01.02

Cerca, M., Ferrari, L, Corti, G., Bonini, M., Manetti, P. 2010. Analogue model of inversion tectonics explaining the structural diversity of Late Cretaceous shortening in southwestern Mexico. Lithosphere 2, 172-187. https://doi.org/10.1130/L48.1

Chattopadhyay, A., Chakra, M. 2012. Influence of pre-existing pervasive fabrics on fault patterns during orthogonal and oblique rifting: An experimental approach. Marine and Petroleum Geology 39, 74-91. http://dx.doi.org/10.1016/j.marpetgeo.2012.09.009

Chauvin, B., Lovely, P., Stockmeyer, J., Plesch, A., Caumon, G., Shaw, J.H. 2018. Validating novel boundary conditions for three-dimensional mechanics-based restoration: An extensional sandbox model example. AAPG Bulletin 102, 245-266. https://doi.org/10.1306/0504171620817154

Chemenda, A., Déverchère, J., Calais, E. 2002. Three-dimensional laboratory modelling of rifting: application to the Baikal Rift, Russia. Tectonophysics 356, 253-273. https://doi.org/10.1016/S0040-1951(02)00389-X

Clifton, A.E., Schlische, R.W., Withjack, M.O., Ackermann, R.V. 2000. Influence of rift obliquity on fault-population systematics: results of experimental clay models. Journal of Structural Geology 22, 1491-1509. https://doi.org/10.1016/S0191-8141(00)00043-2

Colletta, B., Letouzey, J., Pinedo, R., Ballard, J.F., Balé, P. 1991. Computerized X-ray tomography analysis of sandbox models: Examples of thin-skinned thrust systems. Geology 19, 1063-1067. https://doi.org/10.1130/0091-7613(1991)019<1063:CXRTAO>2.3.CO;2

Corbi, F., Funiciello, F., Moroni, M., Van Dinther, Y., Mai, P.M., Dalguer, L.A., Facenna, C. 2013. The seismic cycle at subduction thrusts: 1. Insights from laboratory models. Journal of Geophysical Research: Solid Earth 118, 1483-1501. https://doi.org/10.1029/2012JB009481

Corbi, F., Sandri, L., Bedford, J., Funiciello, F., Brizzi, S., Rosenau, M., Lallemand, S. 2019. Machine Learning Can Predict the Timing and Size of Analog Earthquakes. Geophysical Research Letters 46, 1303-1311. https://doi.org/10.1029/2018GL081251

Corti, G., Bonini, B., Conticelli, S., Innocenti, F., Manetti P., Sokoutis, D. 2003. Analogue modelling of continental extension: a review focused on the relations between the patterns of deformation and the presence of magma. Earth-Science Reviews 63, 169-247. https://doi.org/10.1016/S0012-8252(03)00035-7

Corti, G., Van Wijk, J., Cloetingh, S., Morley, C.K. 2007. Tectonic inheritance and continental rift architecture: Numerical and analogue models of the East African Rift system. Tectonics 26, TC6006. https://doi.org/10.1029/2006TC002086

Corti, G. 2012. Evolution and characteristics of continental rifting: Analog modeling-inspired view and comparison with examples from the East African Rift System. Tectonophysics 522–523,1–33. https://doi.org/10.1016/j.tecto.2011.06.010

Dauteuil, O., Bourgeois, O., Mauduit, T. 2002. Lithosphere strength controls oceanic trans-form zone structure: insights from analogue models. Geophysical Journal International 150, 706-714. https://doi.org/10.1046/j.1365-246X.2002.01736.x

Donnadieu, F., Kelfoun, K., Van Wijk de Vries, B., Cecchi, E., Merle, O. 2003. Digital photogrammetry as a tool in analogue modelling: applications to volcano instability. Journal of Volcanology and Geothermal Research 123, 161-180. https://doi.org/10.1016/S0377-0273(03)00034-9

Dooley, T., McClay, K.R., Pascoe, R. 2003. 3D analogue models of variable displacement extensional faults: applications to the Revfallet Fault system, offshore mid-Norway. In: Nieuwland, D.A. (ed). New Insights into Structural Interpretation and Modelling. Geological Society, London, Special Publications, 212, 151-167. https://doi.org/10.1144/GSL.SP.2003.212.01.10

Dooley, T., Schreurs, G. 2012. Analogue modelling of intraplate strike-slip tectonics: A review and new experimental results. Tectonophysics 574–575, 1–71 http://dx.doi.org/10.1016/j.tecto.2012.05.030

Dooley. T., Hudec, M.R. 2020. Extension and Inversion of Salt-Bearing Rift Systems. Solid Earth Discussions (preprint) https://doi.org/10.5194/se-2020-3

Eisenstadt, G., Sims, D. 2005. Evaluating sand and clay models: do rheological differences matter? Journal of Structural Geology 27, 1399-1412. https://doi.org/10.1016/j.jsg.2005.04.010

Fedorik, J., Zwaan, F., Schreurs, G., Toscani, G., Bonini, L., Seno, S. 2019. The interaction between strike-slip dominated fault zones and thrust belt structures: Insights from 4D analogue models. Journal of Structural Geology 122, 89-105. https://doi.org/10.1016/j.jsg.2019.02.010

Fort, X., Brun, J.-P., Chauvel F. 2004. Salt tectonics on the Angolan margin, synsedimentary deformation processes. AAPG Bulletin 88, 1523-1544.

Ge, Z., Rosenau, M, Warsitzka, M., Gawthorpe, R.L. 2019. Overprinting translational domains in passive margin salt basins: insights from analogue modelling. Solid Earth 10, 1283–1300. https://doi.org/10.5194/se-10-1283-2019

Glerum, A., Brune, S., Stamps, D.S., Strecker, M.R. 2020. Victoria continental microplate dynamics controlled by the lithospheric strength distribution of the East African Rift. Nature Communications.
**NO DOI YET**

Gravelau, F., Malavieille, J., Dominguez, S. 2012. Experimental modelling of orogenic wedges: A review. Tectonophysics 538-540, 1–66 https://doi.org/10.1016/j.tecto.2012.01.027

Hall, J. Sir. 1815. On the vertical position and convolutions of certain strata and their relation with granite. Royal Society of Edinburgh Transactions, 7, 79-108. https://doi.org/10.1017/S0080456800019268

Hubbert, M.K. 1937. Theory of scaled models as applied to the study of geological structures. Geological Society of America Bulletin 48, 1459-1520.

Hughes, A., Adam, J., Burgess, P. 2020. Integrating analogue and numerical modelling techniques for improved simulation of coupled regional tectonic processes and syn-depositional systems. EGU General Assembly. EGU2020-5059 https://doi.org/10.5194/egusphere-egu2020-5059

Holland, M., Urai, J.L., Martel, S. 2006. The internal structure of fault zones in basaltic sequences. Earth and Planetary Science Letters 248, 286–300. https://doi.org/10.1016/j.epsl.2006.05.035

Jackson, C.A.-L., Bell. R.E., Torevatn, A., Tvedt, A.B.M. 2017. Techniques to determine the kinematics of synsedimentary normal faults and implications for fault growth models. In: Childs, C., Holdsworth, R.E., Jackson, C.A.-L., Manzocchi, T., Walsch, J.J., Yielding, G. (eds). The Geometry and Growth of Normal Faults. Geological Society, London, Special Publications 439. https://doi.org/10.1144/SP439.22

Katz, R.F., Ragnarsson, R., Bodenschatz, E., 2005. Tectonic microplates in a wax model of sea-floor spreading. New Journal of Physics 7, 37 https://doi.org/10.1088/1367-2630/7/1/037

Keep, M., McClay, K.R. 1997. Analogue modelling of multiphase rift systems. Tectonophysics 273, 239-270. https://doi.org/10.1016/S0040-1951(96)00272-7

Klinkmüller, M., Schreurs, G., Rosenau, M., Kemnitz, H. 2016. Properties of granular analogue model materials: A community wide survey, Tectonophysics, 684, 23–38, https://doi.org/10.1016/j.tecto.2016.01.017

Koyi, H. 1997. Analogue modelling: From a qualitative to a quantitative technique – a historical outline. Journal of Petroleum Geology 20, 223-238.
https://doi.org/10.1130/GSAB-48-1459

Le Calvez, J.H. 2002. Physcial modelling of normal faults and graben relays above salt. PhD Thesis, University of Texas, Austin.
http://hdl.handle.net/2152/11057

Le Calvez, J.H., Vendeville, B.C. 2002. Experimental designs to model along-strike fault interaction. In: Schellart, W .P ., Passchier, C. (eds.) Analogue modelling of large-scale tectonic processes. Journal of the Virtual Explorer 7, 1-17.
https://doi.org/10.3809/jvirtex.2002.00043

Lindanger, R., Øygaren, M., Gabrielsen, R.H., Mjelde, R., Randen, T., Tjøstheim, B.A. 2004. Analogue (plaster) modelling and synthetic seismic representation of hangingwall fault blocks above ramp-flat ramp extensional faults. First Break 22, 33-41.
http://old.earthdoc.org/publication/publicationdetails?publication=25747

Martí, J., Geyer, A., Folch, A., Gottsmann, J. 2008. A Review on Collapse Caldera Modelling. In: Gottsmann, J., Martíacute, J. Caldera Volcanism: Analysis, Modelling and Response. Developments in Volcanology 10, 233-283
https://doi.org/10.1016/S1871-644X(07)00006-X

Martin, A.K. 1984. Propagating rifts: Crustal extension during continental rifting. Tectonics 3, 611-617.
https://doi.org/10.1029/TC003i006p00611

Mattioni, L., Sassi, W., Callot, J.-P. 2007 Analogue models of basin inversion by transpression: role of structural heterogeneity. In: Ries, A.C., Butler, R.W.H., Graham, R.H. (eds). Deformation of the Continental Crust. The Legacy of Mike Coward. Geological Society, London, Special Publications, 272, 3974 17.
https://doi.org/10.1144/GSL.SP.2007.272.01.20

McClay, K.R. 1990. Extensional fault systems in sedimentary basins: a review of analogue model studies. Marine and Petroleum Geology 7, 206-233.
https://doi.org/10.1016/0264-8172(90)90001-W

McClay, K.R., White, M.J. 1995. Analogue modelling of orthogonal and oblique rifting. Marine and Petroleum Geology 12, 137- 151.
https://doi.org/10.1016/0264-8172(95)92835-K

McClay, K.R. 1996. Recent advances in analogue modelling: uses in section interpretation and validation. In: Buchanan, E.G., Nieuwland, D.A. (eds). Modern Developments in Structural Interpretation, Validation and Modelling. Geological Society Special Publications 99, 201-225.
https://doi.org/10.1144/GSL.SP.1996.099.01.16

McClay, K.R., Dooley, T., Lewis, G. 1998. Analog modeling of progradational delta systems. Geology 26, 771-774.
https://doi.org/10.1130/0091-7613(1998)026<0771:AMOPDS>2.3.CO;2

McClay, K.R., Dooley, T., Whitehouse, P., Mills, M. 2002. 4-D evolution of rift systems: Insights from scaled physical models. AAPG Bulletin 86, 935-959.
https://doi.org/10.1306/61EEDBF2-173E-11D7-8645000102C1865D

McFall, B.C., Fritz, H.M. 2016 Physical modelling of tsunamis generated by three-dimensional deformable granular landslides on planar and conical island slopes. Proceedings of the Royal Society A 472, 20160052.

http://dx.doi.org/10.1098/rspa.2016.0052

Michon, L., Merle, O. 2000. Crustal structures of the Rhinegraben and the Massif Central grabens: An experimental approach. Tectonics 19, 896-904. https://doi.org/10.1029/2000TC900015

Michon, L., Merle, O. 2003. Mode of lithospheric extension: Conceptual models from analogue modeling. Tectonics 22, 1028. https://doi.org/10.1029/2002TC001435

Michon, L., Sokoutis, D. 2005. Interaction between structural inheritance and extension direction during graben and depocentre formation: An experimental approach. Tectonophysics 409, 125-146. https://doi.org/10.1016/j.tecto.2005.08.020

Molnar, N.E., Cruden, A.R., Betts, P.G. 2017. Interactions between propagating rotational rifts and linear rheological heterogeneities: Insights from three-dimensional laboratory experiments. Tectonics 36, 420-443. https://doi.org/10.1002/2016TC004447

Molnar, N.E., Cruden, A.R., Betts, P.G. 2018. Unzippingg continents and the birth of microcontinents. Geology 46, 451–454 https://doi.org/10.1130/G40021.1

Molnar, N.E., Crusden, A. R., Betts, P.G. 2019. Interactions between propagating rifts and linear weaknesses in the lower crust. Geosphere 15, 1617-1640. https://doi.org/10.1130/GES02119.1

Montanari, D., Agostini, A., Bonini, M., Corti, G., Del Ventisette, C., 2017. The Use of Empirical Methods for Testing Granular Materials in Analogue Modelling. Materials 10, 635. https://doi.org/10.3390/ma10060635

Naylor, M.A., Mandl, G., Sijpesteijn, C.H.K. 1986. Fault geometries in basement-induced wrench faulting under different initial stress states. Journal of Structural Geology 8, 737-752. https://doi.org/10.1016/0191-8141(86)90022-2

Naylor, M.A., Laroque, J.M., Gauthier, B.D.M. 1994. Understanding extensional tectonics: insights from sandbox models. Roure, F.; Ellouz, N.; Shein, V.S.; Skvortsov, I.I. (eds). Geodynamic evolution of sedimentary basins. International Symposium on Geodynamic Evolution of Sedimentary Basins, Moscow (Russian Federation). Technip, 92 (France), 69-83.

Nestola, Y., Storti, F., Cavozzi, C. 2015. Strain rate-dependent lithosphere rifting and necking architectures in analog experiments. Journal of Geophysical Research: Solid Earth 120, 584-594. https://doi.org/10.1002/2014JB011623

Oldenburg, D.W., Brune, J.N. 1972. Ridge Transform Fault Spreading Pattern in Freezing Wax. Science 178, 301-304. https://doi.org/10.1126/science.178.4058.301

Panien, M., Schreurs, G, Pfiffner, A. 2005. Sandbox experiments on basin inversion: testing the influence of basin orientation and basin fill. Journal of Structural Geology 27, 433-445. https://doi.org/10.1016/j.jsg.2004.11.001

Panien, M., Schreurs, G, Pfiffner, A. 2006(a). Mechanical behaviour of granular materials used in analogue modelling: insights from grain characterisation, ring-shear tests and analogue experiments. Journal of Structural Geology 28, 1710-1724.

https://doi.org/10.1016/j.jsg.2006.05.004

Panien, M, Buiter, S.J.H., Schreurs, G., Pfiffner, O.A. 2006(b). Inversion of a symmetric basin: insights from a comparison between analogue and numerical experiments. In: Buiter, S.J.H., Schreurs, G. (eds). AnalogueandNumericalModellingofCrustal-ScaleProcesses. Geological Society, London, Special Publications 253, 253-270. https://doi.org/10.1144/GSL.SP.2006.253.01.13

Peron-Pinvidic, G., Manatschal, G., "IMAGinING RIFTING" Workshop Participants. 2019. Rifted Margins: State of the Art and Future Challenges. Frontiers in Earth Sciences 7, 208 https://doi.org/10.3389/feart.2019.00218

Philippon, M., Willingshofer, E., Sokoutis, D., Corti, G., Sani, F., Bonini, M., Cloetingh, S. 2015. Slip re-orientation in oblique rifts. Geology 43, 147-150. https://doi.org/10.1130/G36208.1

Poppe, S., Holohan, E.P., Galland, O., Buls, N., Van Gompel, G., Keelson, B., Tournigand, P.-Y., Brancart, J., Hollis, D., Nila, A., Kervyn, M. An Inside Perspective on Magma Intrusion: Quantifying 3D Displacement and Strain in Laboratory Experiments by Dynamic X-Ray Computed Tomography. Frontiers in Earth Science 7, 62. https://doi.org/10.3389/feart.2019.00062

Quirk, D.G., Schødt, N., Lassen, B., Ings, S.J., Hsu, D., Hirsch, K.K., Von Nicolai, C. 2012. Salt tectonics on passive margins: examples from Santos, Campos and Kwanza basins. In: Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T., Hodgkinson, R. (eds). Salt Tectonics, Sediments and Prospectivity. Geological Society, London, Special Publications 363, 207 – 244. http://dx.doi.org/10.1144/SP363.10

Ramberg, H. 1981. Gravity, Deformation and the Earth's Crust. Academic Press, London.

Reber, J., Cooke, M.L. Dooley, T.P. 2020. What model material to use? A Review on rock analogs for structural geology and tectonics. Earth-Science Reviews. https://doi.org/10.1016/j.earscirev.2020.103107

Ritter, M.C., Leever, K., Rosenau, M., Onchen, O. 2016. Scaling the sandbox—Mechanical (dis) similarities of granular materials and brittle rock. Journal of Geophysical Research: Solid Earth 121, 6863-6879. https://doi.org/10.1002/2016JB012915

Rudolf, M., Boutelier, D., Rosenau, M., Schreurs, G., Oncken, O. 2016. Rheological benchmark of silicone oils used for analog mod- eling of short- and long-term lithospheric deformation, Tectono- physics 684, 12–22 https://doi.org/10.1016/j.tecto.2015.11.028

Schellart, W.P., Strak, V. 2016. A review of analogue modelling of geodynamic processes: Approaches, scaling, materials and quantification, with an application to subduction experiments, J. Geo- dyn., 100, 7–32. https://doi.org/10.1016/j.jog.2016.03.009

Schlagenhauf, A., Dominguez, S., Malavieille, J., Manighetti, I. 2008. Incremental growth of normal faults: Insights from a laser-equipped analog experiment. Earth and Planetary Science Letters 273, 299–311. https://doi.org/10.1016/j.epsl.2008.06.042

Schreurs, G., Hänni, R., Panien, M., Vock, P. 2003. Analysis of analogue models by helical X-ray computed tomography. In: Mees, F., Swennen, R., Van Geet, M., Jacobs, P. Applications of X-ray Computed Tomography in the Geosciences. GeologicalSociety, London, Special Publications 215, 213-223. https://doi.org/10.1144/GSL.SP.2003.215.01.20

Souriot, T., Brun, J.-P. 1992. Faulting and block rotation in the Afar triangle, East Africa: The Danakil "crank-arm" model. Geology 20, 911-914. https://doi.org/10.1130/0091-7613(1992)020<0911:FABRIT>2.3.CO;2

Sun., Z., Zhong, Z., Keep, M., Zhou, D., Cai, D., Li, X., Wu, S., Jiang, J. 2009. 3D analogue modelling of the South China Sea: A discussion on breakup pattern. Journal of Asian Earth Sciences 34, 544-556. https://doi.org/10.1016/j.jseaes.2008.09.002

Tentler, T. 2003a. Analogue modeling of overlapping spreading centers: insights into their propagation and coalescence. Tectonophysics 376, 99-115. https://doi.org/10.1016/j.tecto.2003.08.011

Tentler, T. 2003b. Analogue modeling of tension fracture pattern in relation to mid-ocean ridge propagation. Geophysical Research Letters 30, 1268. https://doi.org/10.1029/2002GL015741

Trippanera, D., Acocella, V. Ruch, J. 2014. Dike‐induced contraction along oceanic and continental divergent plate boundaries. Geophysical Research Letters 41, 7098-7104. https://doi.org/10.1002/2014GL061570

Tron, V., Brun, J.-P. 1991. Experiments on oblique rifting in brittle-ductile systems. Tectonophysics, 188, 71–88. https://doi.org/10.1016/0040-1951(91)90315-J

Van Mechelen, J.L.M. 2004. Strength of moist sand controlled by surface tension for tectonic analogue modelling. Tectonophysics 384, 275-284. https://doi.org/10.1016/j.tecto.2004.04.003

Vendeville, B., Cobbold, P.R., Davy, P., Brun, J.-P ., Choukroune, P . 1987. Physical models of extensional tectonics at various scales. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (eds.) Continental Extensional Tectonics. Geological Society, London, Special Publications 28, 95-107. https://doi.org/10.1144/GSL.SP.1987.028.01.08

Vendeville, B.C. 2005. Salt tectonics driven by sediment progradation: Part I—Mechanics and kinematics. AAPG Bulletin 89, 1071-1079. https://doi.org/10.1306/03310503063

Vink, G.E. 1982. Continental Rifting and the Implications For Plate Tectonic Reconstructions. Journal of Geophysical Research 87, 10,667-10,688. https://doi.org/10.1029/JB087iB13p10677

Wang, J., Jiang, Z., Zhang, Y., Gao, L., Wei, X., Zhang, W., Liang, Y., Zhang, H. 2015. Flume tank study of surface morphology and stratigraphy of a fan delta. Terra Nova 27, 42-53. https://doi.org/10.1111/ter.12131

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

Withjack, M.O., Henza, A.A., Schlische, R.W. 2017. Three-dimensional fault geometries and interactions within experimental models of multiphase extension. AAPG Bulletin 101, 1767-1789.
https://doi.org/10.1306/02071716090

Wu, J.E., McClay, K., Whitehouse, P., Dooley, T. 2009. 4D analogue modelling of transtensional pull-apart basins. Marine and Petroleum Geology 26, 1608-1623.
https://doi.org/10.1016/j.marpetgeo.2008.06.007

Zwaan, F., Schreurs, G., Naliboff, J., Buiter, S.J.H. 2016. Insights into the effects of oblique extension on continental rift interaction from 3-D analogue and numerical models. Tectonophysics 693, 239–260.
https://doi.org/10.1016/j.tecto.2016.02.036

Zwaan, F., Schreurs, G. 2017. How oblique extension and structural inheritance influence rift segment interaction: Insights from 4D analog models. Interpretation 5, SD119–SD138.
http://dx.doi.org/10.1190/INT-2016-0063.1

Zwaan, F., Schreurs, G., Adam, J. 2018. Effects of sedimentation on rift segment evolution and rift interaction in orthogonal and oblique extensional settings: Insights from analogue models analysed with 4D X-ray computed tomography and digital volume correlation techniques. Global and Planetary Change 171, 110– 133.
https://doi.org/10.1016/j.gloplacha.2017.11.002

Zwaan, F., Scheurs, G., Buiter, S.J.H. 2019. A systematic comparison of experimental set-ups for modelling extensional tectonics. Solid Earth 10, 1063-1097.
https://doi.org/10.5194/se-10-1063-2019

Zwaan, F., Schreurs, G., Rosenau, M. 2020. Rift propagation in rotational versus orthogonal extension: Insights from 4D analogue models. Journal of Structural Geology 135
https://doi.org/10.1016/j.jsg.2019.103946