Analogue modelling of basin inversion: the role of oblique kinematics and implications for the Araripe Basin (Brazil)

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Abstract.

Basin inversion is a process that takes place when a sedimentary basin is subjected to compressional stresses resulting in reactivation of pre-existing faults and/or localization of deformation along new reverse faults. The Araripe Basin (NE Brazil) is an example of a Cretaceous intracontinental aborted rift with its sedimentary infill found at ca. 1000 m altitude~~ in the present day~~. Post-rift basin inversion ~~is proposed~~ has been proposed by previous authors as the cause of this topographic high~~,~~, but ~~. hHhowever h~~ow inversion ~~mechanisms~~ affected this basin~~, however, is still~~ remains a matter of debate, with two end member scenarios: reactivation of pre-existing normal faults leading to local uplift, or regional ~~tectonic~~ uplift~~, but neither~~. Neither end member fully explains the observations from seismic and field data. ~~.~~ In this study, we therefore conducted analogue models ~~of basin inversion~~ to explore how basin inversion in the Araripe Basin could have taken place~~test these scenarios~~. We present two series of crustal-scale brittle-viscous experiments: i) ~~extension~~ extension followed by ~~compression~~ compression without sedimentation, with a variation ~~of~~ in ~~rifting~~ divergence and ~~inversion~~ convergence directions (orthogonal or 45° oblique) and ii) ~~extension~~ extension ~~and~~ followed by ~~compression~~ compression with syn-rift sedimentation, with the same variation in rifting and inversion directions. We ~~used~~ applied a seed representing a structural weakness ~~that was applied~~ at the base of the brittle layer to localize deformation along the model axis. We found that orthogonal rifting without sedimentation forms through-going ~~border~~ graben boundary faults, whereas oblique rifting initially creates ~~initial en echelon~~*en échelon* faults that eventually link up creating large ~~border~~ graben boundary faults. Rift basins with syn-rift sedimentation evolved in a similar fashion, however sedimentary loading resulted in increased subsidence. During both oblique and orthogonal inversion, most ~~deformation~~ shortening is accommodated along new ~~low~~ low-angle reverse faults~~. Within that framework,~~. S~~S~~ignificant intra-graben fault reactivation ~~occurred~~ occurred in all models without syn-rift sedimentation. By contrast, ~~syn-rift sedimentation~~ orthogonal inversion of models with syn-rift sedimentation did not reactivate rift faults, whereas ~~caused~~ only minor reactivation of rift faults took place ~~in~~ during oblique

inversion since the sediments acted as a buffer during ~~compression~~convergence.~~;~~ ~~no rift fault reactivation occurred in orthogonal compression situations.~~ Based on ~~these~~our modelling results, ~~Comparing the existing scenarios for inversion in the Araripe Basin with our model results and field data show that these scenarios do not fully explain the natural example. Therefore, w~~we propose an alternative scenario for ~~basin inversion in~~the evolution of the Araripe Basin, ~~based on our models,~~ involving oblique ~~compression~~ inversion and the development of ~~low-~~ low-angle reverse faults, which better ~~explains inversion in the Araripe Basin~~fits observations from seismic lines and field data from the region.

1 Introduction

The ~~tectonic~~ inversion of sedimentary basins as a result of compressional tectonics is a widely discussed topic due to its importance for the development of mineral (Sibson and Scott, 1998) and hydrocarbon deposits (Turner and Williams, 2004). Especially inverted intraplate rift basins that are currently ~~situated~~ exposed above sea level can play an important role for the understanding of their offshore equivalents, since they provide access to outcrops that otherwise can only be analyzed via indirect geophysical methods (e.g., Stanton et al., 2014; Rebelo et al., 2021).

In this context, the Araripe Basin in NE Brazil ~~(Fig. 1),~~ is an excellent example of an exposed inverted intraplate rift basin (Fig. 1). This Early Cretaceous rift basin is part of the aborted Brazilian Northeast Rift System (BNRS) (de Matos, 1992) located at the intersection of the equatorial and central segments of the South Atlantic Ocean (Moulin et al., 2010). This rift system formed within the well-developed network of NE-SW and E-W striking Precambrian ductile shear zones in the basement of the Borborema Province (Fig. 1a) (Vauchez et al., 1995; Brito Neves et al., 2000; Ganade de Araujo et al., 2014). The rift structures of the Araripe Basin ~~are mainly~~mainly strike NE-SW ~~and E-W~~ (Fig.1a), indicating brittle reactivation of the basement shear zones during rifting (de Matos, 1992)~~, especially the dextral~~ ~~sinistral~~ ~~reactivation of the E-W Patos Shear Zone bounding the north of the basin~~ (Fig. 1a). However, the exact kinematics of rifting during Araripe Basin remain a matter of debate, with some authors proposing orthogonal kinematics, whereas others invoke transtension (e.g., Rosa et al. 2022)~~.~~.

After rifting and subsequent thermal subsidence (Assine, 2007), the basin registered a phase of inversion (Fig. 1b) (Marques et al., 2014) and its sedimentary infill is presently situated, at its highest point, at 1000 m above sea level and ca. 500 m above the surrounding basement. Similarly, the Borborema Province generally contains high topographies and evidence of recent uplift (Lamarque and Julià, 2019; Neto et al., 2019), and o~~. O~~ther basins in the BNRS also present evidence of tectonic inversion (Gurgel et al., 2013; Nogueira et al., 2015; Vasconcelos et al., 2021; Bezerra et al., 2020; Ramos et al., 2022). In the Araripe Basin, Marques et al. (2014) proposed that inversion resulted from far-field ENE-WSW directed horizontal maximum compressive stress. They concluded that this deformation is consistent with the formation of new oceanic crust in the South Atlantic to the east and the development of the Andes to the west, resulting in overall compression of the South America plate (Marques et al., 2013).

According to Marques et al. (2014), this compression caused ~~the complete~~large-scale inversion of the initial high angle normal faults of the Araripe Basin (Fig. 1e) through ~~an~~ oblique ~~compression~~ convergence and injection of soft material into these faults. By contrast, Peulvast and Bétard, (2015) proposed that the present-day topographic elevation of the basin is due to ~~the~~ regional uplift of the Borborema Province and the action of differential erosion (Fig. 1d). The Peulvast and Bétard (2015) scenario fits with the general absence of large-scale inversion of normal faults as seen on seismic sections from the Araripe Basin (Ponte and Ponte-filho, 1996, Rosa et al., 2022). However, on closer inspection, these seismic sections do in fact show a limited degree of normal fault inversion (Ponte and Ponte-filho, 1996, Rosa et al., 2022), and localized reverse faulting linked to basin inversion is observed in nearby basins of the same age as well (e.g., the Rio do Peixe Basin, Vasconcelos et al., 2021). As such, the exact mechanism causing inversion, and to what degree rift structures were reactivated in the Araripe Basin remains unclear, requiring further

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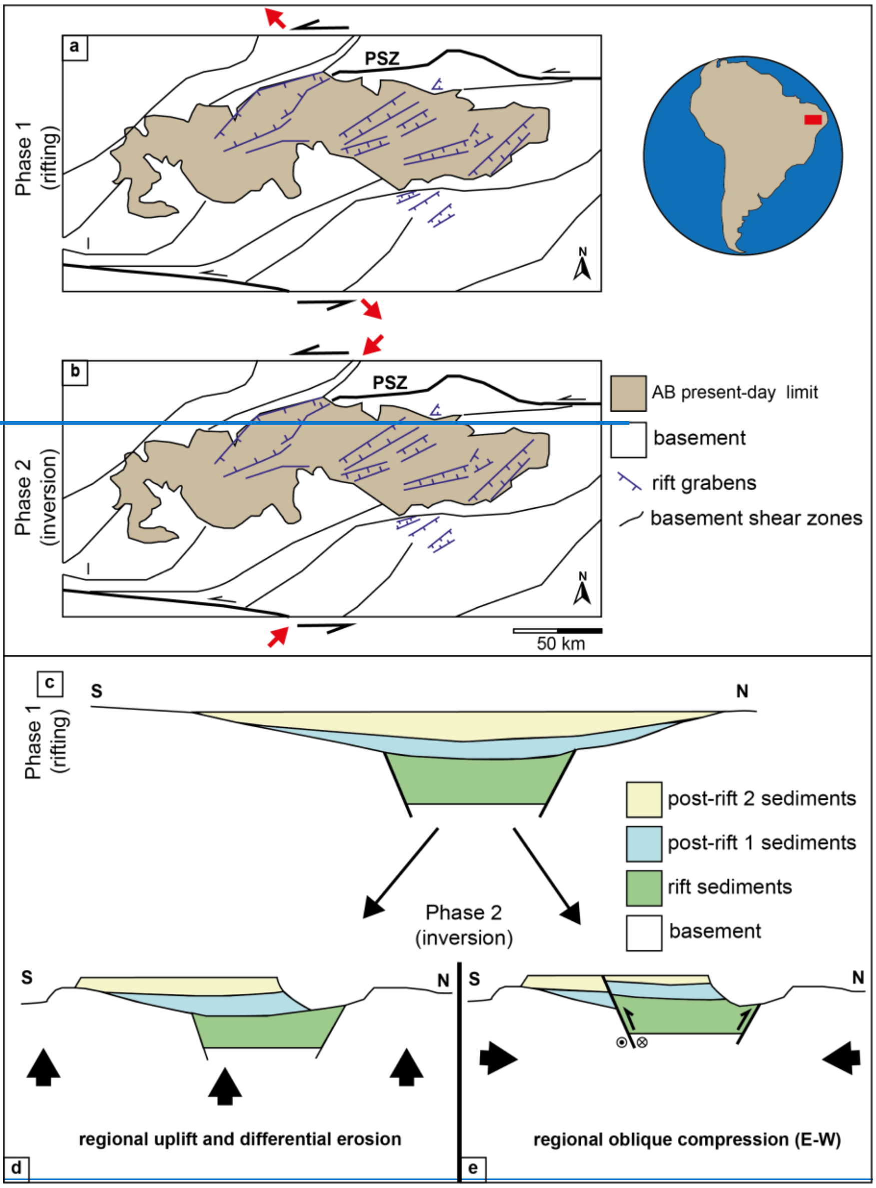
research with new approaches. One of these new approaches is the use of analogue modelling, which has shown to be a useful tool to understand the evolution of inverted basins and the mechanisms involved in various settings (Brun and Nalpas, 1996; Nalpas et al, 1995; Panien et al., 2005a; del Ventisette et al., 2005, 2006; Marques and Nogueira, 2008; Pinto et al., 2010a; di Domenica et al., 2014; Jara et al., 2018; Zwaan et al., 2022b).

In this paper we therefore present the results of new analogue modeling experiments with a novel set-up, which are aimed at evaluating ~~whether~~ whether ~~horizontal compression~~tectonic compression could have ~~indeed have~~ caused the inversion observed in the Araripe Basin. ~~the normal fault reactivation and full basin extrusion in the Araripe Basin as proposed by Marques et al. (2014), or whether regional uplift and differential erosion as proposed by Peulvast and Bétard (2015) forms a better explanation.~~ In our models we test the influence of orthogonal (α=0) or oblique (α=45°) ~~extension~~divergence, followed by either orthogonal or oblique ~~compression~~convergence, as well as syn-rift sedimentation on ~~rift~~ initial basin development and on subsequent inversion structures. We then compare our model results with data from ~~the Araripe Basin~~nature~~, example in order to provide~~and propose an updated scenario for inversion ~~in~~of the Araripe Basin involving oblique inversion and the development of low-angle reverse faults outside the basin.~~- new insights on this basin compressional inversioninversion models by Marques et al. (2014) and Peulvast and Bétard (2015) and propose a new interpretation of how inversion took place in the basin.~~


a
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Phase 1 (rifting)
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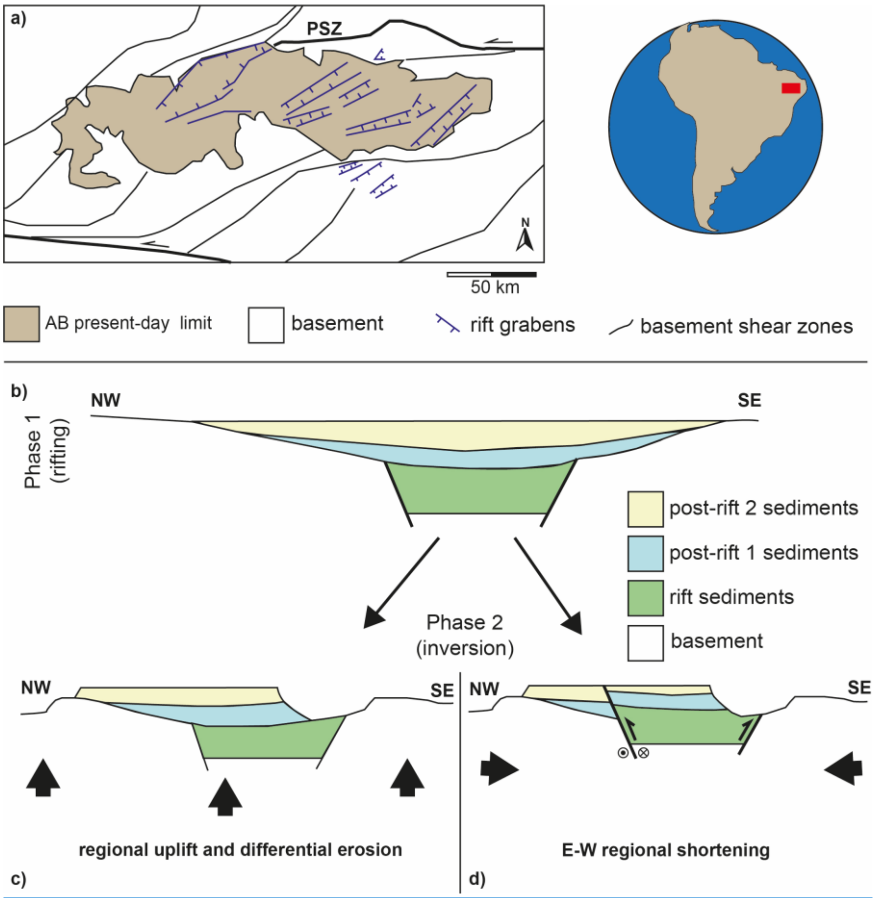


Figure 1: a) Structural geology of the study area and present-day Araripe Basin (AB). ~~(a)~~ NE-SW rift related structures (in blue) and Precambrian basement shear zones (in black), modified after Camacho and de Oliveira ~~E~~ e Sousa (2017). PSZ: Patos Shear Zone. ~~b) Inversion kinematics after Marques et al. (2014).~~ b~~c~~) Schematic N-S ~~cross~~ section representing rift and ~~post~~ post-rift formations in the Araripe Basin prior to inversion. ~~d~~c) Schematic representation of the Araripe Basin inversion model based on regional uplift followed by differential erosion proposed by Peulvast and Bétard (2015). ~~e~~d) Schematic representation of the Araripe Basin inversion model as a result of regional oblique ~~compression~~ convergence proposed by Marques et al. (2014).

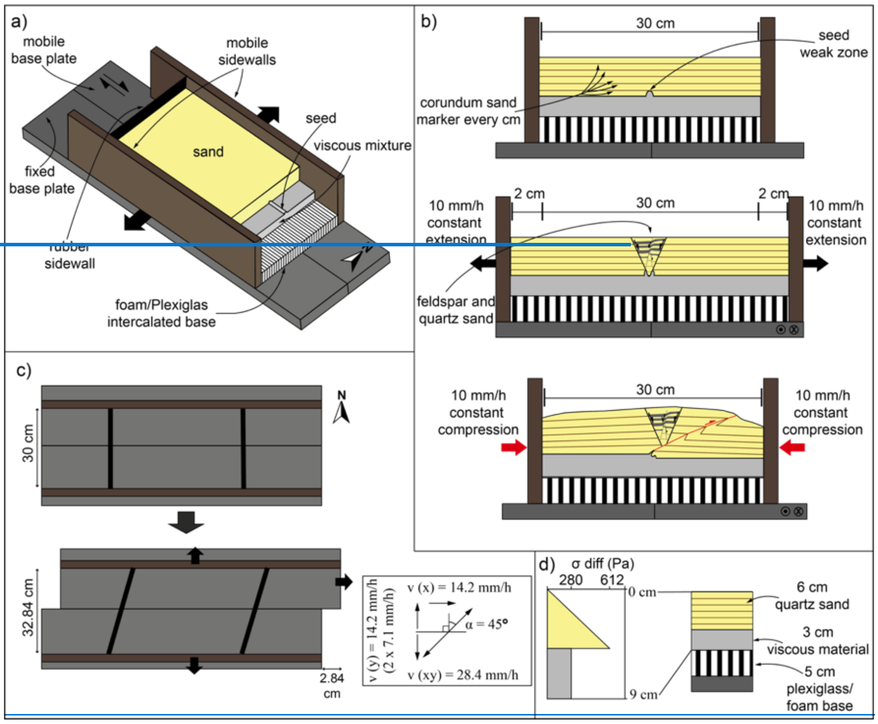
2 Methods

2.1 Model set up

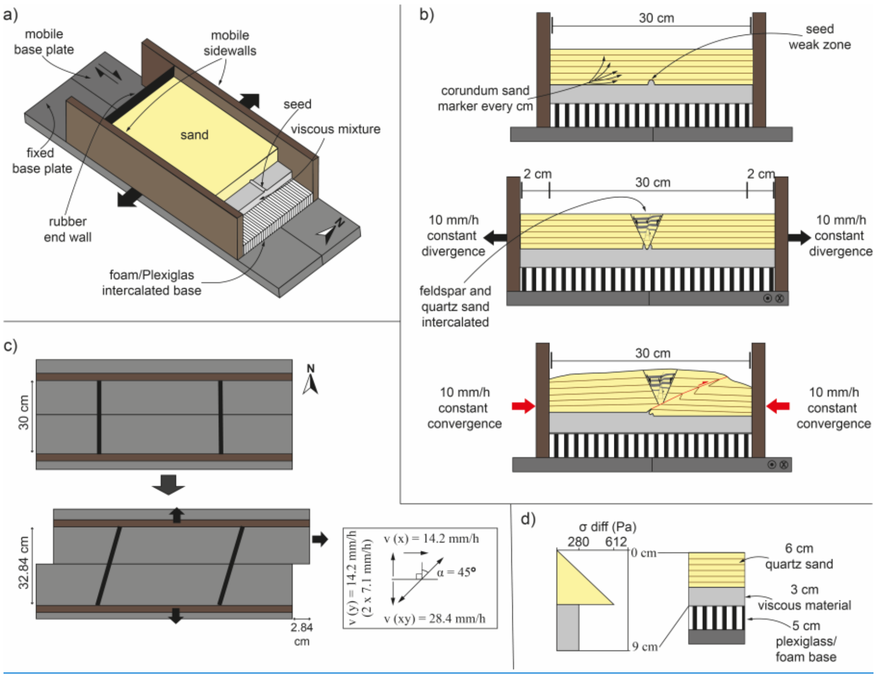
For this study of crustal-scale basin inversion processes, we used an experimental set-up involving two long mobile sidewalls, two rubber ~~sidewalls~~ end walls (fixed between the mobile walls, closing the short model ends), and a base consisting of a mobile and a fixed base plate (Fig. 2a). We positioned a 5 cm ~~high~~ thick block consisting of ~~an intercalation of~~intercalated foam (1 cm thick) and Plexiglas (0.5 cm thick) bars above the base plates and between the long sidewalls (Fig. 2a,b). This foam/Plexiglas block, initially 36.5 cm wide, was compressed prior to adding the model materials in order to reach the initial ~~experiment~~ width of 30 cm (Fig. 2a,b). ~~This set-up has been regularly used for orthogonal and oblique rifting, and compression transpression models (Schreurs and Colletta, 1998, 2002; Zwaan and Schreurs, 2017; Zwaan et al., 2016, 2018a, 2020; Schmid et al, 2022a, b).~~ ~~The d~~Divergence of the mobile long sidewalls, achieved by high-precision computer-controlled motors, simulates an initial rifting phase inducing uniform orthogonal ~~extension~~ divergence into the overlying brittle and viscous model materials that represent the brittle upper crust and ductile lower crust, respectively. For orthogonal convergence during the subsequent inversion phase, the sidewalls are simply moved together again. During oblique divergence and oblique convergence, which we apply to account for possible different deformation kinematics during basin formation and inversion, such as proposed by e.g. Marques et al. (2014) and Rosa et al. (2022), additional lateral motion of ~~the~~ one mobile base plate ~~on one side of the experiment~~ was applied (Fig. 2c).

In order to localize deformation in our models, creating a graben during the initial rifting phase, we introduce a linear seed on the top of the viscous layer that was made from the same viscous material as used for the lower crustal layer (~~e.g.~~e.g., Le Calvez & Vendeville 2002; Molnar et al., 2019, 2020; Zwaan and Schreurs, 2017). This seed was a semi-cylindrical ridge with a c. 1 cm diameter, and was placed in the same position in each model (i.e. along the central axis of the model, Fig. 2a,b).

Our general model set-up has been regularly used for orthogonal and oblique rifting, and transpression models (Schreurs and Colletta, 1998, 2002; Zwaan and Schreurs, 2017; Zwaan et al., 2016, 2018a, 2020; Schmid et al, 2022a, b), but so far only Guillaume et al. (2022) have applied a similar foam-based set-up for basin inversion modelling, with the fundamental difference that shortening in their models was perpendicular to the divergence direction. Our model set-up design is also fundamentally different from previous basin inversion model set-ups involving base plates and/or sidewalls for orthogonal and oblique basin inversion (e.g. Brun and Nalpas, 1996; Nalpas et al, 1995, see also Zwaan et al. 2022b, and references therein).



a)
mobile base plate
mobile sidewalls
seed
viscous mixture
sand
fixed base plate
rubber sidewall
foam/Plexiglas intercalated base
b)
30 cm
seed weak zone
corundum sand marker every cm
2 cm
10 mm/h constant extension
feldspar and quartz sand
10 mm/h constant compression
c)
30 cm
32.84 cm
2.84 cm
N
v (x) = 14.2 mm/h
v (y) = 14.2 mm/h (2 x 7.1 mm/h)
α = 45°
v (xy) = 28.4 mm/h
d)
σ diff (Pa)
280
612
0 cm
9 cm
6 cm quartz sand
3 cm viscous material
5 cm plexiglass/ foam base



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30 cm
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corundum sand marker every cm
2 cm
10 mm/h constant divergence
feldspar and quartz sand intercalated
10 mm/h constant convergence
c)
30 cm
32.84 cm
2.84 cm
N
v (x) = 14.2 mm/h
v (y) = 14.2 mm/h (2 x 7.1 mm/h)
α = 45°
v (xy) = 28.4 mm/h
d)
σ diff (Pa)
280
612
0 cm
9 cm
6 cm quartz sand
3 cm viscous material
5 cm plexiglass/ foam base

Figure 2: Experimental set-up adopted for this study. a) 3D cut-out view showing the brittle-viscous layers on top of the Plexiglas/foam base of the experiment (north arrow added for reference in the models). b) Schematic example of a sedimentation model run in 2D. c) Top view example of movement direction of the experimental apparatus used in this study (oblique ~~extension~~ divergence example, with definition of divergence and ~~compression~~ convergence obliquity as angle α. Note that angle α is positive for dextral oblique divergence, as well as for sinistral oblique convergence. Vice versa, angle α is negative for sinistral oblique divergence and for dextral oblique convergence). d) Schematic strength profile indicating the crustal setting represented in our models.

2.2 Materials

We utilized brittle and viscous analogue materials (material properties summarized in Table 1) to reproduce the brittle and ductile parts of the upper and lower crust in our experiments.

A 3 cm thick viscous layer served to replicate a 10 km thick lower crust. This material consists of a near-Newtonian (η = ca. $1.5 \cdot 10^5$ Pa · s ; n = 1.05-1.10, Zwaan et al., 2018c) mixture of SGM-36 Polydimethylsiloxane (PDMS) and corundum sand ($\rho_{specific}$ = 3950 kg/m^3, https://www.carloag.ch). We mixed the components according to a 0.965: 1.00 weight ratio, resulting in a viscous mixture with a density of ca. 1600 kg/m^3.

We applied a 6 cm thick layer of fine quartz sand (ø = 60-250 µm~~,~~ and ϕ = 31.4-36.1˚, ~~Table 1~~Zwaan et al. 2018a) sieved on top of the viscous layer, representing a 20 km brittle upper crust ~~(Zwaan et al. 2018a)~~. The sand was flattened at 1 cm intervals with a scraper to avoid lateral variation in sand layer thickness during the model preparation. We sieved the sand from ca. 30 cm height to ensure a constant brittle layer density of ca. 1560 kg/m^3 (e.g. Klinkmüller et al., 2016; Schmid et al., 2020).

We used layers of feldspar sand (grain size range~~ø~~ = 100-250 ~~µu~~µm and ϕ = 29.9-35˚, Zwaan et al., 2022c) intercalated with layers of quartz sand for sedimentary infill in order to provide a visual record of syn-rift units on ~~cross~~ sections (Fig. 2b). The sand application was done by hand, using a paper cone with an opening of 3 mm at the tip. The flux of sand was controlled by pressing the opening of the cone and we filled the graben up to the general model surface. ~~The use of feldspar sand as syn-rift sediment is not considered to significantly impact model evolution due to the very similar characteristics to our quartz sand (Zwaan et al., 2022).~~

Furthermore, we added thin <1 mm thick marker intervals of fine corundum sand (grain size range~~ø~~ = 88-125 µm~~mu~~) to the quartz sand layer, which allowed for the tracing of deformation in ~~cross~~ section view (Fig. 2b). These thin intervals were sieved in during the scraping intervals (every cm) and are not considered to have an impact on model evolution.

Table 1: Materials properties

Granular materials	**Quartz sand**[a]	**Corundum sand**[b]	**Feldspar sand**[h]
Grain size range (ø)	60-250 µm	88-125 µm	100-250 µm
Specific density ($\rho_{specific}$)[c]	2650 kg/m^3	3950 kg/m^3	ca. 2700 kg/m^3

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Sieved density (ρ_{sieved})	1560 kg/m^3	1890 kg/m^3	ca. 1300 kg/m^3
Angle of internal peak friction (ϕ_{peak})	36.1°	37°	35°
Coefficient of internal peak friction (μ_{peak})[d]	0.73	0.75	0.70
Angle of dynamic-stable friction (ϕ_{dyn})	31.4°	32.0°	29.9°
Coefficient of dynamic-stable friction (μ_{dyn})[d]	0.66	0.62	0.58
Angle of reactivation friction (ϕ_{react})	33.5°	-	32.0°
Coefficient of reactivation friction (μ_{react})	0.66	-	0.62
Cohesion (C)	9 ± 98 Pa	39 ± 10 Pa	51 Pa
Viscous material	**Pure PDMS[a,e]**	**PDMS/corundum sand mixture[a]**	
Weight ratio PDMS : corundum sand	-	0.965 kg : 1.00 kg	
Density (ρ)	965 kg/m^3	ca. 1600 kg/m^3	
Viscosity (η)	ca. 2.8 · 10^4 Pa.s	ca. 1.5 · 10^5 Pa.s [f]	
Type[f]	Newtonian (n = ca. 1)[g]	near-Newtonian (n = 1.05-1.10)[g]	

a Quartz sand, PDMS and viscous mixture characteristics after Zwaan et al. (2016; 2018a, 2018b)
b Corundum sand characteristics after Panien et al. (2006)
c Specific densities after Carlo AG (2022)
d $\mu = \tan(\phi)$
e Pure PDMS rheology details after Rudolf et al. (2016)
f Viscosity value holds for model strain rates < 10-4 . s^{-1}
g Power-law exponent n (dimensionless) represents sensitivity to strain rate
h Feldspar sand characteristics after Zwaan et al. (2022c)

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2.3 Model parameters

For this study we completed two main series of four experiments each, and an initial series of reference experiments (Table 2). Series A contains our reference experiments that simulated the initial (orthogonal) rifting phase only, with and without syn-rift sedimentation. Series B explores the effects of basin inversion without syn-rift sedimentation. Series C tests the effects of syn-rift sedimentation during ~~graben~~ basin inversion. The initial rifting phase of our Series B and C basin inversion models involved either orthogonal or 45° oblique divergence (where obliquity is defined by angle alpha, i.e. the angle between the normal to the rift axis and the divergence direction, Fig. 2c). The subsequent phase of shortening involved either orthogonal or (-)45° oblique convergence (see details in Table 2). The experiments ran for 2 hours with 40 mm of divergence (at 20 mm/h) and another 2 hours with 40 mm of convergence, except for ~~M~~models B3 and C3 since the initial oblique opening did not generate sufficient space for a subsequent ~~40 mm of~~ orthogonal ~~divergence.~~convergence component of 40 mm. Therefore, total convergence in models B3 and C3 was 28 mm (over 85 min) instead, which was however sufficient convergence to establish well-developed inversion features.

We implemented syn-rift sedimentation in 5 of our experiments (in Model A2 and in ~~M~~models C1-4), by halting the machine every 15 min (8 sedimentary intervals in total) and filling the accommodation space by hand (pouring), with feldspar and quartz sand in alternating intervals (Fig. 2b). The two experiments with oblique rifting have only 7 sedimentation intervals because after the first 15 minutes, insufficient accommodation space was available, requiring us to start the first sand filling after 30 minutes instead.

Table 2: Parameters of analogue models performed in this study

Model Series	Model Name	Direction and velocity of divergence/convergence				Sedimentation	~~Cross-~~ ~~s~~Sections made
		Phase 1 (40 mm of divergence)		Phase 2 (40 mm of convergence)			
		Direction (angle α)	Velocity (v) mm/h	Direction (angle α)	Velocity (v) mm/h		
Series A Reference rifting models	A1	0°	20	-	-	No	Yes
	A2	0°	20	-	-	Yes	Yes
Series B Rifting and inversion	B1	0°	20	0°	20	No	Yes[***]
	B2[#]	0°	20	-45°	20	No	No
	B3[*$]	45°	20	0°	20	No	No
	B4	45°	20	45°	20	No	No
Series C Rifting and inversion with sedimentation	C1	0°	20	0°	20	Yes	Yes
	C2[#]	0°	20	-45°	20	Yes	Yes
	C3[*$]	45°	20	0°	20	Yes	Yes
	C4	45°	20	45°	20	Yes	Yes

*** Sections not used in this paper, presented in the supplementary material**

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~~* Models with reduced inversion time due to the oblique extension divergence with reduced orthogonal openingdivergence component.~~# Models with initial orthogonal ~~extension~~divergence underwent dextral inversion (α = -45°) due to technical limitations of our model apparatus. However, one can simply mirror the result to obtain the sinistral inversion equivalent (α = 45°)

$ Models with reduced inversion time due to the oblique divergence with reduced orthogonal divergence component.

~~** Sections not used in this paper, presented in the supplementary material~~

2.4 Scaling

Model scaling is important to guarantee that experiments completed in the laboratory are representative of their counterparts in ~~natural examples~~nature. For the brittle materials, the main parameter is the angle of internal friction (35°-37°), which is similar to internal friction angle values found in the upper crust (31°-38°, Byerlee, 1978, Table 3).

In order to scale the viscous material, we must consider its strain rate-dependent rheology. The stress ratio between model and nature (σ^*, convention: $\sigma^* = \sigma_{model}/\ \sigma_{nature}$) is calculated as follows: $\sigma^* = \rho^* \cdot h^* \cdot g^*$, where ρ^*, h^* and g^* represent density, length, and gravity ratios, respectively (Hubbert, 1937; Ramberg, 1981). Combined with the viscosity ratio (η^*), the stress ratio yields the strain rate ratio $\acute{\varepsilon}^*$ (Weijermars and Schmeling, 1986): $\acute{\varepsilon}^* = \sigma^*/\eta^*$. Subsequently, the velocity and time ratios (v^* and t^*) are derived from the strain rate ratio: $\acute{\varepsilon}^* = v^*/h^* = 1/t^*$. We adopt a relatively high lower crustal viscosity of ca. $5 \cdot 10^{21}$, representing a typical early magma-poor rift system (e.g. Buck, 1991). Thus, one hour in our model represents ca. 1.3 Myr in nature, and 20 mm/h of ~~extension/compression rate~~ divergence/convergence in the model embodies a realistic deformation velocity of ca. 5 mm/yr in nature. The scaling parameters are presented in Table 3.

The dynamic similarity of the model and natural example can also be examined. Firstly, the dynamic similarity between the model brittle layer and its upper crustal equivalent can be determined through the ratio R_s between the gravitational stress and the cohesive strength or cohesion C (Ramberg, 1981; Mulugeta, 1988): R_s = gravitational stress/cohesive strength = $(\rho \cdot g \cdot h)/C$. The~~A~~ 9 Pa cohesion in the sand and a natural cohesion of 5 MPa for upper crustal rocks, gives us a R_s of 102 and 110 for model and nature, respectively. Secondly, the dynamic similarity between our viscous material and lower crust equivalent is derived from the Ramberg number R_m (Weijermars and Schmeling, 1986): R_m = gravitational stress/viscous strength = $(\rho \cdot g \cdot h^2)/(\eta \cdot v)$, and both have the value of 68. We consider our models properly scaled since their R_s and R_m values are ~~the same~~similar ~~as~~ to their natural equivalent.

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Table 3: Scaling parameters

		Model	Nature
General parameters	Gravitational acceleration (g)	9.81 m/s^2	9.81 m/s^2
	Divergence velocity (v)	5.6 · 10^{-6} m/s	1.7 · 10^{-10} m/s
Brittle layer	Material	Quartz sand	Upper crust
	Peak internal friction angle	35°-37°	31-38°
	Thickness (h)	6 · 10^{-2} m	2 · 10^4 m
	Density	1560 kg/m^3	2800 kg/m^3
	Cohesion (C)	9 Pa	5 · 10^6 Pa
Viscous/ductile layer	Material	PDMS/corundum sand mixture	Lower crust
	Thickness (h)	3 · 10^{-2}m	1 · 10^{4}m
	Density	1600 km/m^3	2900 kg/m3
	Viscosity	1.5 · 10^5 Pa·s	1 · 10^{21}Pa·s
Dynamic scaling values	Brittle stress ratio (R_s)	102	110
	Ramberg number (R_m)	68	68

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2.5 Model monitoring and analysis

The experiments were primarily monitored through time-lapse photographs of the model surface, taken every minute for the duration of the model run. One central camera (Nikon D810, 36 MPx) provided map view pictures, while two obliquely oriented cameras (D810, 36 MPx) were positioned on both sides of the central one to provide stereoscopic imagery. The central camera was controlled using ~~the~~ Nikon Camera Control Pro software and cameras for stereoscopic imagery were remotely triggered by passing on the signal from the central camera via an ESPER Triggerbox (Schmid et al., 2022).

To facilitate the first order ~~of~~ surface deformation analysis, we sieved a thin grid (4 by 4 cm) of corundum sand on the model surface. We furthermore sprinkled the model surface with coffee powder to provide markers for later Digital Image Correlation (DIC) analysis. For the models involving syn-rift sedimentation, a fine layer (< 1 mm) of quartz sand was sieved on the top of the experiment at the end of rifting phase to create a blank surface for a new grid and new coffee markers, allowing for optimal tracing of deformation during the inversion phase. Note that we defined a North reference in ~~the~~ the models ~~apparatus~~ in order to facilitate the description of our model ~~the~~ results (Fig. 2)

To quantify and visualize the surface deformation evolution of the experiments, we applied a detailed analysis of the time-lapse photographs through DIC techniques (e.g. Adam et al., 2005; Boutelier et al., 2019; Marshak et al., 2019; Zwaan et al., 2021; Schmid et al., 2022). The DIC analysis was performed by comparing top view images of subsequent time steps using LaVision's DaVis software (version 10.2). We used a calibration plate with a cross pattern of known dimensions as a reference to unwarp and rectify images and scale calculated displacements. Maximum and ~~Minimum~~ minimum normal strains are defined as the magnitude of the largest (i.e., stretching) and smallest (i.e., shortening) axes of the strain ellipse, and are independent of ~~coordinate orientation~~reference frame (e.g. Broerse et al., 2021). It is therefore a suitable marker to quantify extension and shortening ~~(extensional and compressional deformation)~~in our experiments, respectively.

To reconstruct the model topography in detail, we used the pair of high-resolution oblique photographs for selected time steps. Agisoft Photoscan photogrammetry software served to merge this pair of synchronous photographs, using marked coordinates in the experiment for geo-referencing, and to create digital elevation models (DEMs) ~~for the end of Phase 1 and 2~~at the end of both the rifting and inversion phases. The DEMs, shown in map view, as well as the extracted topography profiles over time, are combined with the PIV results for a complete interpretation of model surface evolution (e.g. Maestrelli et al., 2020; Zwaan et al., 2022a).

Finally, ~~cross~~ sections were made to reveal the internal structures of the models at the end of the model run (at the end of the rifting phase for Series A models, and after inversion for Series B and C). In order to produce these ~~cross~~ sections, we added water with soap at the edges of the model until the sand was saturated and stable, and cut 6 sections orthogonal to the model axis, each 10 cm apart. Pictures were taken for analysis of internal structures~~,~~ and ~~the~~ quantification of subsidence. The ~~cross~~ sections of the reference models (Series A) provide insights into ~~the~~ graben structures prior to inversion.

3 Results

The results of our model analysis are presented in summary figures for each experiment (Figs. 3-8). We show the incremental maximum and minimum normal strain from the DIC analysis for the early stage (first 30 minutes) and end stage of each phase (~~90~~85-120 minutes interval), topography maps for the end of each deformation phase, and topographic profiles over 30 minutes increments. Model ~~cross-~~sections are presented for Series A and C~~, and for one model in series B (Model B1)~~.

3.1 Series A – Reference models

The Series A models provided a reference for the Series B and C analysis. These models had a constant orthogonal divergence direction (α = 0°) and a divergence ~~-~~velocity of 20 mm/h (Fig. 3). In Model A1 no sedimentation ~~occurred~~was applied during rifting, whereas in Model A2, eight phases of syn-rift sedimentation were applied at 15 minutes intervals.

3.1.1 Orthogonal rift without syn-rift sedimentation - Model A1

~~Extensional deformation~~Deformation in Model A1 ~~became highly~~ localized in the first 30 minutes ~~of the Model A1 run~~ (Fig. 3a), ~~forming~~ with two graben~~-~~ boundary faults rooting in the viscous seed (Fig.3i$_{I-III}$)~~,~~ ~~which accommodated~~ accommodating extension in one E-W striking graben. Towards the end of the rifting phase (t = 120 min, Fig. 3b), a second-generation intra-graben fault developed between the two conjugate graben boundary faults. The strain analysis indicates higher strain values in the southern graben border fault and within the second-generation intra-graben fault (Fig. 3b). However, the northern graben border fault also remained active until the end of the experiment (Fig. 3b). ~~Cross-s~~Section view shows drag folds ~~related to~~associated with the northern and southern graben boundary faults (Fig. 3i). The final topography profiles (Fig. 3d; t = 60 min, 90 min and 120 min) show a v-shaped depression ~~ale topography~~ on the southern side of the graben floor. This topographic feature can be related to the drag fold of the southern graben block seen in ~~cross-~~section view (Fig. 3i$_{II}$), indicating that the drag fold initiated after the first hour of experiment and continued evolving until the end of the rifting phase. In ~~the middle~~ C~~cross-~~section II ~~-~~(Fig. 3i$_{II}$), we measured graben width between the two master faults bounding the grabens ~~border faults~~ and the value is 56.2 mm. To measure the total fault offset, we used the uppermost corundum sand marker that showed a total of 19.2 cm of ~~vertical downward displacement~~subsidence ~~of 19.2 mm in total~~.

3.1.2 Orthogonal rifting with syn-rift sedimentation – Model A2

~~At~~ In the early rifting stages of Model A2 (t = 30 min), strain analysis shows ~~the concentration of~~ deformation concentrating at the graben boundary faults (Fig. 3e). However, during these early rifting stages, the maximum normal strain values are lower inside the graben (Fig. 3e,f) than observed in Model A1 (Fig. 3a,b). ~~Later in the~~Towards the end of the model run~~experiment~~, strain was homogeneously distributed between the boundary faults and the set of conjugate faults in the ~~middle~~ center of the graben (Fig. 3f,j). ~~The s~~Syn-rift sedimentation in Model A2 (Fig. 3j) caused an increase of graben width and subsidence compared to ~~the~~ rifting ~~phase~~ without sedimentation in Model A1 (Fig. 3i): the offset of the first corundum sand marker shows a difference of ~~~~~ ca. 1 cm between ~~Model~~ models A1 (19.2 mm; Fig. 3i_{II}) and A2 (30.9 mm; Fig. 3j_{II}), and the graben structure was ~~~~~ ca. 1 cm wider in Model A2 (65.2 mm) than in Model A1 (56.2 mm).

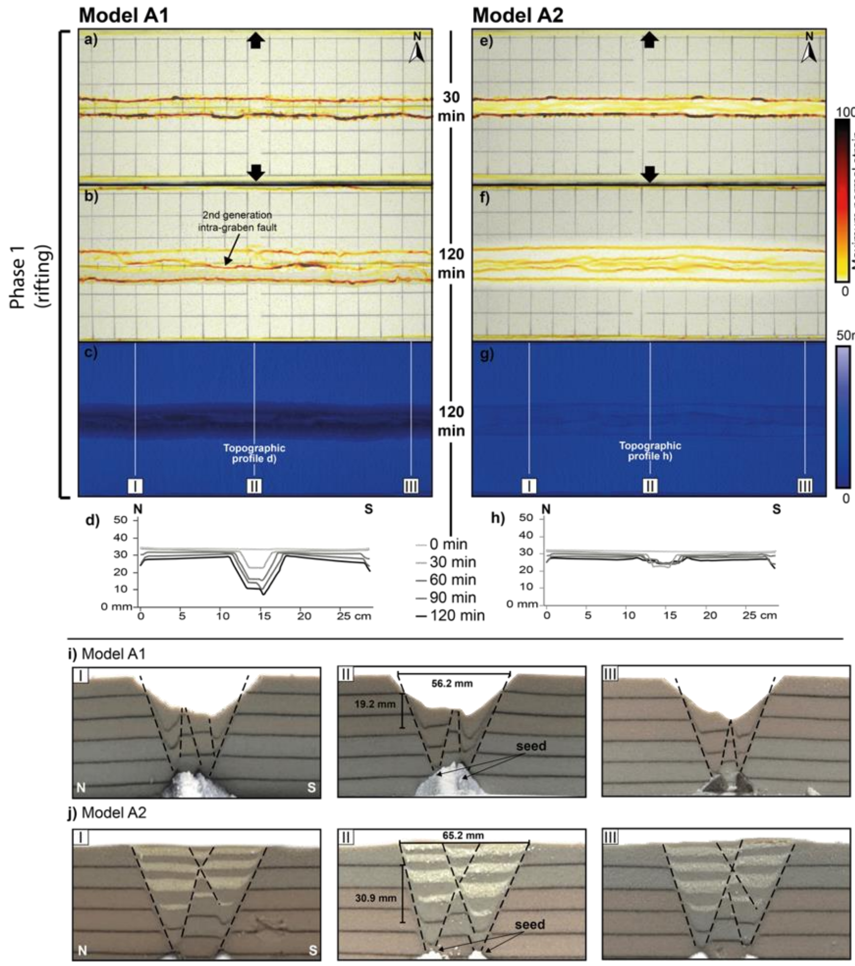

Figure 3: Evolution of deformation during rifting for ~~M~~models A1 and A2. a), ~~and~~ b), e) and f) display~~s~~ top view maximum normal strain results for early and late-stage rifting, respectively~~model DIC analysis for Mmaximum normal strain at early and late rifting stages~~, ~~.~~ c) and g) show top views of digital elevation models at the end of rifting~~Digital elevation model for late rifting stage~~. d) and h) Topographic profiles for every 30 minutes of rifting. ~~e) and f) display top view model DIC analysis for Maximum normal strain at early and late rifting stage. g) Digital elevation model for late rifting stage. h) Topographic profiles for every 30 minutes of rifting.~~ Note that topography is shown prior to syn-rift sedimentation for that interval. i-j) ~~Cross-s~~Sections for~~rom~~ ~~(i)~~ Model A1 and Model ~~and (j) Model~~ A2, respectively. Section locations are indicated in (c~~b~~) and (g~~f~~). Graben geometry measurements are indicated in the middle ~~cross-~~sections (i_{II} and j_{II}).

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3.2 Series B – inversion without sedimentation

Here we show the results for the ~~series~~ Series B models that underwent two deformation phases (rifting and inversion) but without syn-rift sedimentation. We first present ~~M~~models B1 and B2 that involved orthogonal rifting, followed by ~~M~~models B3 and B4 with oblique rifting. These model pairs subsequently ~~between then~~ underwent either orthogonal or oblique inversion.

3.2.1 Orthogonal rifting ~~–~~followed by orthogonal (Model B1) ~~and~~ or oblique (Model B2) inversion ~~(B2)~~

The results from ~~M~~models B1 and B2 show very similar outcomes ~~between them after~~at the end of phase 1 and are also very similar to reference Model A1 (Figs. 3a-b; 4a-b and i-j). Early rifting (t = 30 min, Fig. 4a and i) localized more strain along the graben normal faults than in the later rift phase as~~;~~ during the late rift stage (t = 120 min, Fig. 4b and j), strain was distributed between the graben boundary faults and the intra-graben faults. ~~The t~~Topography analysis (Fig. 4c, g, k and o) shows a maximum graben subsidence of ~~∼~~ca. 20 mm in both models.

~~During~~ After the first 60 minutes of orthogonal inversion ~~phase~~, Model B1 ~~initially first 60 minutes~~ localized strain both along the intra-graben faults and along new reverse faults on both sides of the graben (Fig. 4d). Towards the end of the model run, most parts of the southern reverse fault became relatively inactive while the northern reverse fault grew and localized higher strain (Fig. 4e). ~~At~~ During the final~~this~~ stage (t = 120 min~~ute~~), also the intra-graben faults had become inactive (Fig. 4e). The areas immediately adjacent to the north and south ~~t~~of the graben were uplifted, while the ~~bottom~~ floor of the inverted graben reached the same elevation as the pre-rift surface (Fig. 4f, h).

After the first 60 minutes ~~hour~~ of oblique inversion in Model B2, strain was localized along the graben ~~border~~ boundary faults (Fig. 4l) showing direct reactivation of the original graben faults only, in clear contrast to the orthogonal inversion of Model B1 (Fig. 4d). At the end of Phase 2, however, a single oblique reverse fault had appeared at the model surface grid, north of the graben, while all previous rift related faults were inactive (Fig. 4m). The final topography data show~~s~~ a significantly higher maximum elevation than the pre-rift surface of ~~∼~~ca. 15 mm in orthogonal inversion Model B1 (Fig. 4f, h), while the oblique inversion Model B2 (Fig. 4n, p) had ~~an~~ ~~∼~~ca. 7 mm higher elevation than the pre-rift surface.

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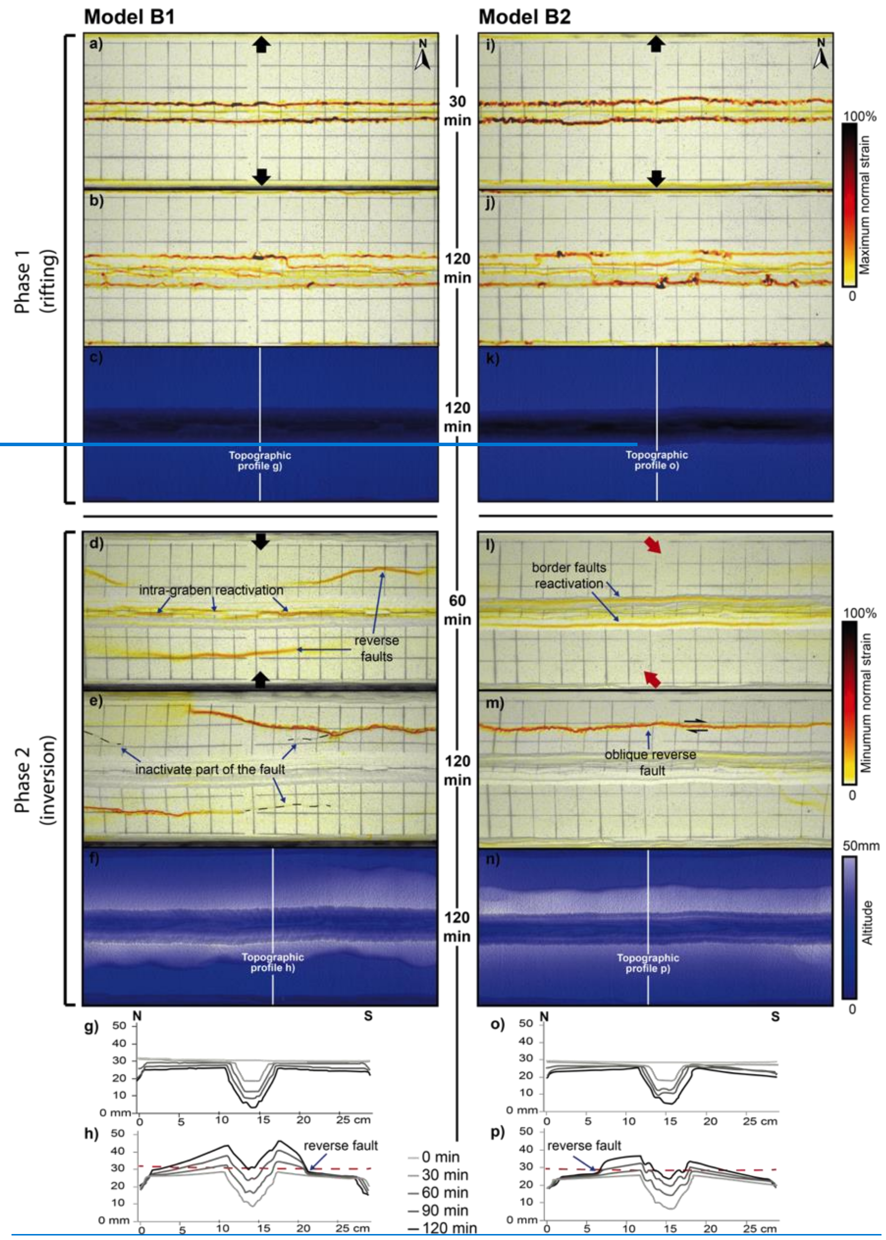

Model B1
Model B2
Phase 1 (rifting)
Phase 2 (inversion)
30 min
120 min
120 min
60 min
120 min
120 min
Topographic profile g)
Topographic profile o)
Topographic profile h)
Topographic profile p)
intra-graben reactivation
reverse faults
inactivate part of the fault
border faults reactivation
oblique reverse fault
100%
Maximum normal strain
0
Minumum normal strain
50mm
Altitude
N
S
reverse fault
0 min
30 min
60 min
90 min
120 min
0 mm
25 cm

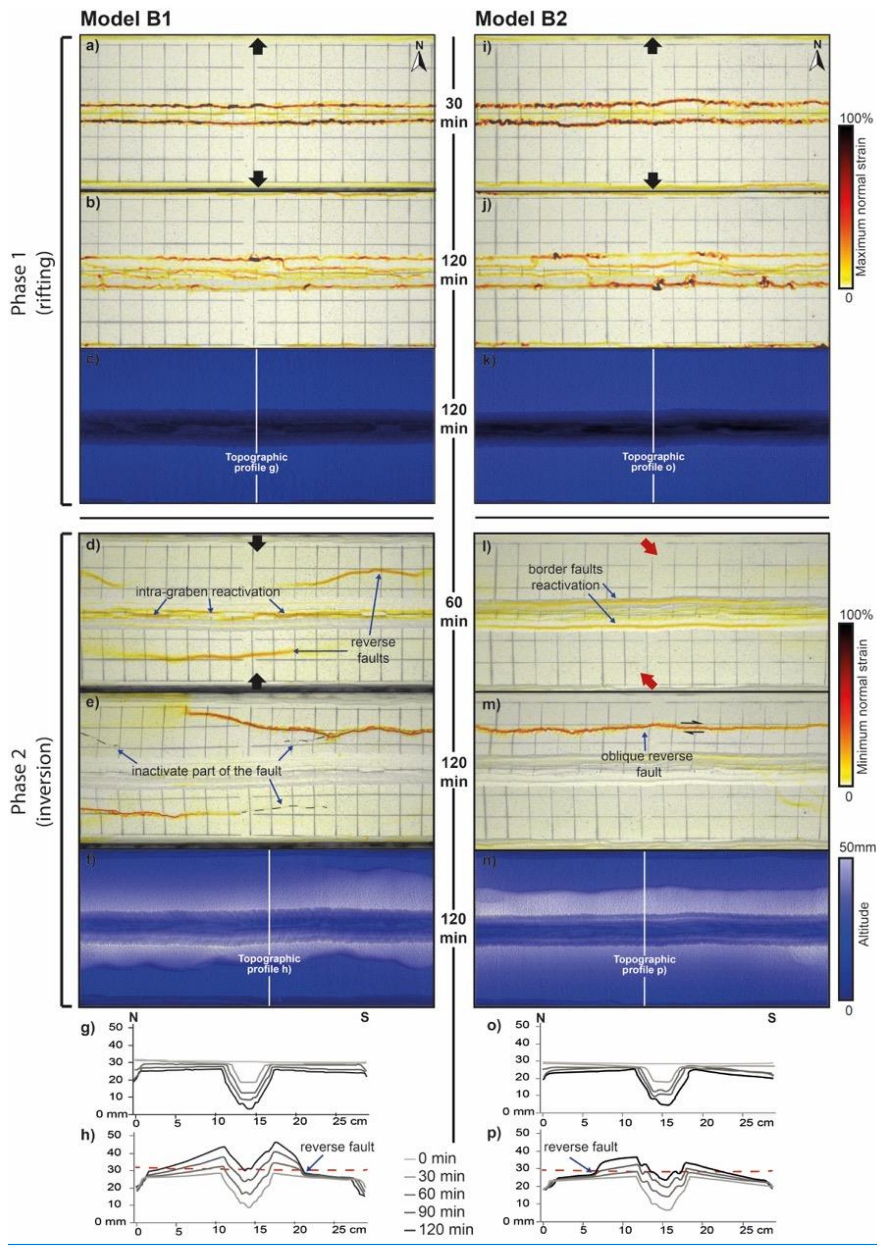

Figure 4: Evolution of deformation during rifting and inversion for ~~M~~models B1 and B2. a, b) and l-j) Top view maximum normal strain results for early and late-stage rifting, respectively. c, k) Digital elevation models at the end of rifting. d, e) and l, m) Top view minimum normal strain results for early and late-stage inversion, respectively. f, n) Top view of digital elevation model at the end of inversion. g, o) Topographic profiles for every 30 minutes of rifting. h, p) Topographic profiles for every 30 minutes of inversion. ~~a) and b) displays t~~T~~op view model DIC analysis for M~~m~~aximum normal strain at early and late rifting stage~~s~~. c)~~ and k) ~~Digital elevation model~~s ~~for late rifting stage. d)~~, ~~and e)~~, l) and m) ~~displays t~~T~~op view model DIC analysis for M~~m~~inimum normal~~

~~strain. f)~~ and n) ~~Digital elevation model~~s ~~for late inversion stage. g, o) Topographic profiles for every 30 minutes of rifting phase. h, p) Topographic profiles for every 30 minutes of inversion phase.~~ The dashed red horizontal line indicates the initial surface level at the start of the model run.

3.2.2 Oblique rifting ~~–~~followed by orthogonal (Model ~~(~~B3) ~~and~~ or oblique (Model B4) inversion ~~(B4)~~

Oblique rifting (α = 45°) of ~~M~~models B3 ~~(Fig. 5a)~~ and B4 ~~(Fig. 5i), with 45° oblique rifting,~~ resulted in the development of two bands of ~~*en echelon*~~*en échelon* normal faults bounding an E-W striking ~~-~~graben after the first 30 minutes of deformation (Fig 5a,i). At the end of Phase 1, the strain results show~~s~~ that these ~~*en echelon*~~*en échelon* faults had become interconnected, forming through-going, E-W striking graben-bounding normal faults, connected by oblique, WNW-ESE trending, lower strain ~~diagonal~~ zones within the graben (Fig. 5b,j).

After 60 minutes, ~~Tthe~~ of orthogonal inversion, ~~of~~ Model B3 ~~resulted in the activation~~showed the formation of a new straight fault along the central axis of the graben and the ~~formation~~ development of a new reverse fault south of the graben (Fig. 5d,e). By the end of the inversion phase, after 120 minutes, the reverse fault remained active while the fault in the ~~middle of~~centre of the graben ~~started~~ became less active, with some parts being completely inactive (Fig. 5e). Uplift was more prominent in the area between the reverse fault and the graben, ~~while~~ whereas in the northern part of the ~~experiment~~ model a more widespread uplift ~~is~~ was recorded (Fig. 5f, g).

After ~~the first~~ ~~hour~~ 60 minutes of oblique inversion in Model B4, the ~~diagonal g~~oblique low strain zones within the graben ~~structures~~ were partially reactivated, while a significant portion of the deformation localized in a new reverse fault to the north of the graben, and deformation started to localize in the southern area of the ~~experiment~~ model as well (Fig. 5l). ~~During the later stages~~ After 120 minutes of inversion, the northern reverse fault became almost completely inactive, and deformation localized on the southern reverse fault (Fig. 5m). The map view grid analysis shows~~ed~~ the oblique movement ~~of~~ along the reverse faults (Fig. 5m). Rift faults ~~concentrated~~ experienced only minor reactivation and became almost completely inactive by the end of the inversion phase (Fig. 5m; 120 minutes). The topography profiles indicate uplift of the rift structures (17 mm elevation of the ~~bottom of the~~ graben floor) and the new reverse faults on both sides of it (Fig 5p), and while the northern reverse fault became inactive, ~~widespread~~ distributed uplift affected the northern part of the model (Fig. 5p). Along the topographic~~y~~ profile, the maximum uplift ~~not related to~~away from the reverse faults was 5 mm in the north (where the fault became inactive) and 2 mm in the south.

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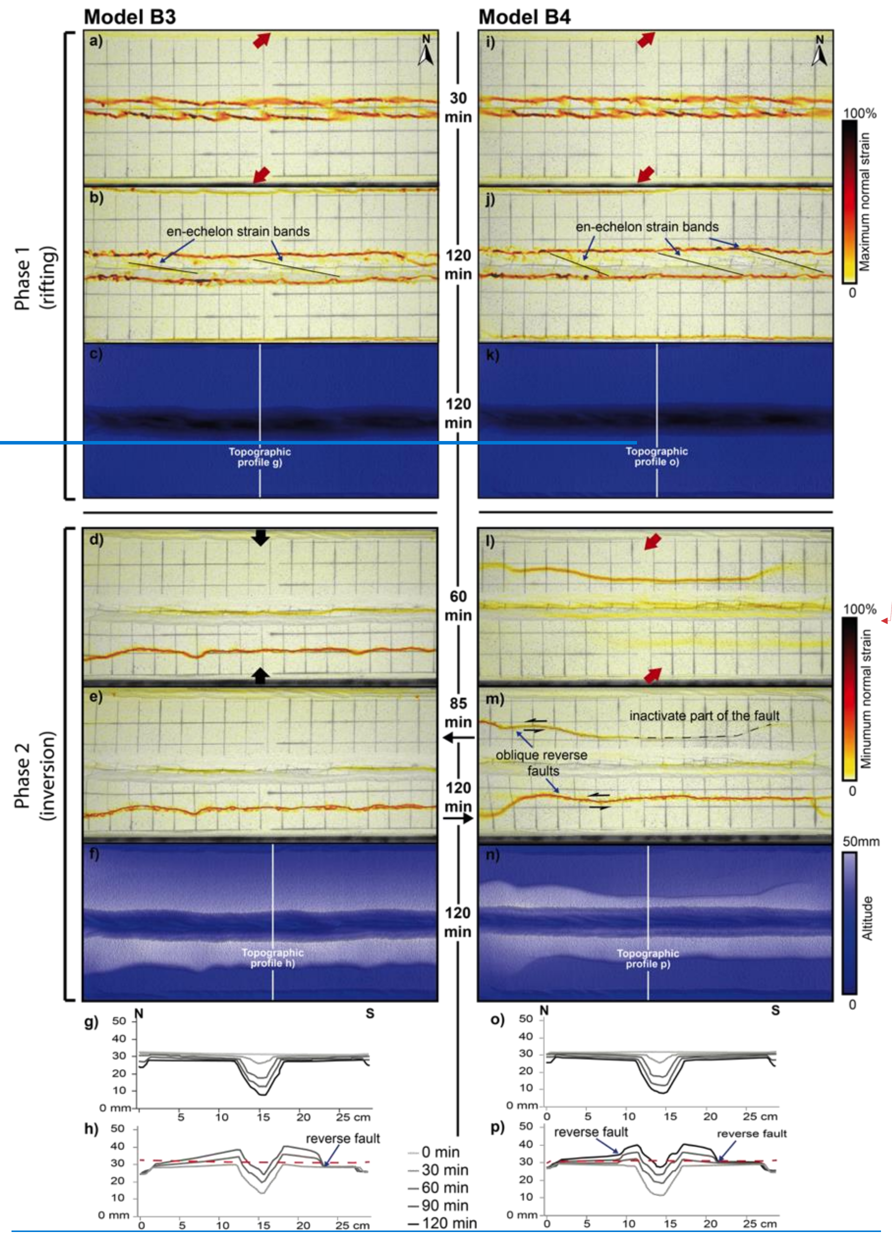

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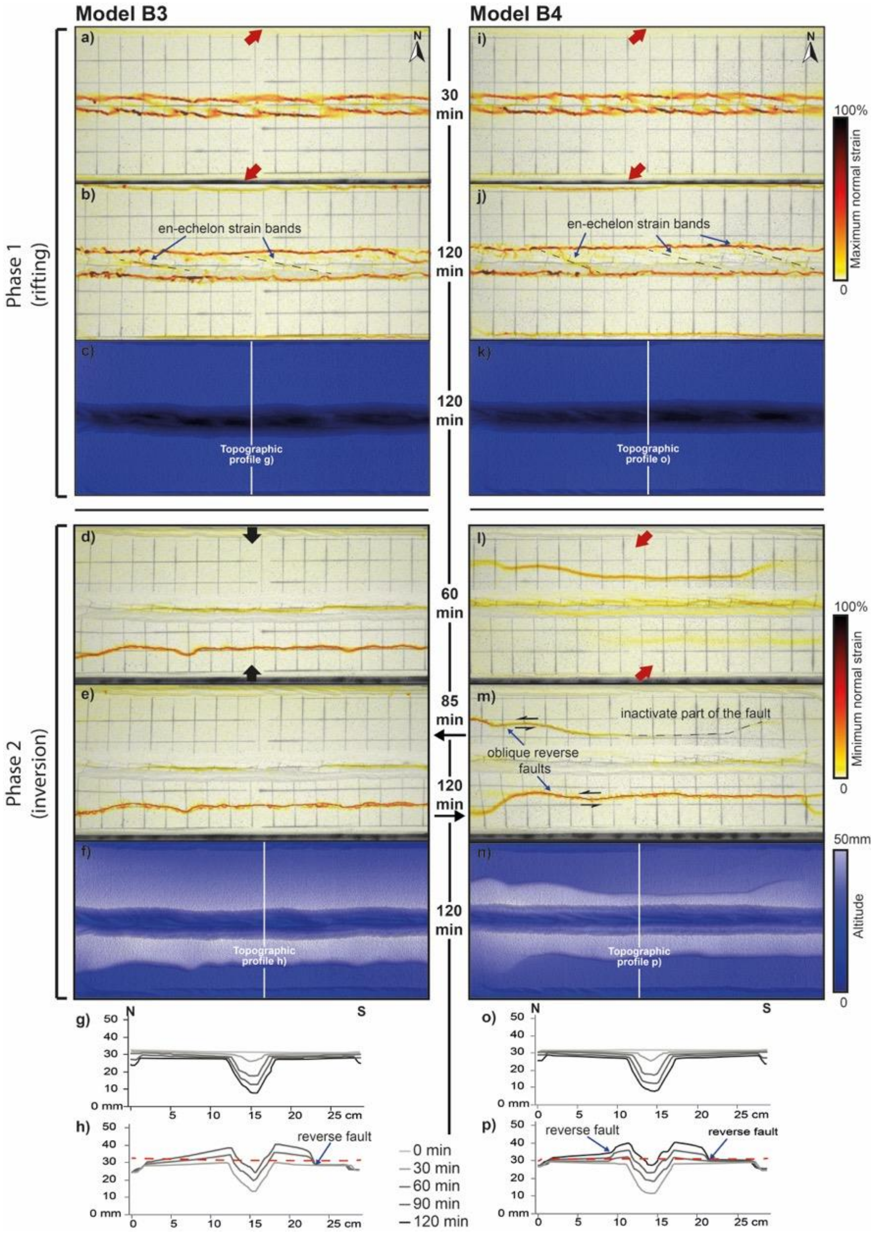


Figure 5: Evolution of deformation during rifting and inversion for ~~M~~models B3 and B4. **Top view maximum normal strain results for early and late-stage rifting, respectively. c, k) Digital elevation models at the end of rifting. d, e) and l, m) Top view minimum normal strain results for early and late-stage inversion, respectively. f, n) Top view of digital elevation model at the end of inversion. g, o) Topographic profiles for every 30 minutes of rifting. h, p) Topographic profiles for every 30 minutes of inversion. The dashed red horizontal line indicates the initial surface level at the start of the model run. Note that ~~a, i), and b, j) display tTop view model DIC analysis for Mmaximum normal strain at early and late rifting stage, respectively. c, k) Digital elevation models for late rifting stage. d, l,) and e, m) display tTop view model DIC analysis for Mminimum normal strain. f and~~**

~~n) Digital elevation models for late inversion stage. g and o) Topographic profiles for every 30 minutes of rifting phase. h and p) Topographic profiles for every 30 minutes of inversion phase.~~ Model B3 has a reduced inversion time of 85 minutes instead of 120 minutes, as indicated in the figure.

3.3 Series C – inversion with sedimentation

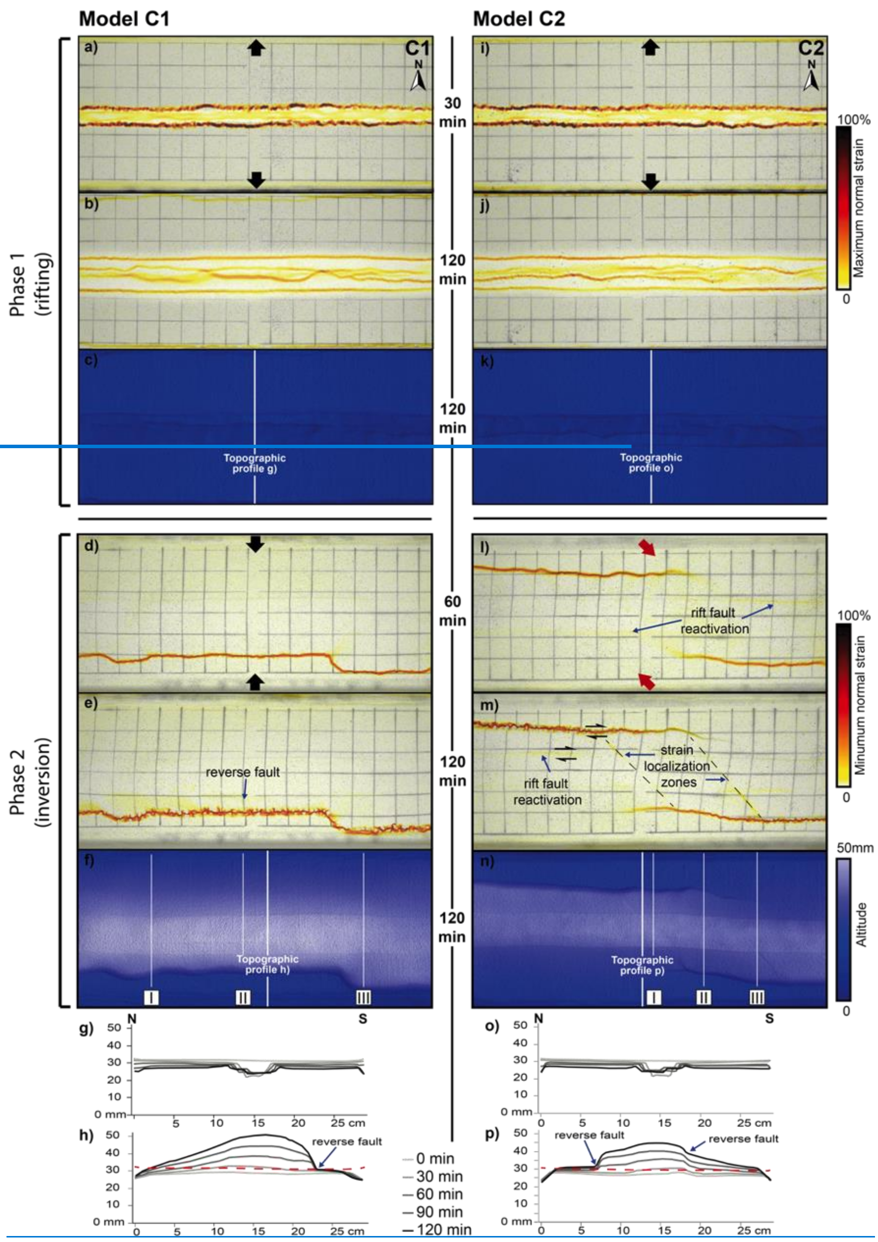
Here we present the results for our Series C models with the rifting phase divided in 8 sedimentation intervals of 15 minutes each, with 20 mm/h of displacement during both the rifting and ~~subsequence~~ subsequent convergence phases. The results are presented in pairs according to the models' initial divergence direction (orthogonal and oblique~~, or α = 0° and α =~~ ~~45°~~, respectively) (Figs. 6, 8).

3.3.1 Orthogonal rifting with sedimentation ~~–~~followed by orthogonal (Model C1) ~~and~~ or oblique (Model C2) inversion ~~(C2)~~

The early stages of rifting of both ~~M~~models C1 and C2 resulted in high strain localization ~~in~~ a the graben ~~border~~ boundary faults and lower strain rates inside the graben (Fig. 6a,i). During later rifting stages, the maximum normal strain values were lower along the graben ~~border f~~boundary faults and instead rather evenly distributed among all faults within the graben (Fig. 6b,j). These results for the early and late stages of rifting show great similarity to the ~~ones in~~results from Model A2 (Fig. 3e,f). ~~Cross s~~Section thickness measurements from each of the 15 minutes syn-rift sedimentation intervals (I1-I8), indicate a progressive increase of subsidence in the first two sedimentation intervals (up to 8 mm/interval, inset in Fig. 7a$_I$; I1 to I3). From interval I4 to I8, we observed a decrease in the subsidence rate (down to ca. 4 mm/interval, inset in ~~insets in~~ Fig. 7a; I4-8).

~~The o~~Orthogonal inversion in Model C1 ~~(Model C1, Fig. 6d-e)~~ concentrated deformation on a new reverse fault at the southern part of the model (Fig. 6d-e). Strain data show ~~high~~ localization along this reverse fault, while no reactivation ~~at all~~ is visible in the ~~previous~~ inherited rift~~ing~~ structures. In ~~cross~~ section view (Fig. 7a$_{I,II}$) it becomes clear that the whole graben structure was uplifted by the reverse fault while the model surface was folded. The section shows that the ~~is resulted in a curved and thick shear zone along the~~ reverse fault, in fact a ca. 1 cm thick shear zone by the end of the model run, ~~that~~ was seeded in the viscous layer, ~~the latter~~ which itself ~~also rose during rifting~~was also thickened (most probably already during rifting as seen in sections from models A1 and A2, Figs 3i, j,~~.~~ 7a).

Compared to orthogonal inversion Model C1, oblique inversion in ~~of~~ Model C2 shows a different effect on the reactivation of previous rift structures ~~in Model C2~~ (Fig. 6l-m). We observed minor reactivation of the previously formed ~~normal~~ graben-bounding normal faults during the subsequent ~~45°~~ oblique inversion phase, and main strain localization along newly formed reverse faults in the NW and SE quadrants, connected by strain localization zones parallel to the inversion direction. ~~The~~ Our topography analysis shows a small (~~~~~ca. 2 mm) pop-up structure related to minor inversion of the graben border faults (Fig. 6n,p), with a small dextral strike-slip component ~~in~~ visible on the surface grid as well (Fig. 6m)~~n,p)~~. In ~~cross~~ section view, the newly formed reverse faults were in fact thick (ca. 1 cm)~~er~~ shear zones in those locations where only one of them developed, whereas the shear zones were thinner (< 5 mm) when multiple reverse faults developed (Fig. 7b).



Model C1
Model C2
a)
b)
c)
d)
e)
f)
i)
j)
k)
l)
m)
n)
C1
C2
N
30 min
120 min
120 min
60 min
120 min
120 min
100%
Maximum normal strain
0
Phase 1 (rifting)
Phase 2 (inversion)
Topographic profile g)
Topographic profile o)
rift fault reactivation
100%
Minumum normal strain
0
reverse fault
strain localization zones
rift fault reactivation
50mm
Altitude
0
Topographic profile h)
Topographic profile p)
I
II
III
g)
o)
h)
p)
N
S
50
40
30
20
10
0 mm
0
5
10
15
20
25 cm
reverse fault
reverse fault
reverse fault
0 min
30 min
60 min
90 min
120 min

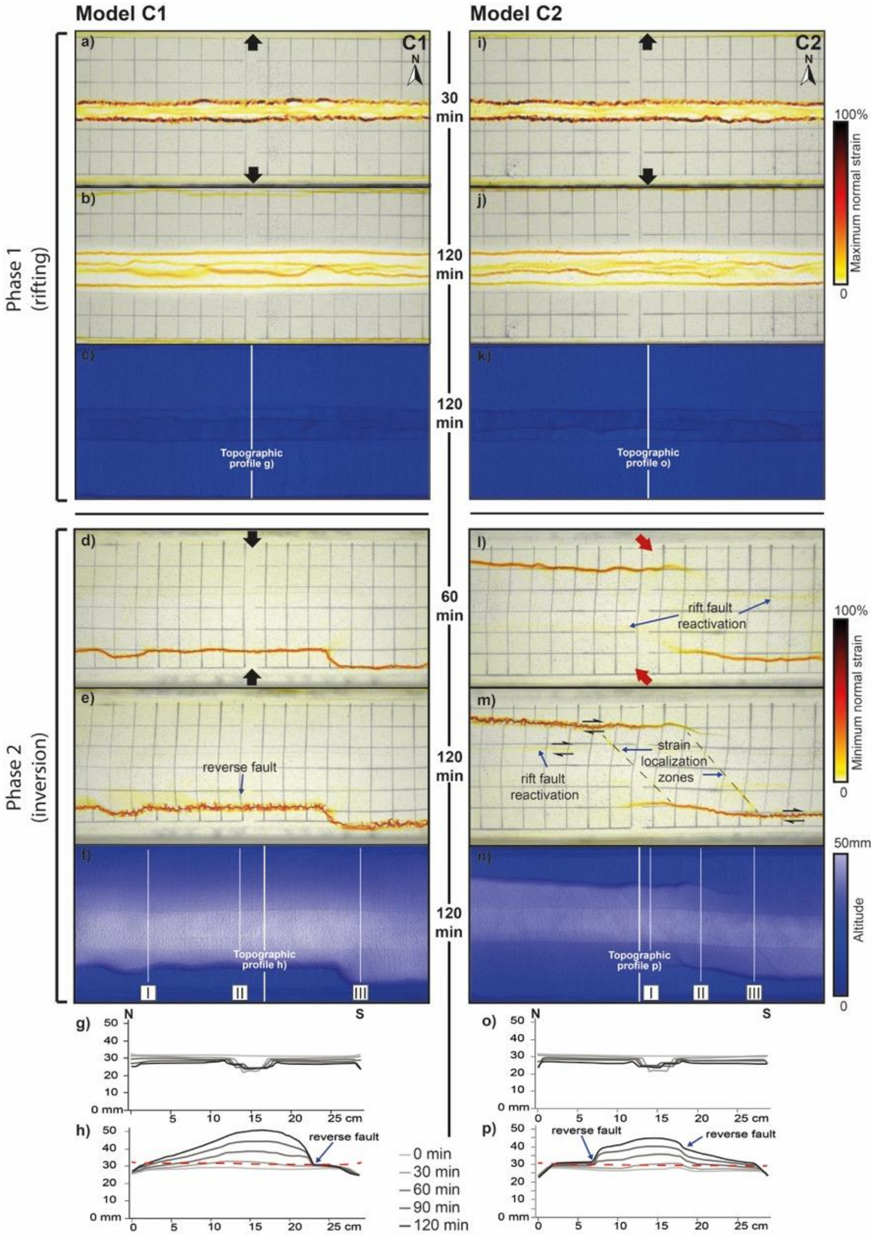
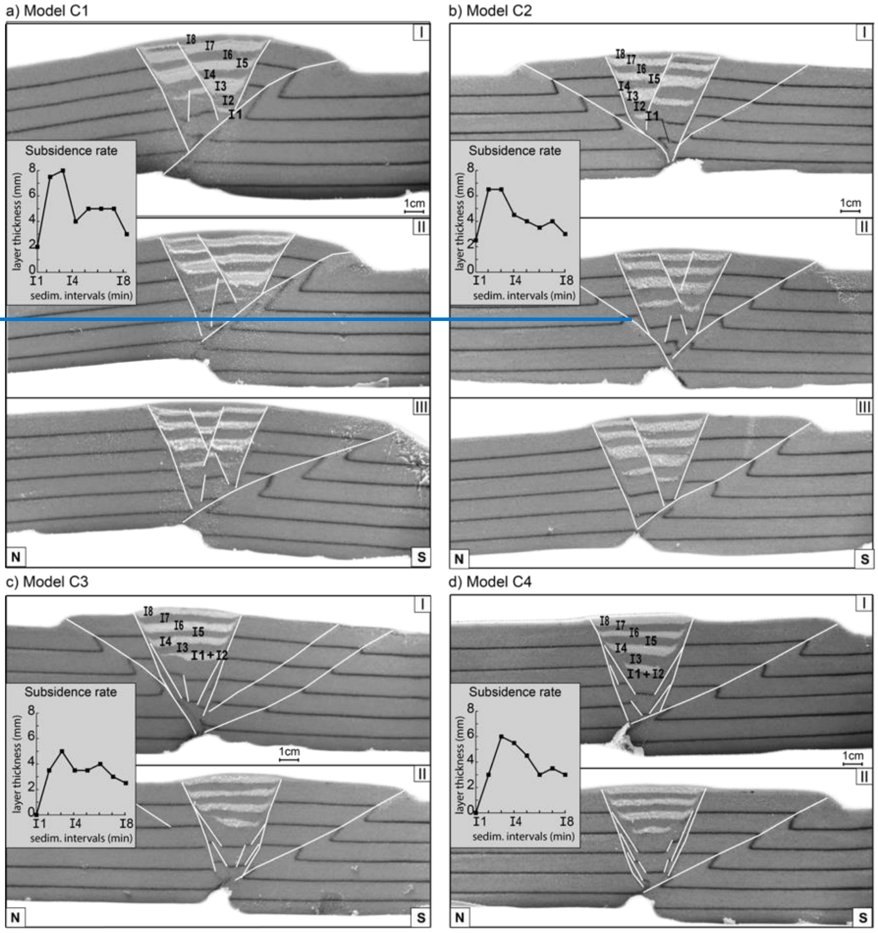


Figure 6: Evolution of deformation during rifting and inversion for ~~M~~models C1 and C2. a, b) and l-j) Top view maximum normal strain results for early and late-stage rifting, respectively. c, k) Digital elevation models at the end of rifting. d, e) and l, m) Top view minimum normal strain results for early and late-stage inversion, respectively. f, n) Top view of digital elevation model at the end of inversion. g, o) Topographic profiles for every 30 minutes of rifting. h, p) Topographic profiles for every 30 minutes of inversion. Topography is shown prior to syn-rift sedimentation for that interval, and the dashed red horizontal line indicates the initial surface level at the start of the model run.

~~a), and b), i) and j) displays tTop view model DIC analysis for Mmaximum normal strain at early and late rifting stages. c) and k) Digital elevation models for late rifting stage. d), and e), l and m) displays tTop view model DIC analysis for Mminimum normal strain. f) and n)Digital elevation models for late inversion stage. g) and o) Topographic profiles for every 30 minutes of rifting phase. h) and p) Topographic profiles for every 30 minutes of inversion phase.~~


a) Model C1
b) Model C2
c) Model C3
d) Model C4
I8
I7
I6
I5
I4
I3
I2
I1
I1+I2
Subsidence rate
layer thickness (mm)
sedim. intervals (min)
1cm
I
II
III
N
S

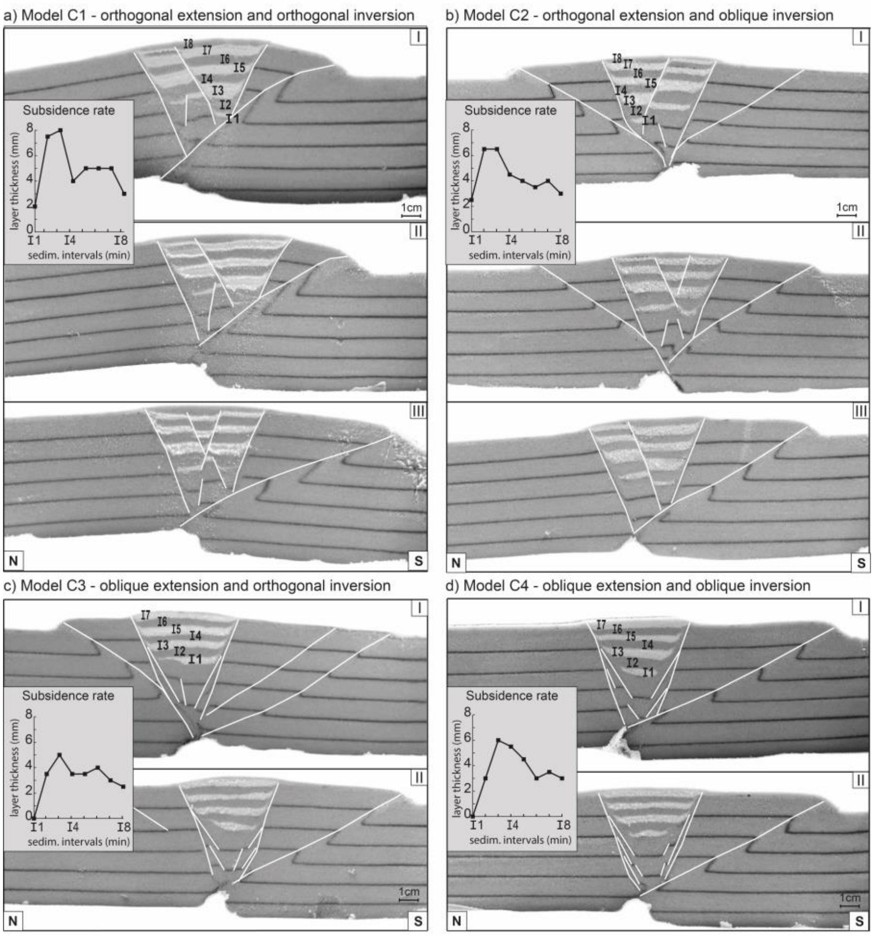


Figure 7: a), b), c) and d) ~~Cross s~~Sections of experiments with sedimentation and measurements on models showing the influence of extension obliquity on sedimentation and subsidence rate. ~~a) Model C1 with orthogonal extension and orthogonal inversion phases. b) Model C2 with orthogonal extension and oblique inversion phases. c) Model C3 with oblique extension and orthogonal inversion phases. d) Model C4 with oblique extension and orthogonal inversion phases.~~ Section locations are shown in Figs. 5 and ~~7~~8. Syn-rift sedimentation units always start~~s~~ with feldspar sand (white) and are divided into 8 intervals of 15 minutes of extension, except for the oblique ~~extension~~ divergence models ~~(~~C3 and C4~~)~~, ~~that~~ where I1 and I2 are represented in the same unit. I1 = 15 min, I2 = 30 min, I3 = 45 min, I4 = 60 min, I5 = 75, I6 = 90 min, I7 = 105 min, I8 = 120 min (after the initiation of rifting). ~~North (N) and Ssouth (S) references~~Section orientations are indicated at the bottom section of each model.

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3.3.2 Oblique rifting with sedimentation ~~–~~followed by orthogonal (Model C3) ~~and~~ or oblique (Model C4) inversion

Models C3 (Fig. 8a) and C4 (Fig. 8i) ~~presented~~ developed clear ~~*en echelon*~~*en échelon* graben boundary faults after the first 30 minutes of ~~experiment in response to the 45°~~ oblique rifting, thus showing ~~a similar result as~~results similar to ~~M~~models B3 and B4 (Fig. 5b, i). ~~After~~ Over the subsequent ~~two~~ 1.5 hours of rifting, the ~~*en echelon*~~*en échelon* faults evolved into two main E-W graben boundary faults, but some faint ~~en echelon~~*en échelon* strain bands remained active within the graben (Fig. 8b,j). Topography analysis shows that ~~the~~ vertical subsidence in the first 30 minutes was lower than during the subsequent 30 minutes phases (2 mm/interval vs. 4.8 mm/interval, Figs. ~~8g,o~~7c, d). ~~In fact, the first sedimentation layer (white feldspar sand in the cross-sections, Fig. 7c-d) represents 30 minutes of rifting, and the subsequent layers represents 15 minutes each, resulting in seven filling layers (Fig. 7c-d).~~ Subsidence was indeed slower in models C3 and C4 when~~if~~ compared to models C1 and C2~~,~~: it took 30 minutes of oblique rifting (two 15 minutes intervals) to create accommodation space for sedimentation, while the first 15 minutes of orthogonal rifting in models C1 and C2 created enough subsidence for applying a sedimentation interval.~~,the first 30 minutes of orthogonal rifting subsidence is comparable with the first 15 minutes in orthogonal rifting.~~ Model C3 and C4 (Fig. 7c,d) did not develop the intra-graben normal faults seen in ~~M~~models C1 and C2 (Fig. 7a,b).

Orthogonal inversion in Model C3 created initial reverse faulting in the north and SE of the models, but without graben ~~normal~~ boundary fault reactivation (Fig. 8d). By the end of the experiment (Fig. 8e), after 85 minutes, the northern reverse fault became completely inactive while the southern one grew laterally (westward), remaining active. Topography analysis shows uplift limited by the reverse faults ~~lines~~ on both sides of the model (Fig. 8f,h). In ~~cross-~~section view, there is an alternation between northern (Fig. 7c$_{I}$) and southern (Fig. 7c$_{II}$) reverse fault activity, and we also observe that reverse faults with larger offsets had an increased thickness.

The oblique inversion in Model C4 (Fig. 8l-m) is predominantly accommodated by a new reverse fault in the south, with limited reactivation of the rift structures. Topography data show additional uplift in the graben in contrast to the orthogonal inversion structures in Model C3 (Fig 8f). The topographic profiles (Fig. 8p) indicate ~~a marked~~limited inversion ~~in~~ of the graben boundary faults, starting after the first hour and continuing until the end of the experiment.

The ~~cross-~~sections of ~~M~~models C3 and C4 (Fig. 7c,d) revealed that the reverse fault nucleated in the seed at the base of the graben, and developed into a ca. 1 cm thick shear zone. Section II from orthogonal inversion Model C3 (Fig. 7c) shows the ~~formation~~ presence of a reverse fault north of the graben, seeding 2 cm below the surface, with no clear link to the previous rift faults or to the viscous material at the base of the graben, ~~like most of the~~which is in contrast to the other -reverse faults ~~shown~~visible in Fig. 7. However, in map view (Fig. 8d-f), it is shown that this is in fact the tip of the same reverse fault present in Section I of Model C3 (Fig. 7c)

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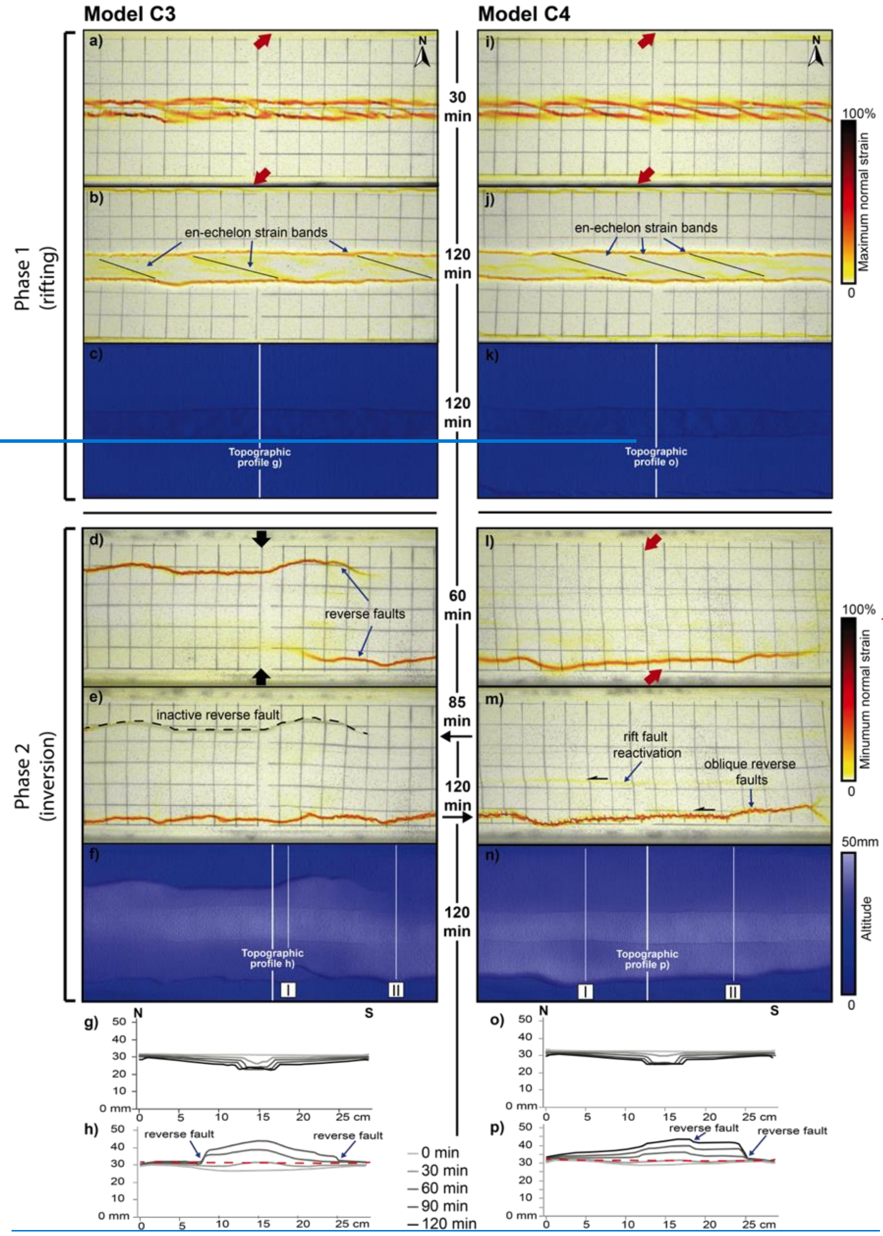

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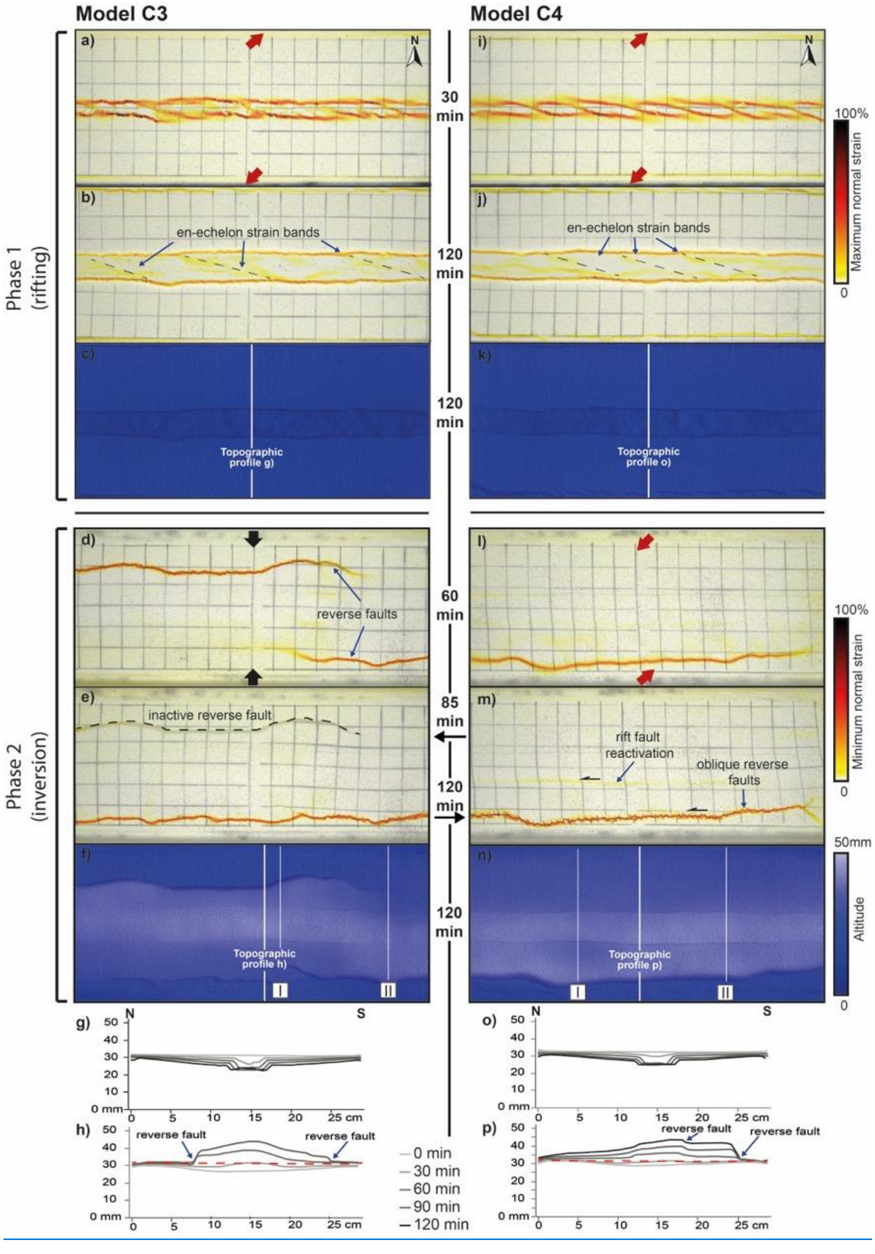


Figure 8: Evolution of deformation during rifting and inversion for ~~M~~models C3 and C4. a, b~~i~~) and l-j~~b, j~~) ~~displays t~~Top view ~~model DIC analysis for~~ m~~M~~aximum normal strain results for ~~at~~ early and late -stage rifting ~~stage~~, respectively. c, k) Digital elevation models ~~for~~ at the end of ~~late~~ rifting ~~stage~~. d, e~~l~~) and le, m) ~~displays t~~Top view minimum normal strain results for early and late-stage inversion, respectively~~Top view model DIC analysis for Minimum normal strain~~. f, n) Top view of d~~D~~igital elevation model at the end of~~for late~~ inversion ~~stage~~. g, o) Topographic profiles for every 30 minutes of rifting ~~phase~~. h, p) Topographic profiles for every 30 minutes of ~~of~~ inversion ~~phase~~. Topography is shown prior to syn-rift sedimentation for that interval, and the dashed red

horizontal line indicates the initial surface level at the start of the model run. Note that Model C3 has a reduced inversion time of 85 minutes instead of 120 minutes, as indicated in the figure.~~Model C3 has a reduced inversion time as indicated in the figure.~~

4 Discussion

4.1 Summary and comparison to previous models

The modeling results, presented in two schematic overview figures (Figs. 9 and 10), show how ~~deformation directions~~imposed kinematics and the presence of syn-rift sedimentation affects initial basin evolution and subsequent inversion.

4.1.1. Rifting phase

The overview of the rifting phase without sedimentation (Fig. 9a and b) ~~shows~~ depicts the general ~~structural~~ differences in graben ~~evolution~~ structure as a result of ~~different~~ divergence direction~~s~~ (~~α = 0° and α = 45°~~orthogonal or oblique). ~~The differences in~~A different divergence ~~orientation~~ direction resulted in different initial graben structures. However, at the final stage of rifting, the graben geometries formed during orthogonal and oblique rifting were very similar (Fig. 9). The main difference ~~remained~~ occurs within the graben, where ~~orthogonal divergence generated~~ parallel pairs of conjugate normal faults formed due to orthogonal divergence, whereas oblique divergence resulted in ~~*en echelon*~~*en échelon* structures. Furthermore, oblique ~~extension~~ divergence caused a decrease in graben width compared to the orthogonal rifting models, due to an increase in boundary fault dip, as also described in previous modelling studies (Tron & Brun 1991; Zwaan and Schreurs, 2016; Zwaan et al., 2018a) (Figs. 3 and 4). This reduction in width and increase in fault angle is caused by the strike-slip component accommodating deformation in oblique rifting settings.

The syn-rift sedimentation models (Fig. 10a and b) ~~demonstrated~~ showed the same initial difference in orthogonal and oblique divergence as the models without sedimentation. The oblique divergence models resulted not only in a narrower graben at the end of the extension phase, but also in a reduction of the final total subsidence observed in ~~cross-~~section (Fig. 7). A narrower graben forming during oblique rift evolution led to smaller loads of sedimentation, consequently there was less ~~weight to cause~~ graben floor subsidence. However, orthogonal and oblique rifting produced a very similar subsidence evolution in response to the syn-rift sedimentation (Fig. 7). The first subsidence interval (I1) was always the smallest, while the subsequent three intervals (I2 to I4) accommodated more subsidence, and from this moment on, sedimentary intervals started thinning again until the last interval (I8). This initial subsidence rate ~~evolution~~ increase likely occurred because the increase in sedimentary load over time enhanced subsidence. However, the reason why we observe a subsidence decline after sedimentation interval I4 remains unclear.

Overall, concerning the total subsidence in models with and without syn-rift sedimentation, we observe that subsidence in the former case was significantly higher while the rift boundary faults remained active for a longer period of time as well. Zwaan et al. (2018a) report a similar basin evolution due to syn-rift sedimentation. In their experiments without syn-rift sedimentation, the absence of sedimentary loading inside the graben leads to a smaller offset along the graben boundary faults since part of the deformation was taken up by intra-graben faults. By contrast, in their models with syn-rift sedimentation, the graben wedge was strengthened, so that faulting remained concentrated along the main graben boundary faults. The latter observation was also made in numerical models by Burov and Poliakov (2001) and Olive et al. (2014).

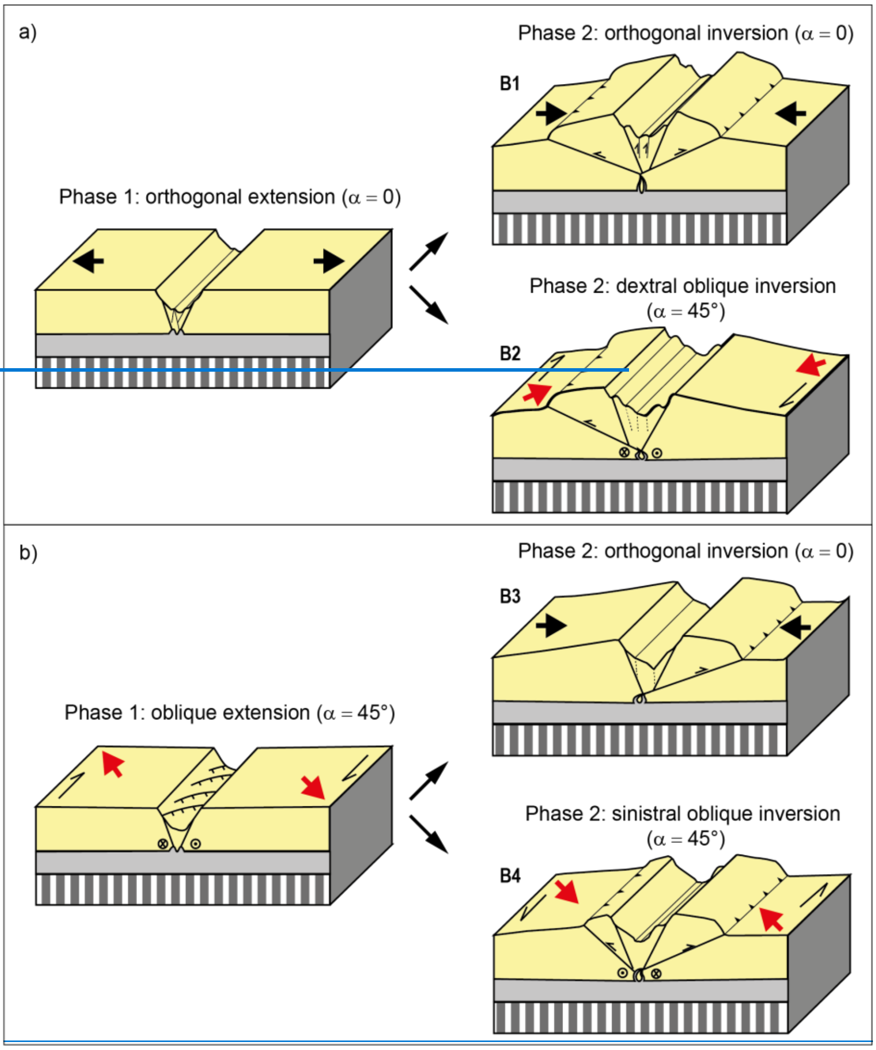
4.1.2. Inversion phase

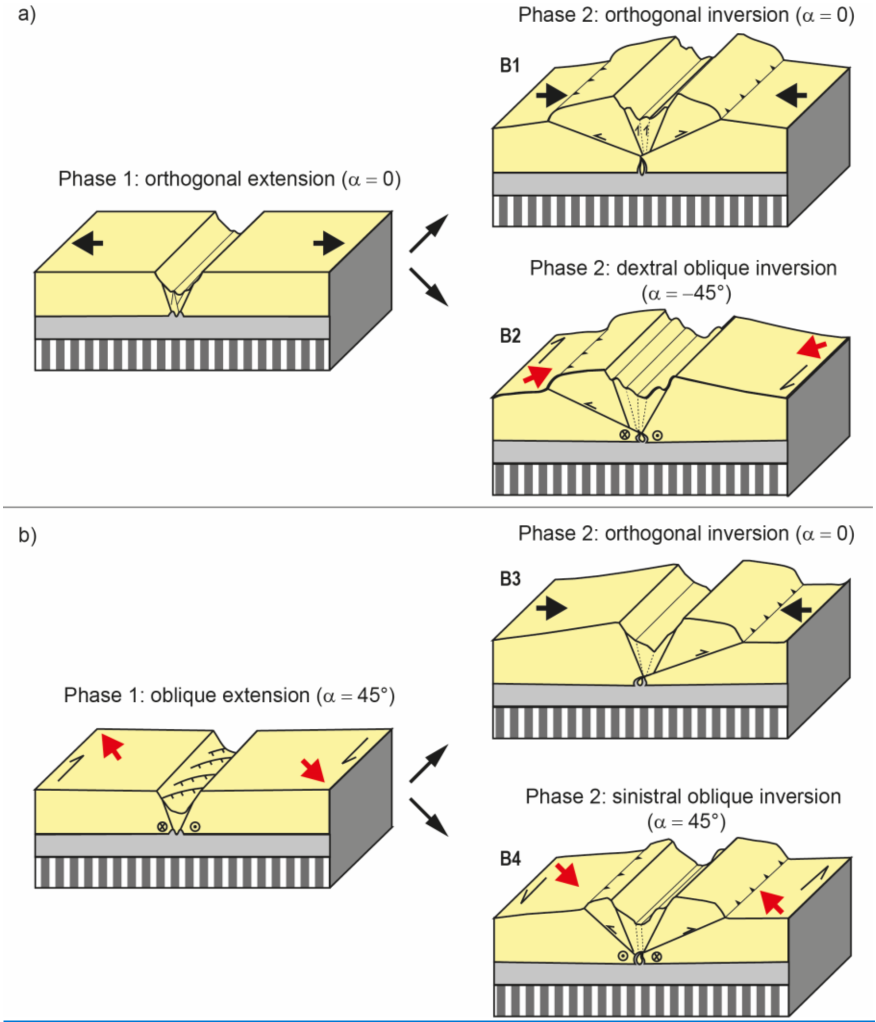
Our experimental results have established an order of importance regarding the parameters controlling fault reactivation throughout the inversion phase (Figs. 9b and 10b). It seems that the rift kinematics, i.e. orthogonal vs. oblique rifting, have no significant influence on inversion structures as the final rift structures were very similar. Much more important are syn-rift sedimentation and inversion kinematics.

Without sedimentation, the rift structures were reactivated during inversion, and ~~the~~ new low-angle reverse faults developed independently of inversion direction (Fig. 9). Both orthogonal and oblique inversion resulted in the development of new low-angle reverse faults rooting at the base of the graben (Fig. 9). The reactivation of the rift structures~~,~~ occurred mainly at the intra graben structures in the orthogonal inversion models (Fig. 4 and 5; ~~M~~models B1 and B3), whereas in oblique inversion models (Fig. 4 and 5; ~~M~~models B2 and B4) both the graben boundary faults and the intra-graben faults showed significant reactivation.

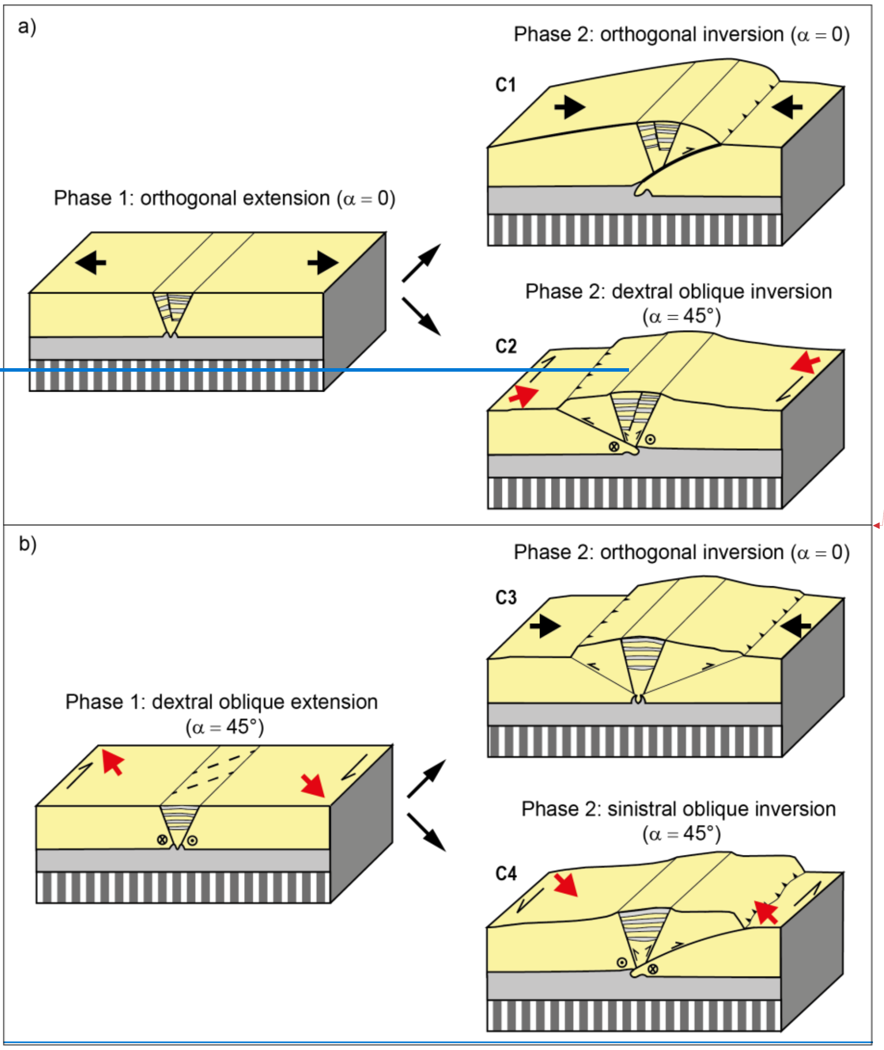
The presence of syn-rift sediments (Fig. 10b) led to major differences in fault reactivation throughout the inversion phase, since the basin infill acted as a buffer to reactivation of the rift structures. ~~During orthogonal inversion graben faults did not undergo any reactivation while deformation localized in the newly formed low-angle reverse faults (Fig. 10). In the oblique inversion models, the reactivation of previous rift structures was observed.~~ Our models results are in accordance with previous studies that described a similar decrease in fault reactivation when syn-rift sedimentation was applied (Pinto et al., 2010~~b, a~~a,b; del Ventisette et al., 2006; Panien et al., 2005b; Dubois et al., 2002). By contrast, Panien et al. (2005) found that graben infill increased rift fault reactivation. This difference was likely due to their use of rheologically weak microbeads as graben infill, while we used feldspar and quartz sands so that the graben infill in our models had a similar rheology to the surrounding granular materials.

Furthermore, we found that during orthogonal inversion graben faults did not undergo any reactivation as deformation localized in the newly formed low-angle reverse faults, whereas limited reactivation of previous rift structures was observed in our oblique inversion models (Fig. 10). ~~Furthermore, o~~Other studies, ~~-~~with different analogue modelling set-ups, have also shown that increasing degrees of oblique ~~compression~~ convergence can promote normal fault reactivation (e.g., Nalpas et al., 1995; Brun and Nalpas, 1996; see also reviews by Bonini et al. 2012 and Zwaan et al. 2022b), and references therein. Indeed, while analyzing inverted rift basins in nature, Ziegler et al. (1995) found that in order to facilitate normal fault reactivation the maximum horizontal compressive stress should be at an angle <45° to the normal fault strike.


a)
Phase 2: orthogonal inversion (α = 0)
B1
Phase 1: orthogonal extension (α = 0)
Phase 2: dextral oblique inversion
(α = 45°)
B2
b)
Phase 2: orthogonal inversion (α = 0)
B3
Phase 1: oblique extension (α = 45°)
Phase 2: sinistral oblique inversion
(α = 45°)
B4



605 **Figure 9: Schematic summary of our experimental results without syn-rift sedimentation**



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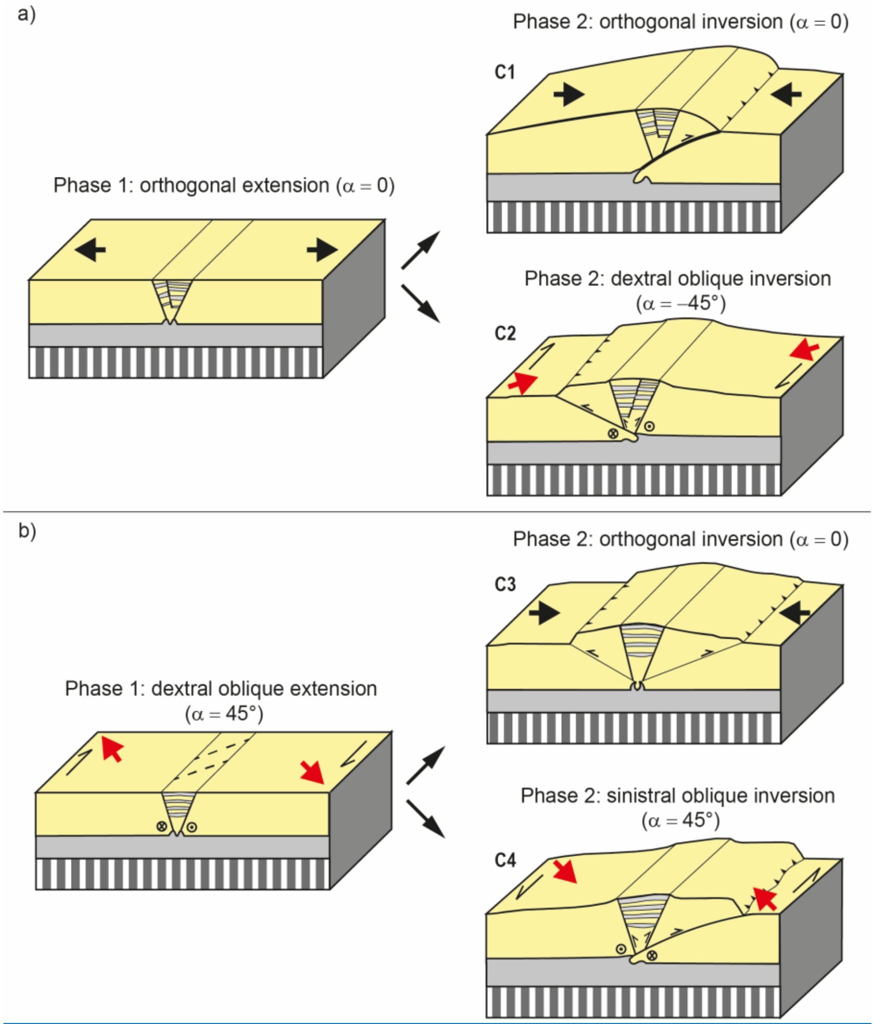

Figure 10: Schematic summary of our experimental results with syn-rift sedimentation

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4.2 Comparing model results with the Araripe Basin

This study was inspired by the Late Jurassic/Early Cretaceous Araripe Basin in NE Brazil, which is presently situated at 1000 m above sea level (Assine, 2007). This elevation is due to post-rift inversion for which two ~~main~~ end-member scenarios have been proposed (regional uplift or rift fault reactivation ~~or regional uplift~~, ~~-~~ Peulvast and Bétard, 2015, and Marques et al., 2014 ~~and Peulvast and Bétard, 2015~~, respectively, Fig. 1). Here we ~~discuss~~ revisit these scenarios in the context of our model results, ~~.~~and propose a third, updated scenario for inversion in the Araripe Basin.

The uplift of the Araripe Basin infill as explained by the Peulvast and Bétard (2015) scenario involves a large-scale rather than local basin inversion produced by regional ~~tectonic~~ uplift (Fig. 1). According to these authors, the present-day high standing mesa formation of the Araripe Basin is the result of differential erosion due to the presence of a strong sandstone formation covering the rift and post-rift sedimentary formations. However, other work demonstrates continuing ca. E-W compression across the South American plate (Assumpção, 1992; Coblentz and Richardson, 1996; Lima, 2003; Marques et al., 2013; Assumpção et al., 2016), combined with fault inversion in the region (e.g. Bezerra et al., 2020; Vasconcelos et al., 2021), suggesting that compressional horizontal stresses must have played a role in the inversion of the Araripe Basin as well.

Marques et al. (2014) proposed that inversion of the basin resulted from such regional horizontal compression acting on the South American plate due to the opening of the South Atlantic Ocean to the east (ridge-push) and the development of the Andes Cordillera to the west. Furthermore, Marques et al. (2014) concluded that these combined ~~forces~~stresses ~~combined~~ were the cause for reactivation and inversion of high angle normal faults. Additionally, the authors stated that the obliquity of the normal faults in relation to the inversion stresses, in combination with fluid injection along the fault planes, facilitated fault reactivation. However, although we observed some fault reactivation in our oblique inversion models, this reactivation did never lead to full inversion of the graben normal faults (Figs. 9 and 10). In fact, no large-scale normal fault reactivation has been observed on seismic sections from the Araripe Basin (Ponte and Ponte-filho, 1996). Instead, Rosa et al. (2022) described limited reverse movement and fault inversion during Early Cretaceous rifting, when the basin changed from a system undergoing NE-SW extension to a system undergoing NW-SE extension. These authors reported positive flower structures on seismic lines that only affected syn-rift units, and suggested that the inversion of normal faults, which Marques et al. (2014) attributed to the most recent inversion of the Araripe basin, might in fact have occurred locally during the initial rifting phase instead. Furthermore, the post-rift sediments of the Araripe Basin cover an area larger than the extent of the original rift grabens and were deposited directly over the pre-Cambrian basement (Assine, 2007), and large-scale offset of these post-rift units is not observed in the field.

However, recent work shows that mild post-rift fault inversion did take place in the basin (Cardoso, 2010) and also other studies detected inversion in basins from the same rifting system the Araripe Basin is part of (e.g. Rio do Peixe Basin, Potiguar Basin, Bezerra et al., 2020; Vasconcelos et al., 2021). These authors analysed seismic data and described a mild to moderate inversion along the normal faults of these basins, although no full-scale basin inversion *sensu* Marques et al. (2014) was observed. Similar observations are

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made on seismic sections from the Araripe Basin (Ponte and Ponte-filho, 1996), supporting the interpretation that horizontal shortening must have played a role in the inversion of the Araripe Basin. However, this shortening must have been accommodated in some other way than large-scale normal fault inversion. ~~Marques et al. (2014) proposed that inversion of the basin resulted from a regional horizontal compression of the South American plate due to the opening of South Atlantic Ocean to the east (ridge-push) and the development of the Andes Cordillera to the west. Furthermore, Marques et al. (2014) concluded that these forces combined were the cause for reactivation and inversion of high angle normal faults. Additionally, the authors stated that the obliquity of the normal faults in relation to the inversion stresses was the facilitator for fault reactivation. However, although we observed some fault reactivation in our oblique inversion models, this reactivation did never lead to full inversion of the graben normal faults (Figs. 9 and 10), which contradicts the Marques et al. (2014) scenario. In fact, no large scale fault reactivation has been observed in the Araripe Basin (Ponte and Ponte filho, 1996).~~ Rosa et al. (2022) ~~described reverse movement and fault inversion during rifting phase in the Early Cretaceous, when the basin changed from an initial NE- oriented transtensional basin to a NW-oriented transtensional basin~~. Rosa et al. (2022) interpreted two Araripe Basin seismic lines showing positive flower structures affecting only rift phase unites and not propagating to the youngest post-rift units, that represents the basin high standing topography feature.~~These authors pointed out that, maybe, inverted faults attributed to the most recent compressional inversion of the Araripe basin might be related to early rift inversion of the main stress axis. Rosa et al. (2022) interpreted two Araripe Basin seismic lines showing positive flower structures affecting only rift phase unites and not propagating to the youngest post-rift units, that represents the basin high standing topography feature.~~

Our modelling results provide a solution to this apparent paradox, which involves the development of large-scale low-angle reverse faults during oblique convergence that take up most of the shortening, thus leading to basin uplift with some, but very limited, reactivation of the original rift structures (Fig. 11). Given the regional E-W shortening causing inversion of the Ararip Basin and the SW-NE orientation of the initial grabens (Fig. 1a), this oblique shortening was most likely of a dextral nature. Furthermore, our models suggest that initial rift kinematics did not have a strong impact on the later inversion structures, the right-stepping *en échelon* basin arrangement of the Araripe basin is similar to oblique rifting structure in our models (Figs. 1a, 5, 8-10), and suggests an initial sinistral oblique rifting phase due to roughly E-W extension. Our new oblique inversion scenario also explains the relatively undeformed uplift of the post-rift sediments and is in line with observations from the nearby Rio de Peixe Basin. In this basin, which is situated to the NE of the Araripe Basin and is part of the same rift trend, ~~The post-rift sediments of the Araripe basin, cover an area larger then the rift grabens domain and was deposited directly over the pre-Cambrian basement (Assine, 2007). In section view (Fig. 1; Assine, 2007; Peulvast and Bétard, 2015), we can observe that the Araripe Basin topographic feature standing out from the basement around it is formed by the post rift units, while rift units are leveled with the basement. Thus, if the normal faults major inversion is the sole responsible for the Araripe Basin uplift, as proposed by Marques et al. (2014), one would expect structural compartmentation along the standing out topographic feature (outside and inside~~

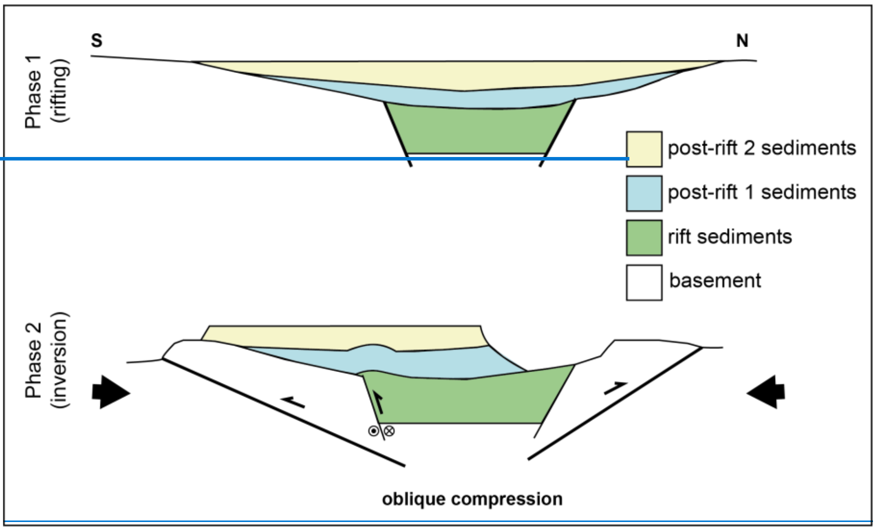
~~the graben domain) and clear normal fault inversion in the seismic lines affecting post-rift units (Ponte and Ponte-filho, 1996; Rosa et al., 2022).~~

~~Immediately to the NE of the Araripe Basin, in the same rift trend,~~ Vasconcelos et al. (2021) described mild to moderate inversion along the rift faults ~~of the Rio do Peixe Basin. The main difference between these basins is the absence of post-rift units and no standing out topographic feature in the last one. The same~~, as well as ~~authors even describe~~ reverse faulting~~s~~ in the basement outside the graben area~~,~~. These observations of the Rio do Peixe Basin are in excellent agreement ~~corroborating~~ with our model results and we propose that ~~s forming new reverse faults outside the graben and mild reactivation of the normal faults.~~

~~A further argument against the Marques et al. (2014) scenario would be that the post-rift sediments outside the original graben domain would not have been uplifted in contrast to what we see in nature (Fig. 1).~~

~~This basin uplift of post-rift sediments outside of the original graben domain can be explained by the Peulvast and Bétard (2015) scenario, who proposed a large-scale topographic rather than local basin inversion produced by a regional tectonic uplift (Fig. 1). According to these authors, the present-day high standing mesa formation of the Araripe Basin is the result of differential erosion due to the presence of a strong sandstone formation covering the rift and post-rift sedimentary formations. However, other work demonstrates the continuing compression across the South American plate (Assumpção, 1992; Coblentz and Richardson, 1996; Lima, 2003; Marques et al., 2013; Assumpção et al., 2016), combined with fault inversion in the region, and suggests that compressional horizontal stresses must have played a role in the Araripe Basin inversion. In fact, recent work shows that mild inversion did take place in the basin (Cardoso, 2010) and also other studies detected inversion in basins from the same rifting system as the Araripe Basin (e.g. Rio do Peixe Basin, Potiguar Basin, Bezerra et al., 2020; Vasconcelos et al., 2021). These authors analysed seismic data and described a mild to moderate tectonic reactivation inversion along the normal faults, however no full-scale basin extrusion inversion is observed. Recent studies showed that lithospheric anomalies under the Araripe Basin could be responsible for the Borborema Province uplift (Garcia et al., 2019; Nemocón et al., 2021). This might imply that the basin went through a vertical push combined with horizontal compression (Garcia et al., 2019). We thus find that independently of any vertical forces acting on the lithosphere below the basin causing regional uplift, the horizontal compression affecting the South American plate is the main responsible for inversion of the Araripe Basin. We thus find that neither of the two end-member scenarios seems to fully explain the inversion observed in the Araripe Basin area.~~

~~However, we propose an alternative scenario based on our analogue model results (Fig. 11). This scenario involves a basin scale uplift facilitated by newly developed reverse faults rooted at the base of the original graben structure. At the same time, we only observed the mild inversion of the rift structures reactivation is shown to be only possible in oblique compression scenario when syn-rift sediments are present. As such~~ this ~~model~~ same scenario involving can readily explain the field observations from the Araripe Basin as well. Furthermore, the inferred ~~but also predicts the~~ presence of large low-angle reverse faults (with a strike-slip component) outside the original rift basin as predicted by our models ~~, which~~ provides a strong~~n~~ incentive for further field investigations to verify ~~this~~ our proposed scenario for inversion ~~in~~of the Araripe Basin.



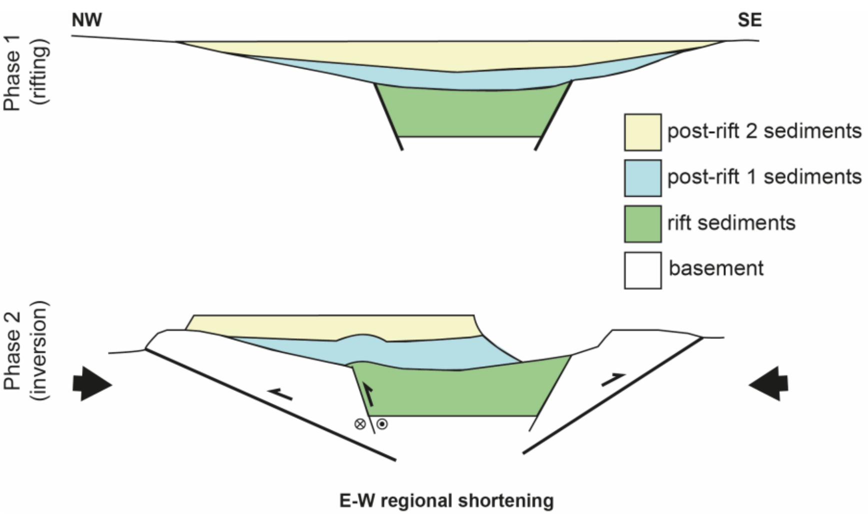


Figure 11: Proposed tectonic ~~evolution~~ scenario for ~~of the~~ Araripe Basin inversion based on our analogue model results and data from literature. The scenario involves an initial rifting phase creating SW-NE oriented basins, followed by dextral oblique ~~compression~~convergence due to general E-W oriented convergence. See text for details. Modified after Marques et al. (2014).

5 Conclusions

In this study we completed a series of new analogue modeling experiments aimed at evaluating the scenarios for basin inversion in the Araripe Basin in NE Brazil ~~(full border fault reactivation vs. regional uplift)~~. We tested the influence of orthogonal ~~(α=0)~~ or oblique ~~(α=45°)~~ extension, followed by either orthogonal or oblique ~~compression~~ convergence on rift development and on subsequent inversion structures. We find that:

- During rifting without sedimentation, orthogonal ~~extension~~ divergence creates through-going border faults, whereas oblique ~~extension~~ divergence leads to the initial formation of ~~en-echelon~~*en échelon* faults that eventually will link up to establish large ~~border~~ graben boundary faults. Rift basins with syn-rift sedimentation follow a similar evolution, however the sedimentary loading ~~causes~~ increased subsidence compared to models without sedimentation.

- During inversion, a major part of the deformation is accommodated by newly formed ~~low~~ low-angle reverse faults. Within that framework, models without sedimentation saw significant intra-graben fault reactivation, roughly independent of inversion direction (~~α=0 or α=45°~~orthogonal or oblique). By contrast, in models with syn-rift sedimentation, inversion caused only minor reactivation of the original ~~rift~~ graben boundary faults during oblique ~~compression~~convergence, due to the sedimentary infill acting as a buffer ~~during compression~~. Orthogonal ~~compression~~ convergence in models with syn-rift sediments did not lead to rift fault reactivation.

- An assessment of the existing scenarios for inversion ~~in~~ of the Araripe basin with our model results as well as data from the field show that these scenarios do not fully explain all observations of the natural example. Therefore, based on our model results we propose an alternative scenario involving dextral oblique ~~compression~~ inversion and the development of ~~low~~ low-angle reverse faults (with a strike-slip component) outside the basin. This scenario ~~better explains the available field observations in the Araripe Basin but also~~ provides an~~d~~ incentive for future (field) studies.

Authors contributions

PCR, FZ and GS planned and designed the experiments. PCR completed the experiments, analysed the model results, and wrote the first manuscript draft. FZ participated in running some of the experiments. FZ and TCS helped performing the model analysis. PCR, FZ, GS, RSS, TCS participated in the interpretation of the model results, and reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Data availability

Detailed overviews of model results are ~~made~~ publicly available in the form of a GFZ data publication (Richetti et al. in prep).

Temporary link: https://1drv.ms/u/s!AnD2tls1Utsrg_8b10PsZiOu7qn1Yw?e=KLkOdi

Example of GFZ data publication: https://doi.org/10.5880/fidgeo.2021.042

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