



Modelling the interactions of discrete inherited structures, pervasive fabrics and extension direction during rifting: application to the Cenozoic Eger Graben

Filip Havlíček^{1,2}, David Uličný^{1,2}, Ondřej Krýza¹, Matěj Machek¹, Michael Warsitzka^{1,3}, and Prokop Závada¹

¹Institute of Geophysics of the Czech Academy of Sciences, Boční II/1401, 14131 Prague, Czechia

²Institute of Geology and Paleontology, Charles University, Albertov 6, 12800 Prague, Czechia

³Bundesgesellschaft für Endlagerung mbH (BGE), Eschenstraße 55, 31224 Peine, Germany

Correspondence: Filip Havlíček (havlicek@ig.cas.cz)

Abstract. Pre-existing mechanical heterogeneities significantly influence the evolution of continental rifts and their resulting fault architecture. The Cenozoic Eger Graben (EG) in the northwestern Bohemian Massif (Central Europe) represents a fossil rift system in which the role of structural inheritance has been relatively unaddressed. This study examines how basement structures inherited primarily from Paleozoic geodynamic events may have controlled syn-rift fault development in a setting where the orientation of the rift axis and basement fabric varied in space relative to the extension direction. Two series of crustal-scale analogue models inspired by the EG setting were designed to investigate the effects of both discrete and pervasive weaknesses on evolving fault populations. The first series simulated reactivation of a segmented basement weakness (velocity discontinuity, VD) under uniform or changing extension directions, testing an existing two-phase extension model. The second employed a uniformly extending elastic model base and approximated the role of pervasive fabrics by imprinting grooved patterns into the basal silicone layer. Surface strain evolution was analysed using digital image correlation, while final fault patterns were compared with the generalised structure of the EG. The results highlight the dominant influence of the initial extension phase during polyphase rifting, with the segmented geometry of the VD exerting further control on fault development. Some two-phase scenarios reproduce the observed fault pattern more successfully than others, suggesting that temporal variations in paleostress orientation remain plausible. However, experiments involving spatially variable basement fabrics demonstrate that faults of contrasting orientation and geometry can develop simultaneously above suitable inherited structures. Several structural features of the Eger Graben may therefore reflect synchronous reactivation of different inherited structures rather than rotation of the extension direction. The influence of pervasive fabrics on modelled fault geometries compares well with natural examples and demonstrates the broader applicability of this experimental approach.

1 Introduction

Rift zones, as areas of crustal and lithospheric extension, are a crucial element of the global plate tectonic cycle and their study is relevant for understanding the geodynamic processes involved as well as their impact on society (Brune et al., 2023; Zwaan



et al., 2024). In a generalised model, in the initial stage of development, a zone of continental extension typically evolves from a distributed array of largely isolated normal faults, which rapidly propagate laterally and eventually coalesce into a few localised, through-going principal fault zones that accommodate most of the subsequent displacement and bound major basins (Cowie, 1998; Gawthorpe and Leeder, 2000; Gupta et al., 1998; Walsh et al., 2002). In any real situation the location and geometry of these incipient faults result from the interplay between the extensional stress field and pre-rift inherited structures. These provide both regional and local variations in crustal strength that facilitate fault nucleation and may locally reorient the prevailing stress field (e.g., Collanega et al., 2019; Corti et al., 2022; Morley, 2010; Morley et al., 2004; Phillips et al., 2016; Ramos et al., 2022, comprehensive reviews in: Samsu et al. (2023); Morley and Chantpraser (2025)). The often-limited spatial extent of both discrete inherited weakness zones (e.g., sutures, ductile shear zones, lithological boundaries, inactive faults) and wider domains of contrasting basement structural fabrics can lead to partition of the developing rift into individual segments (Corti, 2008; Corti et al., 2007; Heilman et al., 2019; Laó-Dávila et al., 2015; McClay et al., 2002; Wu et al., 2024; Zwaan and Schreurs, 2017). Each rift segment can thus be characterised by distinct fault populations with varying orientation and complex non-collinear fault geometries (Osagiede et al., 2020; Reeve et al., 2015; Wilson et al., 2010). Multi-phase extension can further alter the final structural pattern, especially in cases where the orientation of horizontal stresses changes in time with successive phases separated by periods of tectonic quiescence sometimes lasting millions of years (e.g. The North Sea rifts - Bell et al. (2014); Celtic sea basins - Rodríguez-Salgado et al. (2022); the Lofoten Margin - Henstra et al. (2019); Cenozoic rifts of Thailand - Morley (2017); Pongwapee et al. (2019)).

The non-trivial combination of factors of inheritance and changing stress direction leads to increasing complexity of the resulting fault pattern through time. In cases of fossil rifts, especially those where detailed data about the 3D geometry of individual faults and associated depocenters and reliable paleostress indicators are sparse, the kinematic history of the rift can be difficult for researchers to decipher. One way to get a more comprehensive understanding of the dynamic evolution of such rift systems through time is to use geodynamic modelling techniques. Despite some intrinsic limitations, scaled analogue modelling in particular has proven to be an effective method for understanding the dynamics of rifting. A wide range of modelling studies have focused on the reactivation of both **discrete and pervasive inherited weaknesses** (e.g., Chattopadhyay and Chakra, 2013; Corti, 2004; Corti et al., 2007; Maestrelli et al., 2020; Molnar et al., 2019, 2020; Osagiede et al., 2021; Samsu et al., 2021; Tong et al., 2014; Zou et al., 2024; Zwaan et al., 2022; Zwaan and Schreurs, 2017) as well as on the effects of oblique rifting and changes in extension direction through time (e.g., Agostini et al., 2009; Bonini et al., 1997; Corti, 2008; Dubois et al., 2002; Henza et al., 2011, 2010; McClay et al., 2002; McClay and White, 1995; Michon and Sokoutis, 2005; Philippon et al., 2015; Rodrigues et al., 2023; Withjack et al., 2017).

In this contribution we present the results of two sets of analogue models designed to provide experimental constraints on several key aspects of tectonic history of the Cenozoic Eger Graben in northwestern Czechia and surroundings. The Eger Graben represents a fossil rift structure that developed in a crust characterised by a complex pre-rift structural framework. The ways in which the structural inheritance influenced the evolution of the rift remain relatively unexplored, ~~however~~. The first experimental set focuses on reactivation of a single segmented weakness (i.e. a buried fault zone) under two non-coaxial phases of extension, exploring the existing model of two-phase extensional history for the Eger Graben proposed by earlier authors



(Rajchl et al., 2009; Špičáková et al., 2000). The second experimental set, applying a uniform pure-shear-style extensional stress field, addresses the interaction of multiple types of predisposed weaknesses, both pervasive regional fabrics and discrete weak zones, inspired by specific basement structures beneath the central and eastern Eger Graben.

60 2 Geological setting – Eger Graben

The Eger Graben (EG) is the easternmost part of the European Cenozoic Rift System (ECRIS; Prodehl et al., 2006, 1992) located on the northwestern flank of the Bohemian Massif (Fig. 1a). The EG started developing during the late Eocene to early Oligocene following a voluminous extrusion of alkaline magmas in volcanic centres located along the rift axis (Ackerman et al., 2015; Kopecký, 1978; Plomerová et al., 2016; Ulrych et al., 2000, 2011). Its present-day expression consists of several
65 basins which are believed to represent an erosional relict of infill of a larger interconnected rift (Fig. 1b). Thus, in some parts of the rift, specifically the eastern segment and the central segment containing the České Středohoří Volcanic Complex, no major clastic depocenters remain preserved. Rift-related faulting in this segment is still believed to have been significant, recorded in downthrown blocks of the pre-rift sequences mainly formed by Late Cretaceous marine clastics (e.g., Malkovský, 1987; Uličný et al., 2024). Based on stratigraphic, structural and geophysical data from the Most Basin, the largest preserved depocenter with
70 syn-rift sedimentary accumulations up to 500 m thick, Rajchl et al. (2009) proposed a two-phase extensional history for the rift.

According to Rajchl et al. (2009) and Špičáková et al. (2000), the EG was initiated by an episode of N-S directed horizontal extension producing an oblique rift mostly defined by E-W trending, en-echelon faults bounding individual depocenters that accumulated fluvio-deltaic clastics and peat (Fig. 2a). A subsequent phase of NW-SE directed (i.e. roughly orthogonal to the
75 rift axis) extension approximately during early mid-Miocene has been hypothesised by the above authors as having caused the formation of NE to ENE trending fault segments, commonly connecting the earlier, E-trending faults into long composite structures with “zig-zag” geometries (Fig. 2b). Rajchl et al. (2009) also see the fault linkage as the cause of accelerated basin floor subsidence that led to the demise of the shallow peat-forming swamp and a formation of a basin-wide lake. However, a competing hypothesis exists, which attributes the lacustrine environment expansion to climate change, and considers peat
80 compaction, rather than tectonics, mainly responsible for accommodation space creation (Matys Grygar et al., 2017). Nevertheless, the above-described interpreted stress evolution is broadly in accordance with other published Cenozoic paleostress reconstructions for NW Bohemia (Adamovič and Coubal, 1999; Coubal et al., 2015).

Rajchl et al. (2009) made a case for this history to be apparent in the kinked geometry of the Krušné Hory Fault Zone (KHFZ), presently the principal bounding fault separating the rift infill from the Krušné Hory (Erzgebirge) uplift. The presence
85 of localised erosional relicts of basin fill in the footwall block of the KHFZ suggests a diffuse northern border defined by E-W trending relay ramps connecting short fault segments in the initial stages of rift development (Fig. 2a). Such a configuration is supported also by paleogeographic reconstructions (Mach et al., 2014). The greater displacement following successive fault linkage resulted in uplift and erosion of the rift flanks; the northern flank along the KHFZ was uplifted between the mid-Miocene and Quaternary to the present-day elevations up to 1 km a.s.l., to form the Krušné Hory mountain plateau. However,

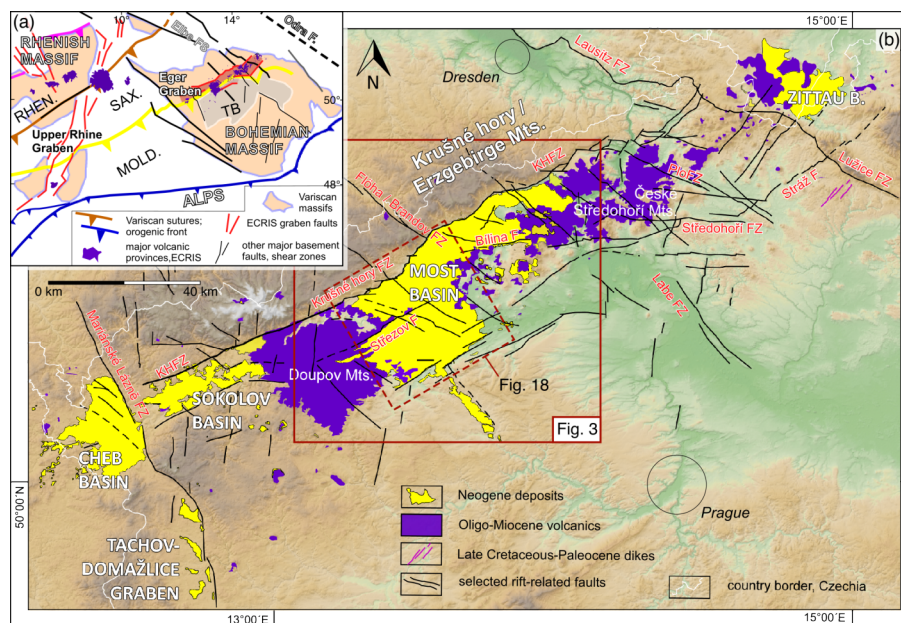


Figure 1. Synoptic map of the Eger Graben within the context of the European Cenozoic Rift System (ECRIS) (a) ECRIS structures in Central Europe highlighting the exposed Variscan massifs and Variscan orogenic domains in European lithosphere. MOLD.: Moldanubian domain; RHEN.: Rhenohercynian domain; SAX.: Saxothuringian domain; TB: Teplá-Barrandian Unit. ECRIS structures, sutures, Variscan massifs after Ziegler and Dèzes (2005) (b) The preserved extent of Neogene depocenters, volcanic centres and major rift related faults in the Eger Graben. KHFZ: Krušné Hory Fault Zone; PlouFZ: Ploučnice Fault Zone. Contains modified Copernicus EEA-10 DEM data and Copernicus Sentinel data (2024).

90 the precise timing and mechanisms of the uplift as well as its relation to the prior rifting event are still debated and remain unclear (c.f. Ziegler and Dèzes, 2007).

2.1 Basement structure of the NW Bohemian Massif

The EG differs from other ECRIS rifts in its general alignment with a major terrane boundary – the Teplá Suture – resulting from the Paleozoic consolidation of European lithosphere during the Variscan orogeny. Other Cenozoic rift structures of the ECRIS instead tend to crosscut the trends of primary Variscan orogenic zonation (Prodehl et al., 1992; Ziegler and Dèzes, 2005, fig. 1a). Although a link between the Teplá Suture and the Eger Graben has been proposed (Babuška et al., 2010; Babuška and Plomerová, 2006, 2012) a more detailed study into the role of crustal scale inherited structures in EG formation has been lacking until recently (Uličný et al., 2024). Below, the highly complex and extensively studied pre-Cenozoic geodynamic history of the northwestern Bohemian Massif is briefly summarised (e.g., Matte et al., 1990; Schulmann et al., 2014, 2009; Žák et al., 2018).

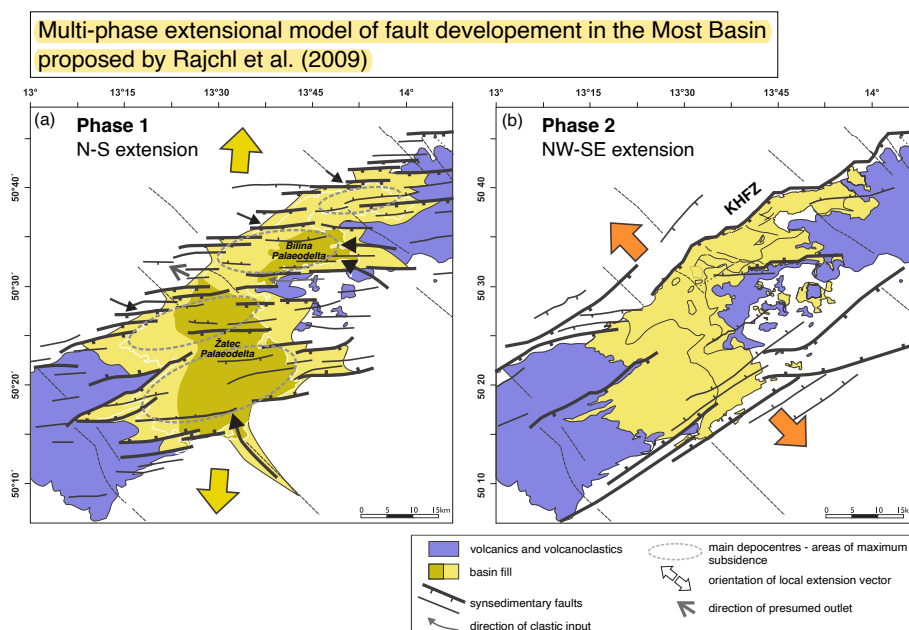


Figure 2. The existing two-phase extensional model for the Most Basin showing the extent of depocenters and fault geometries. (a) Paleogeographic and tectonic situation at the peak of peat formation (early mid-Miocene) in the Most Basin. E-W trending en-echelon faults constitute the primary structural element of the basin as a result of roughly N-S directed extension. (b) The proposed switch to NW-SE stretching causing fault linkage and formation of long rift-parallel faults, particularly on the southern flank. KHFZ: Krušné Hory Fault Zone. Modified and simplified after Rajchl et al. (2009).

100 2.1.1 Variscan architecture of NW Bohemian Massif

As mentioned above, the axis of the Cenozoic Eger Graben in its western and central part roughly follows a tectonic boundary between major units of the Variscan orogen, the Teplá Suture (although the easternmost segment of the rift diverges from the offset suture trace – fig. 3). This lithosphere-scale heterogeneity is believed to be the result of oceanic crust subduction followed by partial underthrusting of the Saxothuringian continental margin under the Teplá-Barrandian unit to the SE (Schulmann et al., 2009, and references therein). Although the trace of the suture is largely concealed by several generations of younger sedimentary basins, geophysical observations have revealed a steep zone of contact spanning the entire lithosphere (Babuška et al., 2008, 2010). The Saxothuringian domain, originally considered a rifted (passive) margin, is a crustal fragment consisting of a Cadomian basement with episodes of magmatism and sedimentation affecting it throughout the early Paleozoic (Dallmeyer et al., 1995; Linnemann et al., 2000). In the Krušné Hory area, the Variscan crustal architecture is dominated by a series of nappes and slivers of crust exhumed from the subduction channel (reaching peak metamorphic conditions at ca. 350 Ma) and thrust over lower grade autochthonous units preserved in the core of antiformal domes (e.g., the Catherine Dome – CD in fig. 4; Konopásek et al., 2001; Mlčoch and Schulmann, 1992). In general, the structural fabric of this unit is highly complicated and spatially variable, and its detailed description is beyond the scope of this study. However, in the SE part exposed at the

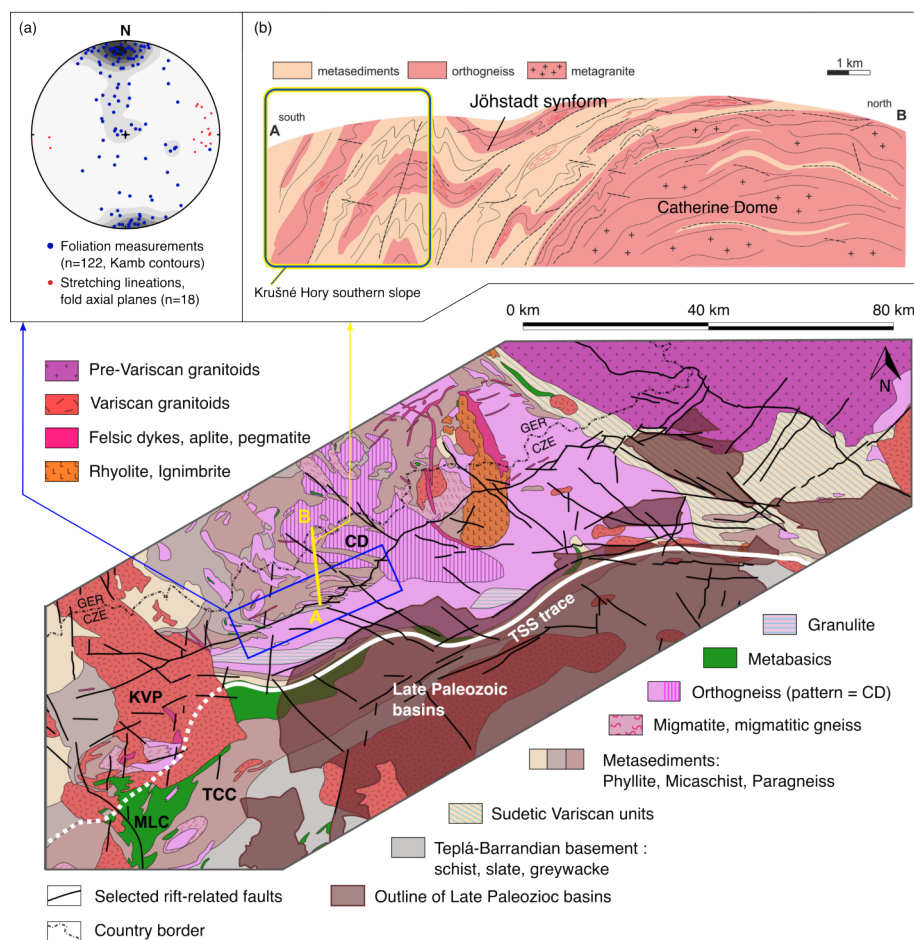


Figure 3. Simplified geological map of the Variscan basement of NW Bohemian massif showing the spatial relationship of basement units, upper Paleozoic post-collisional basins and selected rift-related faults. KVP: Karlovy Vary Pluton; MLC: Mariánské Lázně Complex; CD: Catherine Dome; TCC: Teplá Crystalline Complex; TSS: Teplá-Saxothuringian Suture. Suture trace after Mlčoch and Konopásek (2010). (a) Stereogram of structural measurements, mainly foliation planes, in the Saxothuringian metamorphic basement along the northern flank of the Most Basin. Blue rectangle highlights the approximate area where structural data were collected. Data from Havlíček (2026). (b) N-S structural section across the core of the Catherine Dome and its southern limb. Section from Kryl et al. (2021).

115 rift flank along the KHFZ, in close proximity to the suture zone, the metamorphic fabric attains a consistent E-W trend with a steep dip, mainly towards the south (Kryl et al., 2021; Zulauf et al., 2002, fig. 3a).

The Teplá-Barrandian unit represents a crustal section through a Late Neoproterozoic to Cambrian forearc domain composed mainly of mica schists transitioning into lower grade schists and slates as the degree of metamorphism decreases towards the SE, away from the suture zone (Hajná et al., 2011, 2010; Sláma et al., 2008; Žák et al., 2014). The suture zone itself is marked by high grade mafic to ultramafic complexes, with the Mariánské Lázně Complex being the only well-exposed example (MLC

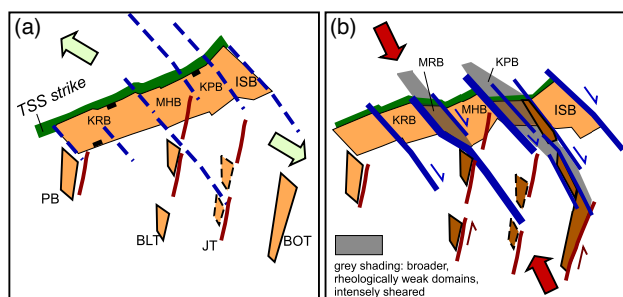


Figure 4. Tectonic sketch of post-Variscan (early Permian) dextral shearing and segmentation of the initially linear belt of upper Paleozoic basins, after Uličný et al. (2009b). (a) Basin formation along the Teplá Suture trace. (b) Subsequent dextral shearing along NW-SE oriented structures of the Elbe Fault System. TSS: Teplá-Saxothuringian Suture; KRB: Kladno-Rakovník Basin; MHB: Mnichovo Hradiště Basin, KPB: Krkonoše Piedmont Basin, ISB: Intra-Sudetic Basin, PB: Pilsen Basin, BLT: Blanice Trough, JT: Jihlava Trough, BOT: Boskovice Trough, MRB: Mšeno-Roudnice Basin.

in fig. 3). Similar units are interpreted further east along the contact, revealed by positive gravity anomalies and locally sampled by core penetrating through the sedimentary cover into the basement (Mlčoch, 2003; Valenta et al., 2011).

2.1.2 Post-collisional deformation and late Paleozoic basin development

During the peak of the orogeny at ca. 340 - 330 Ma the thickened crust was affected by dextral transpressional shearing along major NW-SE oriented shear zones (Arthaud and Matte, 1977; Edel et al., 2003, 2018). One of them is the Elbe Fault System (EFS) which cross-cuts the Eger Rift in its central part and appears to be a deep-rooted structure that bends the Teplá Suture from a roughly NE strike to an easterly trend (Pitra et al., 1999; Scheck et al., 2002). After the cessation of compressional stresses, the thickened orogenic crust destabilised (Franke, 2006) and a system of linear tectonic troughs of half-graben geometry started forming along its axis no later than 314 Ma and remained active until the early Permian (e.g., Opluštil and Cleal, 2007; Opluštil et al., 2016; Tomek et al., 2022). These basins, with a preserved infill thickness up to 1400 m, have their principal boundary faults following the trend of the basement suture zone, thus trending NE-SW in their western part (Kladno-Rakovník Basin, Žatec Sub-basin) and E-W in the central part (Mšeno-Roudnice Basin; Mlčoch and Martínek, 2002; Mlčoch and Skácelová, 2013, fig. 3, fig. 5). According to a model proposed by Uličný et al. (2009b, 2002) the basins started their evolution as a semi-linear, NE-striking chain of half-graben structures that underwent intense dextral shearing where they were cross-cut by the EFS (fig. 4). Thus, by the early Permian, the basin floor architecture in this area was characterised by a complex patchwork of downthrown and sheared blocks resulting from the transtensional deformation.

2.1.3 Bohemian Cretaceous Basin formation and demise

Another important episode of deformation prior to the Cenozoic rifting event occurred between the mid-Cretaceous and Paleocene. The marine depocenters of the Bohemian Cretaceous Basin developed likely as small flexural basins along structures

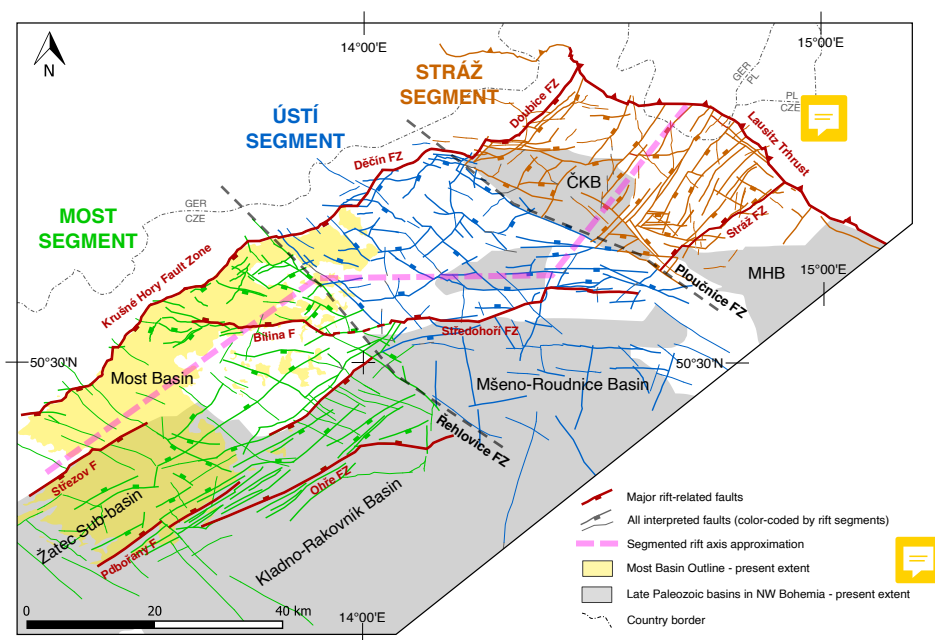


Figure 5. Proposed segmentation of the east-central Eger Graben showing all interpreted faults colour-coded by segments, segment boundaries and the preserved extent of Neogene depocenters. Note the segmented rift “axis” which coincides with the boundaries of underlying upper Paleozoic basins, especially in the Most and Ústí segments. ČKB: Česká Kamenice Basin; MHB: Mnichovo Hradiště Basin. Fault pattern and segmentation after Uličný et al. (2024)

of the EFS (Hindle and Kley, 2021; Voigt et al., 2021) during compressional deformation of west-Central Europe (Hindle and Kley, 2021). The climax of this deformation and associated thrusting at the Lausitz Thrust (“Lužice Fault Zone”; Coubal et al., 2015) during the Paleocene was followed by prolonged period of erosion and planation surface formation. Cretaceous units are preserved under most of the Eger Graben in the area between the Most Basin and the Lausitz Thrust. In the Most Basin itself the Cretaceous layer is usually very thin but thickens considerably towards its NE limit at the Lausitz Thrust. The central and eastern segments of the ER are thus underlain by up to 1 km of Cretaceous basin fill, dominantly clastic, that separates the Paleozoic basement from Cenozoic rift infill and surface expression of its structures (Uličný et al., 2009a).

2.2 Spatial relationships of inherited structures and the Eger Graben

As shown above, the Eger Graben represents a rift structure that formed above a highly heterogeneous basement with several generations of inherited features. The degree and precise mechanisms of influence that these structures exerted on the developing rift remain debated, although even relatively straightforward geometric observations appear insightful. For instance, the southern rift border directly overlies the post-collisional upper Paleozoic basins along most of its length (cf. Jindřich, 1971). Reactivation of the bounding structures of these basins has recently been proposed to have resulted in a segmented nature of the Cenozoic rift in its central-eastern part where the 3 “segments” show distinct fault populations that correspond to the trend of



the presumably reactivated structures below (Uličný et al., 2024, , fig. 5). However, it remains to be understood in greater detail how a syn-rift fault network will develop in response to the reactivation of such a segmented basement weakness, particularly under the proposed conditions of two-phase extension.

In the western part of the rift (Most Basin) there is an apparent contrast in crustal fabrics between the Saxothuringian basement (dominated by a steep E-W metamorphic fabric) on the northern flank and the Teplá-Barrandian basement (dominated by ca. 60° N striking upper Paleozoic half-grabens and their bounding faults) on the southern flank. The structural trends in the crystalline basement of the Teplá-Barrandian unit in this area are mostly unknown since it is concealed deep beneath younger sedimentary cover, although NE to ENE trends of major fabric elements have been reported in the exposed Teplá Crystalline Complex located further west (TCC in fig. 3; Peřestý et al., 2017, 2020). Although Rajchl et al. (2009) have mentioned a possible link between basement structures and the fault pattern inside the Most Basin, their effect remains to be explored in detail, especially considering the two-phase extensional history proposed in their work. Under such conditions, different families of inherited structures would likely be more or less prone to reactivation in each extensional phase. Also, since peculiar, segmented fault geometries were one of the arguments of Rajchl et al. (2009) for the proposed two-phase history, a question arises whether selective reactivation of inherited structures alone under uniform stress conditions could explain these geometries, rather than requiring a rotation of the regional stress field in time.

3 Analogue modelling method

The two model setups described below both aimed to explore the effects of inherited weak zones and fabrics on normal fault development in the upper crust. The two deformation rigs principally differed in the way in which extension was generated at the base of the model. Setup 1 used the edge of a mobile base plate as a discrete “velocity discontinuity” (VD) and allowed for a change in extension direction while Setup 2 used a foam block base producing single-phase pure-shear-style extension in the model crust. Both setups represent purely mechanical models concerning primarily with extension at the crustal scale (see sect. 3.4 Scaling), and as such do not include the effects of weaknesses in the lithospheric mantle, asthenosphere processes nor the thermal evolution of the rifted lithosphere, all important considerations in the study of natural rifted systems (Brune et al., 2023, for review). All modelling work was carried out in the Tectonic modelling laboratory at the Institute of Geophysics of the Czech Academy of Sciences in Prague.

3.1 Materials

Both model setups used the same brittle and viscous materials to simulate the layering of a continental crust. Dry quartz sand is perhaps the most common granular material used to represent the frictional-plastic behaviour of upper crustal rocks in analogue models of rifting (Reber et al., 2020; Schreurs et al., 2006). All the presented models instead used a homogenised mixture of dry quartz sand (bulk density = 1620 kg m⁻³, mean grain size = 170 µm) and hollow silica microspheres (sold under the trade name “fillite”, bulk density = 430 kg m⁻³) in 5:2 ratio to achieve a bulk density of around 915 kg m⁻³ which ensured a realistic density stratification of the model crust. Ring shear measurements of such mixtures carried out by Warsitzka et al. (2021b) at



185 GFZ Potsdam have revealed frictional properties (internal friction angle ca. 33° , cohesion on the order of 10–50 Pa) comparable to the more commonly used pure dry quartz sand, thus making it a suitable analogue material for upper crustal rocks that have been experimentally confirmed to exhibit a generally comparable internal friction angle (Byerlee, 1978).

The viscous to viscoelastic behaviour of lower crustal rocks and mechanically incompetent layers within sedimentary sequences (e.g., evaporite rich layers) is commonly simulated using various types of silicone oils (Cotton and Koyi, 2000; Dooley
190 et al., 2005; Reber et al., 2020; Weijermars, 1986). In this work polydimethyl-siloxane (PDMS, sold as “KORASILON G 20 OH” by Kurt Obermeier GmbH) was used with a density of 970 kg m^{-3} , dynamic viscosity around $2.5 \times 10^4 \text{ Pa s}$ at room temperature, and a near-Newtonian behaviour at low to moderate strain rates (Rudolf et al., 2016).

3.2 Model Setup 1: Discrete basal velocity discontinuity

In general, our first setup represents a widely used sandbox scenario with a thin mobile steel base plate that is pulled using
195 wires attached to an electric motor (cf. Bonini et al., 1997; McClay and White, 1995; Michon and Sokoutis, 2005; Zwaan et al., 2019, and references therein for review; fig. 6a). The edge of the moving plate produces a “velocity discontinuity” (VD) at the model base, transferring asymmetric extension into the overlying crust at a constant speed of 10 mm h^{-1} . At the model base a 0.5 cm layer of PDMS is placed in order to decouple the deformation of the brittle layer from the discrete VD. On top of the PDMS a 3 cm thick layer of the sand–fillite granular mixture is carefully sieved. The sandpack has a rectangular plan (87
200 cm $\times$ 50 cm) and is contained by free slopes on all sides (containment walls used during model layering were removed before the start of the model run). The absence of either moving or static sidewalls removes any undesired edge effects that could be encountered along them. However, since these free slopes still represent an unrealistic boundary condition, only the central part of the model ($>5 \text{ cm}$ from the sandpack upper edge) is considered for further analysis. To facilitate visual comparison with the prototype, arbitrary directions (West, North, etc.) are used in descriptions of the model features in the sections below.

205 The VD itself runs roughly from the SE corner to the NE corner under the sandpack and consists of 3 linear segments (Fig. 6b). The 3 VD segments termed W (“Western”), C (“Central”) and E (“Eastern”) represent a simplified trace of the upper Paleozoic basins underlying most of the Eger Rift, our natural prototype. In this setup θ denotes the angle between a VD segment trend and the E–W axis in the model (i.e. the extension-orthogonal, assuming a South-directed extension). During base plate movement, each VD segment has a different orientation to the extension direction, thus producing a segmented rift
210 in the crust above with a varying degree of “obliqueness” along the rift axis.

In all four models presented below the mobile base plate was pulled for 420 minutes giving a total extension of 70 mm. The extension direction (α) was either to the South ($\alpha = 180^\circ$) or the Southeast ($\alpha = 135^\circ$) with possibility of an abrupt change during the model run. Due to that this setup allowed for a rough reconstruction of the stress history previously presumed for the Eger Graben. This was the case for the two-phase model E8 which initiated with a South-directed Phase 1 followed by a
215 SE-directed Phase 2. Inversely, model E13 started by extension towards the SE followed by South-directed stretching in Phase 2. Models E9 and E14 represented reference scenarios where the extension direction stayed constant during the entire model run, fully to the South or fully to the Southeast, respectively (Table 1).

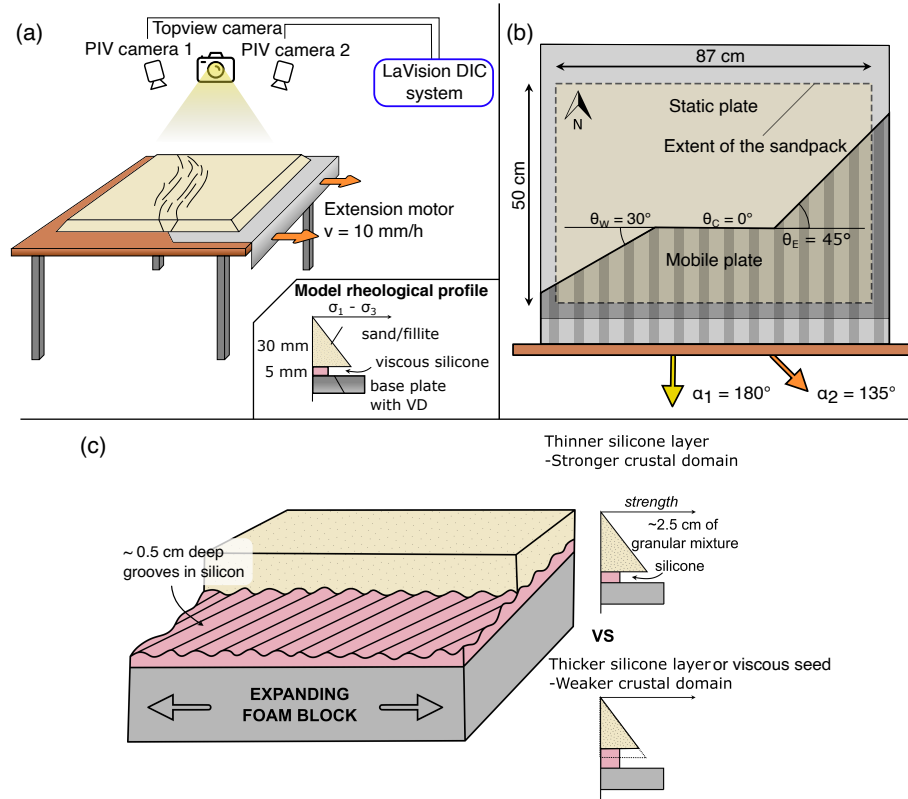


Figure 6. (a) Sketch of the general setup for the discrete VD models (E-series) with surface monitoring provided by a top view camera and 2 stereoscopic cameras for surface deformation analysis, inset shows the idealised rheological profile through the model crust. (b) Base plate plan before the onset of extension which shows the geometry of the segmented VD (mobile plate edge), arrows at the bottom show possible directions of mobile plate movement i.e. South-directed or Southeast-directed extension. (c) Section through the model crust of the foam block base setup (T and A series). Pervasive fabrics are modelled by imprinting grooves into the basal silicone layer; this leads to a pattern of alternating weak and strong zones in the model brittle upper layer.

Table 1. Summary of E-series experiments.

PHASE 1							PHASE 2					
Model	α	Disp.	θ_W^*	θ_C	θ_E	Time	α	Disp.	θ_W	θ_C	θ_E	Time
E8	180°	35 mm	30°	0°	45°	210 min	135°	35 mm	15°	45°	0°	210 min
E13	135°	35 mm	15°	45°	0°	210 min	180°	35 mm	30°	0°	45°	210 min
E9	180°	35 mm	30°	0°	45°	420 min	-	-	-	-	-	-
E14	135°	35 mm	15°	45°	0°	420 min	-	-	-	-	-	-

*Angles θ denote the orientation of respective VD segments ("W", "C" and "E") to the extension-orthogonal in each extensional phase (i.e. $\theta = 0^\circ$ means the VD segment is undergoing orthogonal extension)



3.3 Model Setup 2: Uniformly extending model base

The second set of experiments used a foam base setup which has been used to induce distributed extension of the overlying model crust (cf. Osagiede et al., 2021; Schlagenhauf et al., 2008; Zwaan et al., 2019; Zwaan and Schreurs, 2020). Before the rock analogue materials were laid, the neoprene foam block (dimensions $80 \times 50 \times 12$ cm) was pre-compressed between steel sidewalls running along its longer edges to a width of 45 cm while the shorter edges of the block remained unconstrained. Subsequently, during the model run one of the sidewalls is slowly released using precise electric motors allowing the foam block to expand to its original width at a constant velocity of 25 mm h^{-1} for 120 min amounting to a total uniform pure-shear style extension of the model base of ca. 11 %.

We do note that using an elastic foam block as the driver of extension at the model base carries a risk of inducing unwanted boundary conditions when modelling extension, namely lateral contraction as the foam block is extending, and a possible bulging of its surface during the pre-compression stage (cf. Osagiede et al., 2021). We therefore performed “blind” experiments without cover materials, in order to analyse deformation of the foam block during its pre-compression stage and subsequent extension using digital image correlation (DIC) techniques. These revealed a transverse contraction of 1–1.5 % associated with the 5 cm of extension and a generally flat surface with a height difference between the block centre and regions next to the sidewalls (i.e. a central “bulge”) of less than 0.5 cm. These values were deemed sufficiently low to ensure the setup was suitable for simulating the early stages of rifting (Appendix A).

Setup 2 aimed to explore the interactions of both discrete and pervasive fabrics in the upper crust during rifting. Therefore, the foam block base is treated as an uniformly expanding lower crust, on it a 0.5 cm thick PDMS layer is added to represent an interface between the ductile and brittle parts of the continental crust. A 2.5 cm thick layer of the sand-fillite granular mixture representing the upper crustal rocks is sieved on the top. The PDMS layer does not cover the whole surface of the foam block, only a smaller rectangular area (63×42 cm) which is considered for further analysis of the fault population. The sandpack is contained on all sides by free granular slopes. This basic scenario serves as our reference model T0.

Two model series - “T” and “A” - were performed using this setup. In all of these models inherited weaknesses of one or several types were introduced. Silicone polymers such as the PDMS are materials that can be easily sculpted into objects of various shapes and sizes which have been widely used as “viscous seeds” localizing deformation in analogue setups modelling various aspects of rift evolution (e.g., Le Calvez and Vendeville, 2002; Molnar et al., 2019; Osagiede et al., 2021; Zwaan et al., 2016, 2019; Zwaan and Schreurs, 2020; Zwaan et al., 2022). In general, such seeds act as zones of weakness based on the principle that under relatively low strain rates commonly encountered in analogue models of extension the bulk of the integrated strength of the brittle-viscous model crust is contained in its brittle portion. Since the integrated strength of the brittle layer is proportional to the square of its thickness (geometric derivation of this relationship in Zwaan and Schreurs, 2020), sculpting the basal PDMS layer or placing additional silicone objects on top of it alters said thickness, thus weakening the model crust and facilitating preferential fault nucleation (Fig. 6c).

In the experiments, a range of weaknesses and fabrics altering the strength properties of the brittle model layer was used, as follows:



1. Grooves in the basal silicone surface: One of the primary goals with this experimental setup was to model the effects of pervasive fabrics on rifting, i.e. the extension of a mechanically anisotropic foliated basement. The pervasive fabric on top of the basement was simulated by a grooved surface of the PDMS layer. For the surface preparation, a textured rolling pin was used with regularly spaced 0,5 cm deep grooves which were imprinted into the basal silicone layer and immediately covered by the granular material to preserve their initial shape. This created a pattern of alternating linear zones where the thickness of the brittle layer varied between ca. 2.25 and 2.75 cm throughout a section orthogonal to the grooves trend. In turn, these thickness variations translated into a fabric of weak and strong zones characterised by strengths ca. 20 % lower or higher, respectively, compared to a flat silicone surface (Fig. 6c). Such a setup then allowed for imitating the rifting of an anisotropic vertically foliated crustal block, with an imposed fabric arbitrarily oriented with respect to the extension direction.

2. Viscous seeds were incorporated in the form of linear cylindrical bars of PDMS 0,8 cm in diameter. This weakened the overlying brittle layer to around 46 % of its original strength, thus representing discrete heavily weakened domains in the crust (i.e. buried faults or inherited shear zones).

3. Thickened silicone slab: A third method was used in order to weaken the brittle layer over a wider region. This was achieved by placing an additional rectangular 0,5 cm thick slab of PDMS on top of the basal layer immediately before sieving in the granular materials. The thickness of the basal PDMS layer was thus doubled, reducing the brittle strength to 64 % over this area compared to its surroundings. This aimed to represent a region where the brittle-ductile transition in the crust was at shallower depth, for instance due to a thermal anomaly in the lithosphere prior to the onset of rifting.

The next 4 models, T1 - T4, comprised the T ("Test") series and aimed to test and better understand the behaviour of the aforementioned types of weaknesses and fabrics in more general scenarios before employing them to model a simplified version of parts of the Eger Graben in Series A. In these models, the silicone surface was divided into two equal N-S-oriented domains: a Western half with a linear groove fabric and an Eastern half without any fabric (Fig. 7a). In T1, the fabric was oblique ($\theta_f = 30^\circ$ to extension-orthogonal), while in T2 it was extension-orthogonal. Models T3 and T4 used the same respective fabric orientations but additionally include a centrally placed 0,5 cm thick rectangular silicone slab to localise deformation. In T3, the slab was parallel to the rift axis, forming an orthogonal rift partly opening above a domain with oblique fabric. In T4, the slab was oriented diagonally (ca. 33° to extension-orthogonal), creating an oblique rift that intersects extension-orthogonal fabric in the Western domain.

The subsequent series of experiments A1 - A3 was designed to share similarities with the tectonic situation in the central part of the rift (western portion of the Most Basin) where the graben axis roughly follows the boundary between the Saxothuringian and Teplá-Barrandian crustal blocks (cf. Fig. 3). In all cases the surface was therefore split diagonally into two domains (NW and SE) where the NW domain was characterised by E-W trending grooves moulded into the PDMS layer to simulate steep fabrics of the Saxothuringian basement (Fig. 7b). Model A1 included a distributed fabric also in its SE domain, running parallel to the domain boundary (i.e. $\theta_f = 33^\circ$ to the extension orthogonal). Model A2 expanded on the scenario of A1 by including a region where the silicone layer was thickened. A 0.5 cm thick rectangular slab (55 × 8 cm) was placed on top of the diagonal

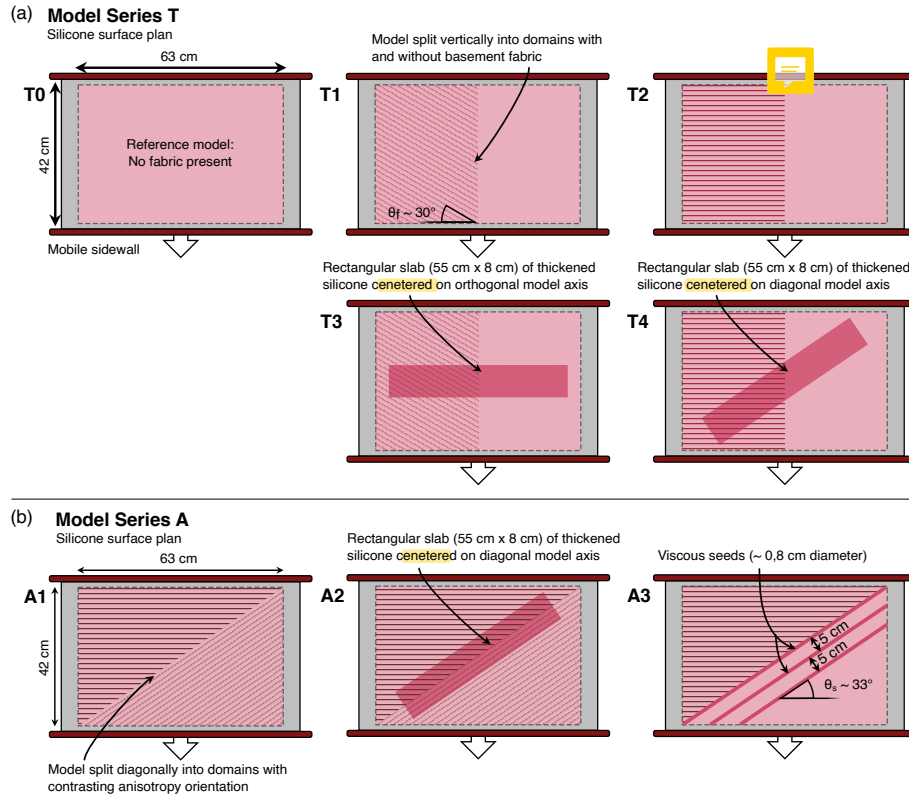


Figure 7. (a) Model Series T (“Test”): Surface plan of the basal silicone layer. These experiments aimed to illustrate the behaviour of pervasive fabrics in more general scenarios not directly inspired by any natural prototype. (b) Model Series A: Surface plan of the basal silicone layer. These experiments are directly inspired by the basement structure of the Most Basin; the two diagonally split domains aim to represent the Saxothuringian and Teplá-Barrandian units. (θ_f and θ_s refer to the angles of incorporated fabrics and viscous seeds, respectively, to the E-W model axis (i.e. extension-orthogonal).

domain boundary to localise deformation in the crust above it, thus facilitating the establishment of an oblique rift zone in the model centre. Basement fabrics in the surrounding areas were the same as in model A1, grooves were also moulded into the surface of this thickened slab. Since the slab was centred precisely on the domain boundary, the fabric on each half of it was the same as in the surrounding domain to which it belonged. Model A3 did not include any distributed fabrics in the SE domain. Instead, linear viscous seeds were used to simulate the reactivation of discrete structures in the model crust. The 3 seeds that were used, once again, ran parallel to the domain boundary ($\theta_s = 33^\circ$ to the extension-orthogonal) with a 5 cm spacing.

3.4 Scaling

Although an analogue model cannot fully encompass all the complexity present in a naturally formed block of the Earth’s crust, it usually needs to be properly scaled with respect to a simplified yet realistic natural prototype in order to provide useful



295 insights into the rifting process. Therefore, standard scaling procedures to ensure geometric, kinematic and dynamic similarity between model and nature were employed for both modelled scenarios (Hubbert, 1937; Ramberg, 1967).

The rheology of brittle materials is strain rate independent, hence the main parameters to ensure kinematic similarity are the angle of internal friction and cohesion. As mentioned above in sect. 3.1, the granular sand-fillite mixture exhibits values (ca. 33°) comparable to those typical of upper crustal rocks (Byerlee, 1978).

300 For scaling viscous materials, the stress ratio ($\sigma^* = \sigma_{MODEL}/\sigma_{NATURE}$) relating the gravitational stresses in the model layer and its natural prototype is first calculated as:

$$\sigma^* = \rho^* g^* h^* \quad (1)$$

where ρ^* , g^* and h^* are the ratios of density, gravitational acceleration and length (thickness), respectively (in all equations, the asterisk (*) notation refers to the model/nature ratio of each parameter). Together with the viscosity ratio η^* , this is then
305 used to find out the strain rate ratio $\dot{\epsilon}^*$

$$\dot{\epsilon}^* = \frac{\sigma^*}{\eta^*} \quad (2)$$

Finally, from it, velocity and time ratios can be derived as follows:

$$v^* = \dot{\epsilon}^* h^* \quad (3)$$

$$310 \quad t^* = \frac{1}{\dot{\epsilon}^*} \quad (4)$$

These are essential in evaluating the model's applicability to a natural case. Furthermore, to ensure proper dynamic scaling the ratio R_s relating the gravitational stresses acting on a brittle material and its cohesive strength is used (Mulugeta, 1988; Ramberg, 1967).

$$R_s = \frac{\rho g h}{C} \quad (5)$$

315 For a viscous layer the Ramberg number R_m which takes into account the viscosity and strain rate dependent strength of such materials (Weijermars and Schmeling, 1986) is computed as:

$$R_m = \frac{\rho g h^2}{\eta v} \quad (6)$$

where η is the dynamic viscosity and v is the divergence velocity. For the model to be considered dynamically scaled, the values of each of these numbers (R_s and R_m) for both model and nature should not mutually differ in more than an order of
320 magnitude. The scaling parameters for both model setups are summarised in Table 2.

In both model setups the divergence velocity translates into slightly more than 5 mm yr⁻¹ in the natural prototype, a value consistent with typical estimates for continental rifting (Brune et al., 2016; Saria et al., 2014). The goal of Setup 1 is to provide

**Table 2.** Summary of material properties and parameters used for model scaling

		SETUP 1		SETUP 2	
		Model	Nature	Model	Nature
Brittle layer	Material	Quartz sand-fillite	Sedimentary cover	Quartz sand-fillite	Upper crust
	Thickness (h)	3×10^{-2} m	3×10^3 m	$2,5 \times 10^{-2}$ m	2×10^4 m
	Density (ρ)	915 kg m^{-3}	2400 kg m^{-3}	915 kg m^{-3}	2700 kg m^{-3}
	Internal friction angle (ϕ)	$\sim 33^\circ$	$30\text{-}38^\circ$	$\sim 33^\circ$	$30\text{-}38^\circ$
	Cohesion (C)	30 Pa	8×10^6 Pa	30 Pa	2×10^7 Pa
	R_s	8.97	8.82	7.48	26.49
Viscous layer	Material	PDMS	Salt	PDMS	Lower crust
	Thickness (h)	5×10^{-3} m	5×10^2 m	5×10^{-3} m	4×10^3 m
	Density (ρ)	970 kg m^{-3}	2400 kg m^{-3}	970 kg m^{-3}	2900 kg m^{-3}
	Viscosity (η)	$\sim 2.5 \times 10^4$ Pa s	10^{19} Pa s	$\sim 2.5 \times 10^4$ Pa s	2×10^{21} Pa s
	R_m	3.42	3.38	1.37	1.37
General	Gravitational acceleration (g)	9.81 m s^{-2}	9.81 m s^{-2}	9.81 m s^{-2}	9.81 m s^{-2}
	Divergence velocity (v)	$2.77 \times 10^{-6} \text{ m s}^{-1}$	$1.74 \times 10^{-10} \text{ m s}^{-1}$	$6.93 \times 10^{-6} \text{ m s}^{-1}$	$1.67 \times 10^{-10} \text{ m s}^{-1}$

a conceptual test of scenarios of propagation of basement weaknesses in a geometric situation generally similar to the EG; the layering does not aim to precisely represent a natural situation. Nevertheless, the model parameters and material properties are scaled to an upper crustal setting so that the brittle layer in our model represents a 3 km thick deforming sedimentary succession. The best natural equivalent for the viscous base layer would be a 0.5 km evaporite rich horizon with a viscosity around 10^{19} Pa s, which is a common feature in analogue models simulating the deformation of sedimentary successions (Dooley et al., 2005; Ustaszewski et al., 2005; Warsitzka et al., 2021a). We do note that no such “salt layer” is present in the basement of the Eger Graben although clay rich layers (or overpressured shales) can also act as decoupling horizons in a deforming sedimentary succession (e.g., Bell, 1993; Turner and Williams, 2004). However, due to their (visco) plastic rheology, a near-Newtonian fluid such as PDMS is not the ideal material to model their behaviour.

In Setup 2, a greater length ratio of 8×10^5 was adopted since the goal was to model the entire thickness of the upper crust. The brittle layer thus translates to a 20 km thick upper crust with a 4 km thick viscous lower crust below (with values changing to 16 km and 8 km over the wide weakened region present in some models). Although this is too thin for a realistic lower crust, we consider this layer only as the topmost portion of it adjacent to the interface with the upper crust, while the uniformly expanding foam block serves as a representation of the material below.

3.5 Monitoring and Analysis

The model surface was imaged from the top using a Nikon Z5 camera with photos taken every 60 seconds for the longer duration experiments of Setup 1 (model series E), and every 30 seconds for the shorter experiments of Setup 2 (model series



T and A). Additionally, 2 stereoscopic cameras were used as part of the LaVision Digital Image Correlation (DIC) system that allows for quantitative mapping of deformation of the model surface. To visualise surface normal and shear strain evolution scientific colour maps “Lipari” and “Vik” (Crameri, 2023) were used to prevent data distortion and ensure universal readability (cf. Crameri et al., 2020).

Line drawings of the fault pattern for the purpose of a statistical representation of fault orientations allowing for comparison with structural pattern of the Eger Graben were taken after each extensional phase in multi-phase models performed under Setup 1. For the foam base models of Setup 2, faults were drawn after the end of respective model runs. Fault traces were processed using QGIS 3.24 software and saved in an ESRI shapefile format. To avoid undesired boundary effects, only faults located in the central part of the model (i.e. more than 5 cm from the edges of the model surface) were considered. Differences in fault pattern characteristics between distinct model surface domains were of particular interest. In the case of Setup 1, faults were characterised based on their location with respect to the three VD segments. For the foam base models faults were classified according to either vertically or diagonally split basement fabric domains they belonged to (i.e. the W vs. E domain and NW vs. SE domain for model series T and A, respectively). In all cases the location of the centre of each fault trace was the deciding factor in determining which domain the fault belonged to.

The orientations of mapped fault traces are displayed in length-weighted probability density polar histograms of fault orientation (rose diagrams) to allow for comparison of the fault pattern between different models and model domains. The orientation of an individual fault is represented by the long axis of an ellipse fitted to the fault map trace weighted by the true length of the fault trace. The statistical handling of digitised fault traces and resulting rose diagrams were obtained using the PolyLX python package originally developed for microstructural analysis (Lexa, 2025).

4 Results

Results of the 3 experimental series are summarised in the text and accompanying figures below. For each model, the evolution of surface maximum normal strain illustrating fault localization and growth is commented first followed by description of the final fault pattern.

4.1 Model series E

4.1.1 E8 (Two-phase extension, South first)

At the onset of two-phase model E8, strain is concentrated along two parallel zones on both sides of the VD. In the Central segment, which is orthogonal to South-directed extension, deformation rapidly localises onto normal faults bounding two parallel grabens, whereas the outer segments form isolated en-echelon faults oblique to both the extension direction and the VD trend (Fig. 8a_{I-II}).

In Phase 2 under SE-directed extension, the Central segment largely preserves its Phase 1 architecture defined by linear grabens along the VD trace. In this segment, new faults form mainly within existing grabens or as right-stepping en-echelon



Model series E: surface strain development

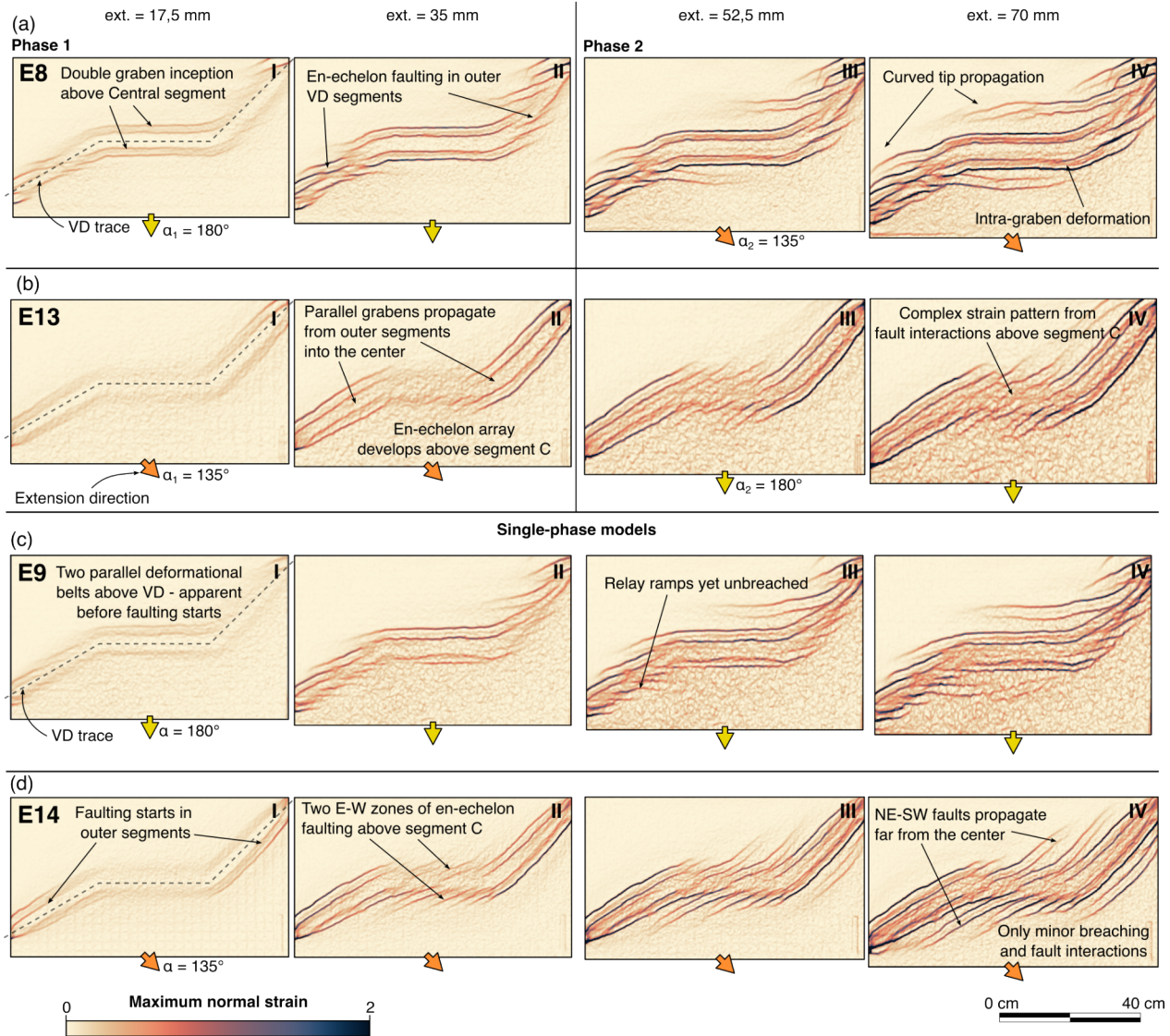


Figure 8. Surface strain evolution of experiments of Model Series E. Two-phase experiments (E8 and E13) are shown first, followed by single phase-experiments (E9 and E14). For each experiment, maps of maximum normal strain (I-IV) are shown after every 105 min. (1/4 of total experiment duration). VD: Velocity Discontinuity.

arrays propagating into the domain from outer segments (Fig 8a_{IV}). In contrast, the outer segments undergo a more substantial reorganization: earlier faults tend to link by relay ramp breaching forming longer zig-zag structures. In segment E, a few new VD-parallel faults occur towards the end of Phase 2 (Fig. 9a).



Two-phase models E8 and E13: final surface structures

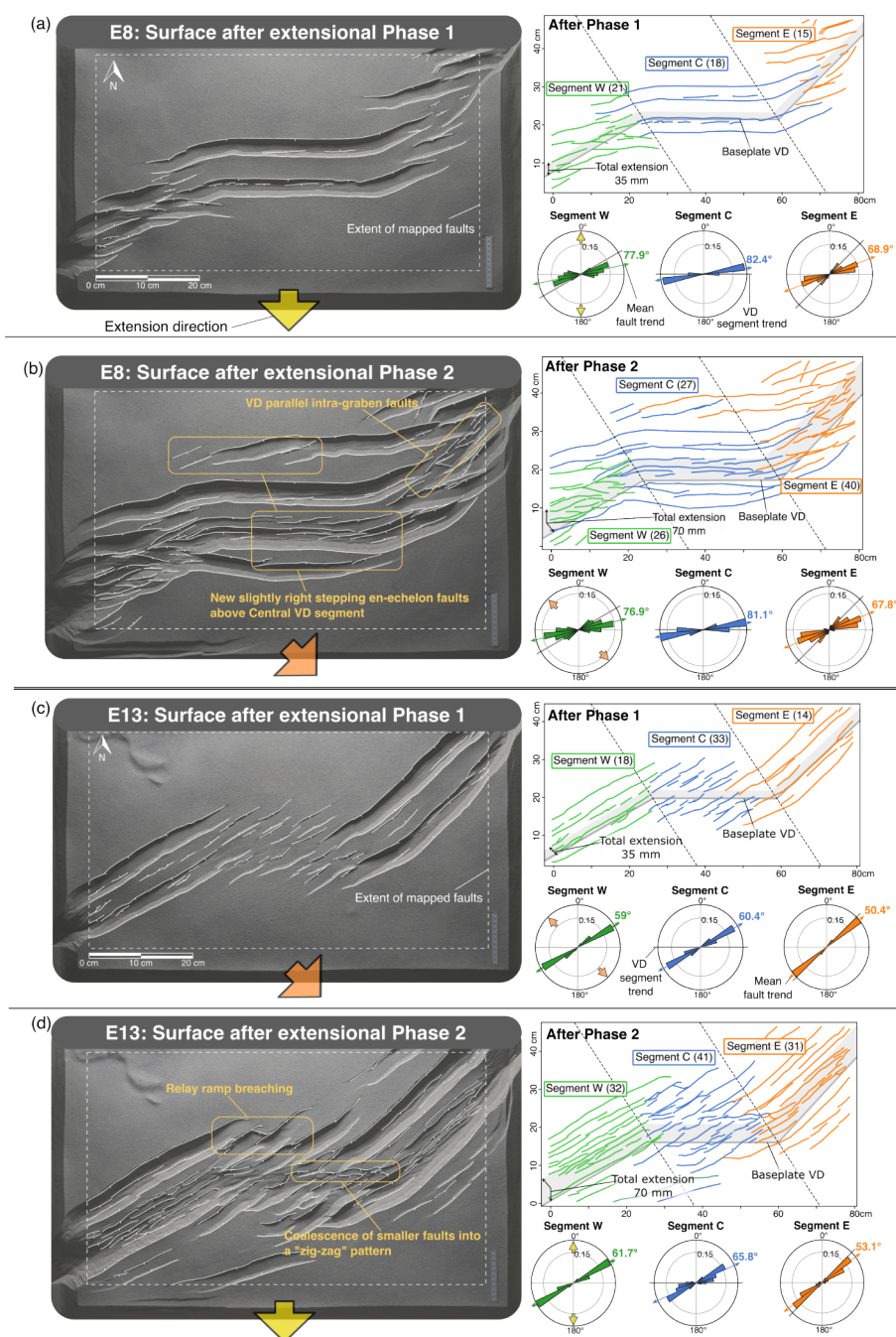


Figure 9. Surface top-view photos, fault traces and fault orientation rose diagrams of finished two-phase experiments E8 and E13. For each experiment the situation after each extensional phase is shown. VD: Velocity Discontinuity.



By the end of the experiment, the overall fault pattern remains generally similar to that established in Phase 1 (Fig. 9a, b). The Central segment is dominated by long, slightly oblique E–W trending faults, with younger structures showing greater obliquity. The outer segments exhibit a wider range of orientations between the VD trend and the inherited E–W trend (Fig. 9b). Although many Phase 2 faults strike parallel to the VD and connect earlier structures, some near–E–W structures keep forming even during Phase 2, particularly in the Eastern segment, where they continue propagating westward into the Central segment despite SE-directed Phase 2 extension.

4.1.2 E13 (Two-phase extension, SE first)

In model E13 the first extensional structures appear in the outer segments close to the edges of the sandpack (Fig. 8b_I). These grabens then propagate into the centre where an array of isolated right-stepping en-echelon faults develops above the two VD parallel deformational zones apparent in the normal strain map (Fig. 8b_{II}). Since 2/3 of the length of the VD are orthogonal or only slightly oblique to the Phase 1 stretching direction the overall structure at the halfway point of the model can thus be described as two branches of an orthogonal rift interacting through a soft-linked accommodation zone (sensu McClay et al., 2002, fig. 9c).

South directed stretching Phase 2 manifests itself quite differently in the outer VD segments and the Central segment. The mature graben bounding border faults in the outer segments remain unbreached and accumulate further displacement (Fig. 8b_{III-IV}). Smaller new faults in the outer segments develop almost exclusively inside the already established grabens. On the other hand, in the central domain the initial fault pattern is highly modified by relay ramp breaching, curving of propagating fault tips and fault coalescence. Along this VD segment trace, a throughgoing composite zig-zag fault zone is thus established towards the end of Phase 2 (Fig. 9d).

In the outer VD segments the final fault pattern is very similar to the situation after Phase 1 with most faults following the underlying VD trend. Only very few small faults show orientations slightly skewed towards the phase two extension-orthogonal E–W trend. Although the Central segment shows more changes to the overall fault pattern compared to the outer segments, the NE–SW fault trend established during Phase 1 remains dominant. Phase 2 manifests itself mainly by propagation of curved fault tips or very short new faults which connect earlier isolated segments (Fig. 9c, d).

4.1.3 E9 (Single-phase South-directed extension)

Single-phase model E9 initially develops similarly to its two-phase counterpart (E8), confirming the robustness and reproducibility of the approach. In the later stages, however, E9 shows less curved tip propagation and delayed relay ramp breaching, particularly above the outer VD segments (Fig 8c_{III-IV}).

As a result, even the outer segments W and E mainly contain E–W trending faults. Some VD-parallel faults do occur in the outer segments, but they are short, confined within existing grabens, and much rarer than in E8 (Fig. 10a). Above the Central segment, the structure closely resembles that of E8, except for the absence of short, oblique en-echelon faults associated with the second phase in the two-phase experiment.

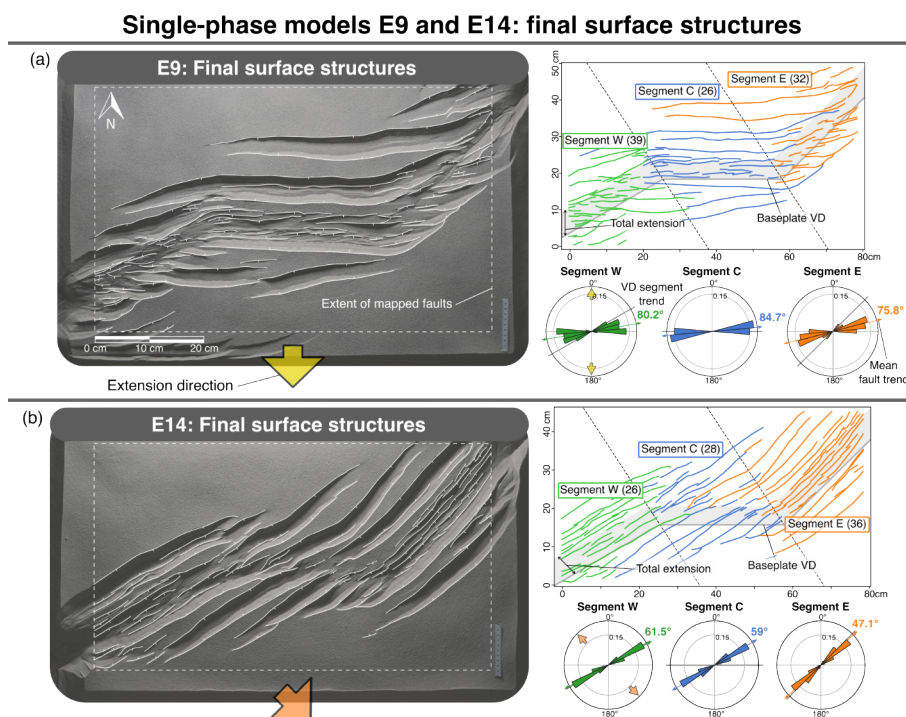


Figure 10. Surface top-view photos, fault traces and fault orientation rose diagrams of finished single-phase experiments E9 and E14. Only the situation at the end of the experiment is shown. VD: Velocity Discontinuity.

4.1.4 E14 (Single-phase SE-directed extension)

In E14, the main difference from its two-phase counterpart E13 occurs in the Central segment, while the outer segments evolve almost identically in both models. In E14, the en-echelon grabens in the Central segment continue propagating outward without significant cross-cutting, relay ramp breaching, or complex fault interactions typical of Phase 2 in E13 (Fig. 8d_{III-IV}).

410 The final pattern consists mainly of faults orthogonal or only slightly oblique (up to around 15°) to the extension direction, including in the Central segment (Fig. 10b). The central accommodation zone remains a domain of overlapping NE–SW trending faults but does not evolve into a throughgoing zig-zag fault zone as observed in E13.

4.2 Model series T

4.2.1 T0 (Reference model)

415 Surface strain analysis of reference model T0 indicates that in the central area first faults nucleate after 25 % total extension. Graben-bounding faults grow by tip propagation and linkage, and with increasing extension, isolated grabens begin to overlap (Fig. 11a_{II-IV}). By the end of the run, an accommodation zone characterised by short en-echelon faults develops in the lower central part of the model (Fig. 12a).



Model series T: surface strain development

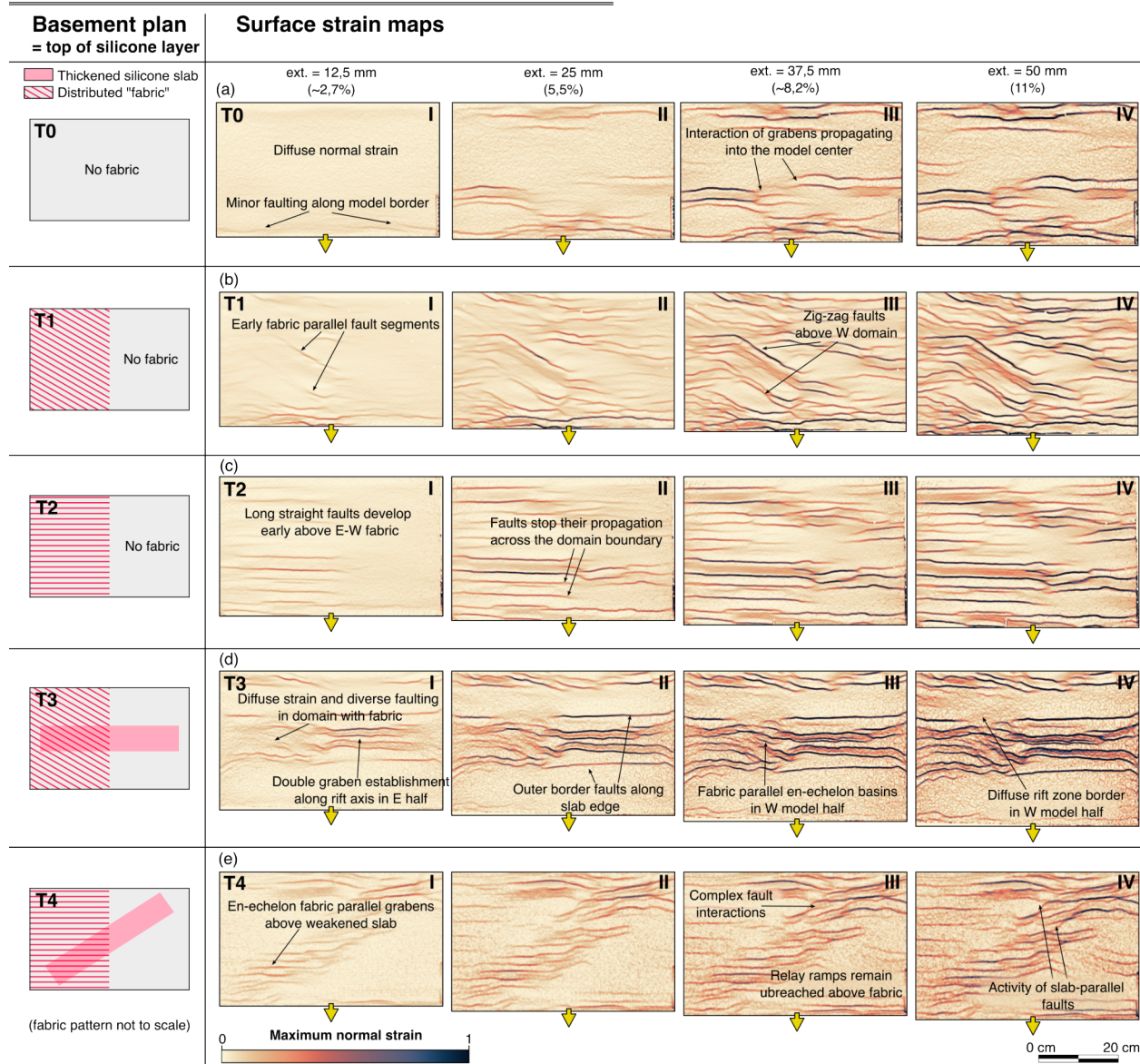


Figure 11. Surface strain evolution of experiments of Model Series T. For each experiment, maps of maximum normal strain (I-IV) are shown after every 30 min. (1/4 of total experiment duration). The first column illustrates the arrangement of structures incorporated into the basal silicone layer of presented experiments.

The final structure consists of dispersed grabens and half-grabens which, in the absence of underlying fabric, are predominantly orthogonal to the extension direction (Fig. 12a). Despite confirmed uniform basal deformation in “blind” experiments (Appendix A), extensional structures appear preferentially concentrated in the southern half of the model. This is a common



Basement plan
= Top of silicone layer

Model series T: final surface structures

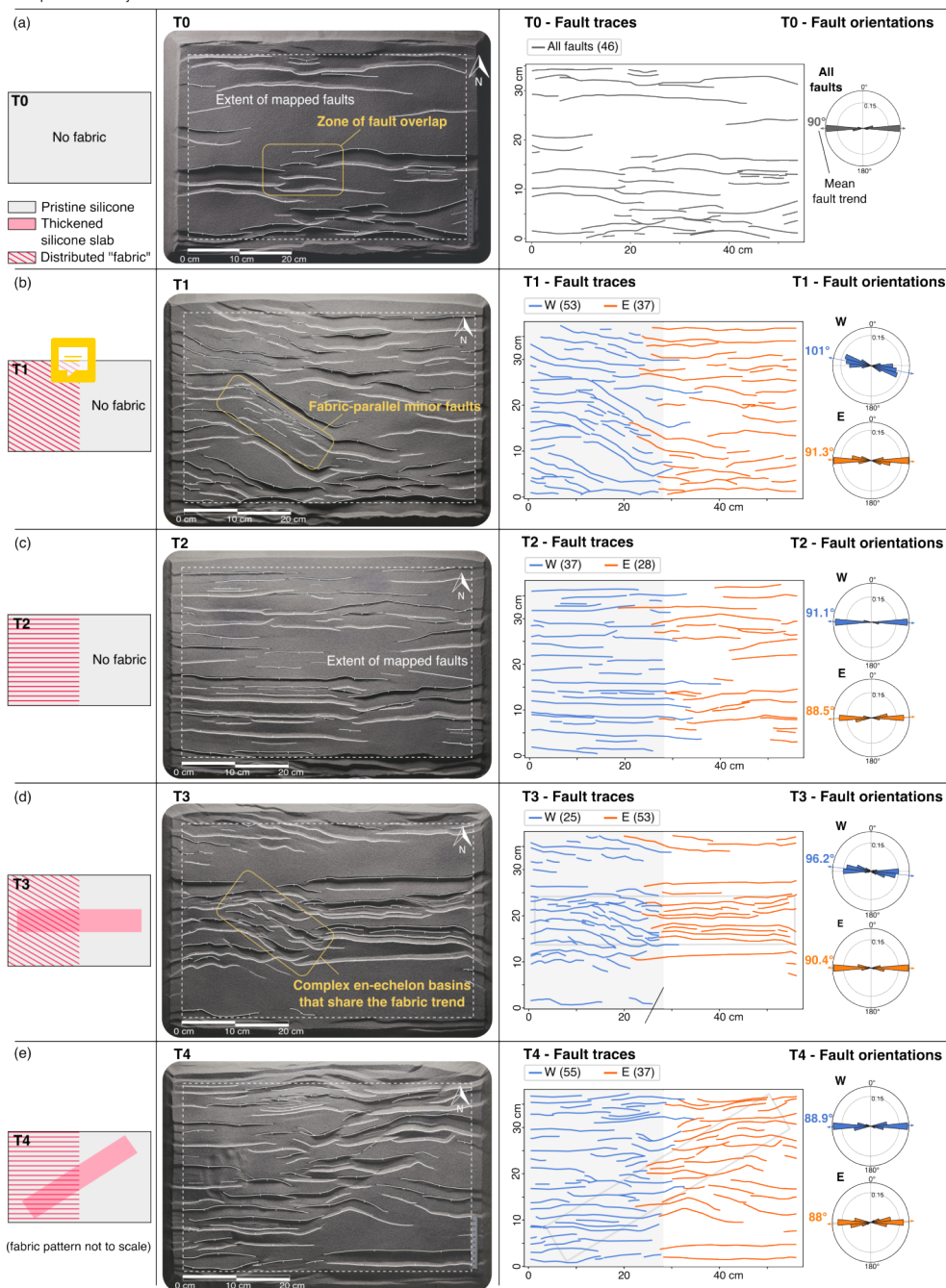


Figure 12. Final surface structures of Model Series T: Top-view photos, fault traces and fault orientation rose diagrams (categorised by basement domain). The first column illustrates the arrangement of structures incorporated into the basal silicone layer of presented experiments.



occurrence in this experimental series which might be the result of an undesired boundary effect; possibly a partial gravitational collapse of the free sandpack margins. Thus, interpretation of subsequent experiments focuses mainly on the central domain.

4.2.2 T1 (Oblique fabric in W half)

425 In model T1, the influence of basement fabric in the Western half is evident from the onset of extension, expressed by fabric-parallel strain perturbations and early fault segments (Fig. 11b_I). As these faults grow, their propagating tips commonly rotate toward a more extension-orthogonal orientation, producing a characteristic zig-zag geometry (Fig. 11b_{II-IV}). Larger faults typically follow the fabric only along parts of their length, whereas some smaller structures - often located in hanging walls of larger faults - more consistently align with the fabric (Fig. 12b).

430 Overall, fabric reactivation is selective, and many faults appear unaffected by the underlying fabric. As a result, the mean fault trend in the Western domain remains only slightly oblique to the E–W rift axis rather than parallel to the fabric (Fig. 12b). In the Eastern domain, where no fabric is present, the fault pattern resembles the reference model T0.

4.2.3 T2 (Orthogonal fabric in W half)

In model T2, E–W-trending fabrics in the Western half promote even earlier fault nucleation than in T1 – long (>20 cm) E–W grabens are already established before extension reaches 25 % of total. These initial faults are typically straight and evenly distributed, propagating toward the domain boundary where lateral growth largely ceases (Fig. 11c_{I-II}).

Later, some faults do propagate across both domains, but more typically they interact through accommodation zones and relay structures aligned along the domain boundary. The final pattern is dominated by E–W faults in both domains, though in the Western (fabric-controlled) domain they are longer, straighter, and generally more numerous (Fig. 12c).

440 4.2.4 T3 (Oblique fabric in W half + thickened slab in model centre oriented orthogonally)

In model T3, the introduction of an extension-orthogonal weakness (thickened silicone slab) strongly localises deformation producing a central rift zone. In the Eastern half, a wide central graben rapidly forms above the weakened zone, bounded by E–W border faults, with a pair of additional parallel grabens developing within it. In contrast, the Western half shows more diffuse and heterogeneous deformation localised on smaller faults of varying orientations, some fabric-parallel and others trending E–W (Fig. 11d_{I-II}).

From the midpoint of the experiment, the Western half of the rift zone is characterised by short, oblique sub-basins aligned with the fabric and largely disconnected from the main E–W rift of the Eastern domain (Fig. 11d_{II-IV}). In the final structure, there is a marked difference in the nature of the rift zone edge between the two model halves. In the Western half the border is diffuse, consisting of relay ramps and zig-zag faults whereas in the opposite half border faults are straight with a consistent E–W trend (Fig. 12d). Additionally, some off-rift fabric parallel minor faults develop in the Western domain, whereas in the Eastern domain deformation remains contained almost entirely within the central rift zone.



4.2.5 T4 (Orthogonal fabric in W half + thickened slab in model centre oriented diagonally)

As in T3, deformation in model T4 primarily localises within the weakened belt defined by the silicone slab. In its SW half, where extension-orthogonal fabric is present, left-stepping en-echelon faults form rapidly (Fig. 11e_I). Early strain also concentrates along the northern edge, although that region might be influenced by undesired boundary effects and thus the central area is of higher interest. In the NE part of the central rift zone which does not contain a distributed fabric, faults develop oblique to both the rift trend and extension direction and interact through relay ramps and transfer zones. In contrast, faults in the opposite half exclusively follow the E–W fabric trend and relay ramps remain largely unbreached (Fig. 11e_{III-IV}).

By the end of the experiment, oblique rift-parallel faults linking individual basins are active in the eastern part of the rift zone. Unlike T3, where faulting is largely restricted above the weakened zone, faults also form in the surrounding areas (Fig. 12e).

4.3 Model series A

4.3.1 A1 (Diagonal domain split, combination of orthogonal and oblique fabric)

Model A1 simulates extension of a crustal block with contrasting fabrics separated by a diagonal boundary. Faults first nucleate in the NW domain and rapidly propagate along the fabric-aligned E–W trend, forming up to 30 cm long grabens by mid-experiment (Fig. 13aI-II). Some later develop minor intra-graben faults, but their propagation typically halts at the limit of the extension-orthogonal fabric they exploit. Consequently, few faults cross the domain boundary, which is commonly marked by short en-echelon E–W faults once the experiment is finished (Fig. 14a).

In the SE domain, early strain perturbations follow the fabric trend, but once faults localise, they only partly exploit the fabric while remaining roughly orthogonal to extension elsewhere. The final structures in the SE domain are shorter, segmented by relay zones, and display a zig-zag geometry (Fig. 14a). In contrast, the NW domain is characterised by straight, E–W trending faults that commonly transect the entire region affected by extension-orthogonal fabric.

4.3.2 A2 (Diagonal domain split, combination of orthogonal and oblique fabric + thickened slab in model centre oriented diagonally)

In model A2, initial extension localises within the central weakened zone above the thickened silicone slab, whose surface is divided by a diagonal boundary separating “orthogonal” and “oblique” fabric domains. Early faults form as en-echelon E–W structures in the western part but kink north-eastward as they cross the boundary and align with the basement fabric and slab edge (Fig. 13bI-II). After 50 % of total extension, deformation concentrates along this diagonal axis, establishing a wide oblique rift zone. Its SE border follows the diagonal fabric trend, whereas the northern margin is diffuse and composed of relay ramps bounded by left-stepping en-echelon faults. Toward the end of the model run, southern border faults curve and propagate into the SE domain, while western tips of the opposite E–W faults bend toward the slab edge and local relay ramp breaching is observed (Fig. 13bIII-IV).



Model series A: surface strain development

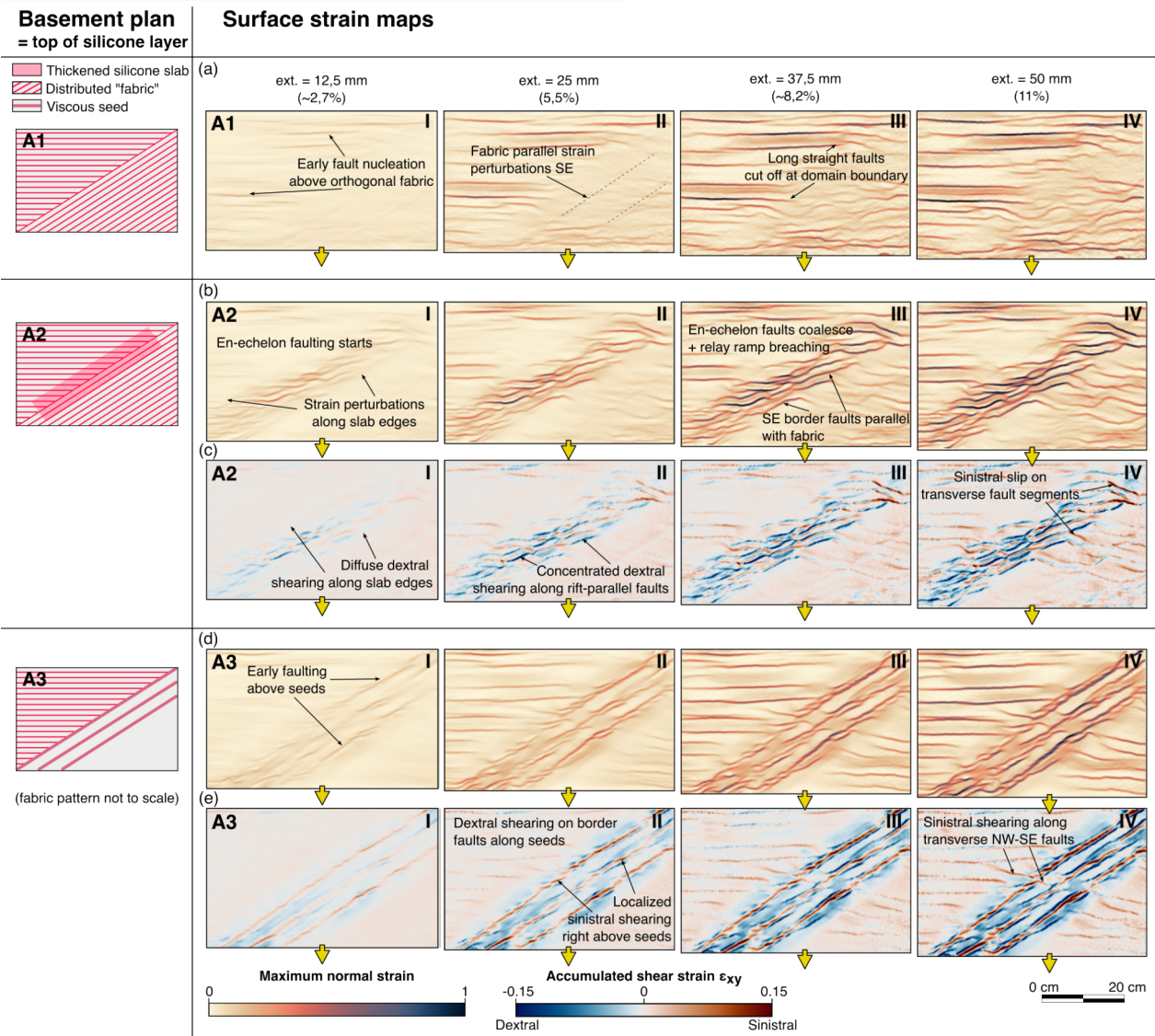


Figure 13. Surface strain evolution of experiments of Model Series A. For each experiment, maps of maximum normal strain (I-IV) are shown after every 30 min. (1/4 of total experiment duration). (c),(e) For experiments A2 and A3 shear strain is also visualised. The first column illustrates the arrangement of structures incorporated into the basal silicone layer of presented experiments.

Shear strain maps initially show diffuse dextral shear along the weakened zone margins. With continued extension, oblique rift-parallel faults accumulate concentrated dextral shear, indicating oblique slip kinematics. In later stages, sinistral shearing is recorded on transverse ESE to SE faults in the northern half and on minor structures within the rift zone and along its southern border (Fig. 13c_{III-IV}).

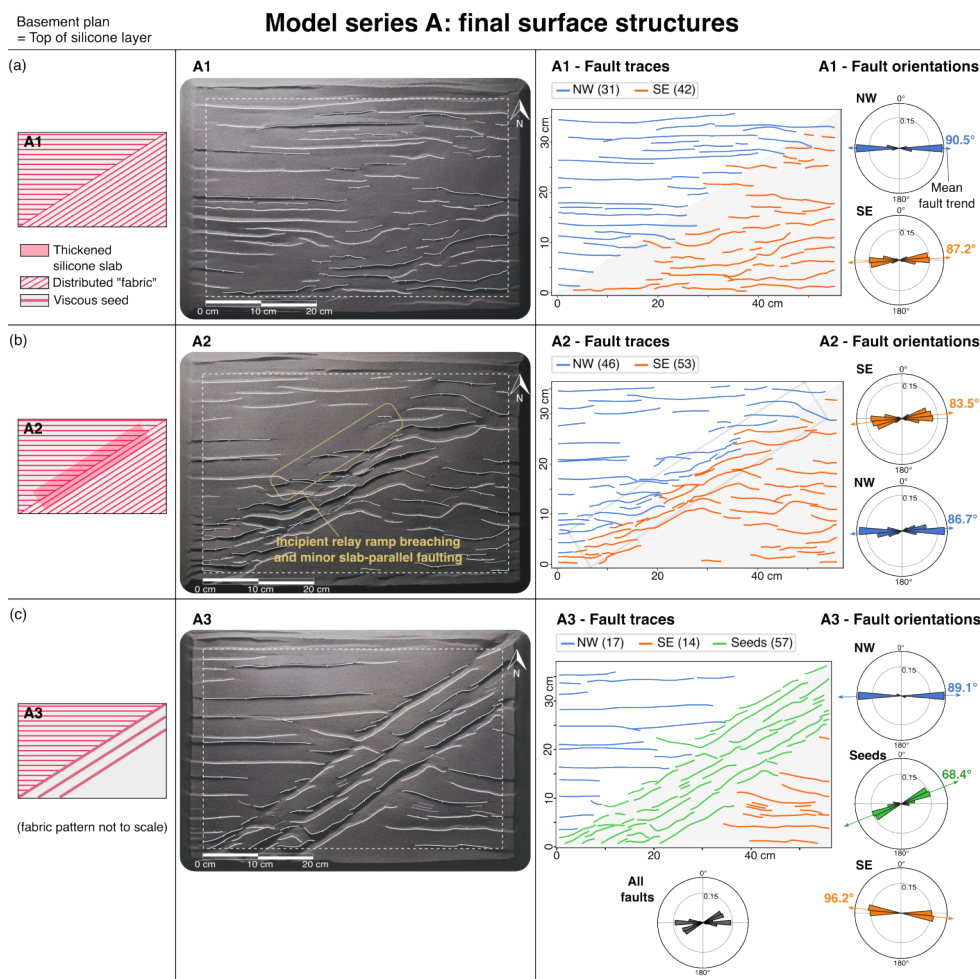


Figure 14. Final surface structures of Model Series A: Top-view photos, fault traces and fault orientation rose diagrams (categorised by basement domain). The first column illustrates the arrangement of structures incorporated into the basal silicone layer of presented experiments.

In the final pattern, peripheral areas of both basement domains resemble model A1. In the NW domain, faults remain mostly E–W, though with more variable strike than in A1, especially where they approach the diagonal rift zone in the model center. Oblique (ca. N60°) faults are more common in the SW domain, particularly above the edge of the thickened slab marking the rift border (Fig. 14b).

4.3.3 A3 (Diagonal domain split, combination of orthogonal fabric and 3 oblique viscous seeds)

In model A3, viscous seeds exert a strong weakening effect and are reactivated early, forming narrow grabens above them contemporaneously with first faults nucleating in the fabric-affected NW domain. As extension proceeds, tips of these initial faults tend to curve and propagate into adjacent domains, generating relay ramps and widening the initial grabens (Fig. 13d_{I-II}).



495 Shear strain maps first indicate diffuse dextral shear around the seeds, later localizing onto seed-parallel faults that accommodate dextral oblique slip (Fig. 13e_{I-IV}). Within the narrow grabens right above the viscous seeds, persistent zones of localised sinistral shear develop. We interpret these as minor antithetic R' shears arising from the transtensional deformation of the region right above the obliquely oriented seed, analogous to results reported by Osagiede et al. (2021) using a similar foam block setup. However, our DIC resolution somewhat limits accurate differentiation of individual presumed R' structures.

500 Additional sinistral motion occurs on transverse ESE-trending faults that cross-cut the seeded domain; these likely evolved from E–W relay ramp bounding faults through rotation and curved tip propagation driven by local stress reorientation in areas surrounding and in between individual seeds.

The final fault pattern differs markedly from other models, displaying a bimodal distribution of fault orientations: fabric-parallel and seed-parallel trends (Fig. 14c). For the purpose of representing fault orientations this model, unlike its predecessors,

505 was split into 3 domains. The NW domain contains straight E–W faults similar to A1 and A2. In the central “seeded” domain, faults are mainly seed-parallel but highly jagged due to their tips changing trend as they propagate into surrounding domains. In the SE domain, extension-orthogonal grabens widen toward the seeded area, and their border faults curve into an ESE trend - a unique orientation oblique to both fabric and seed trends - likely reflecting stress perturbations near the seed-induced weak zones.

510 **5 Discussion**

In the discussion below, the experimental results are first interpreted within the context of previous modelling work and natural rift observations. Second, together with limitations of the modelling approach, the suitability of selected models for addressing structural inheritance in the Eger Graben is discussed.

5.1 Segmented rifting under two-phase extension

515 Two-phase models using the discrete velocity discontinuity (VD) setup highlight the strong influence of the initial stretching direction on the orientation and character of final fault structures when both extensional phases have similar magnitude, consistent with previous analogue studies of polyphase extension (e.g., Bonini et al., 1997; Dubois et al., 2002; Wang et al., 2021; Zwaan et al., 2022). If the amount of first phase displacement is lower and the resulting fault network poorly developed, the second phase tends to dominate the final structure (Henza et al., 2011, 2010). The degree of obliqueness between the initial

520 stretching direction and the VD is also important: oblique extension typically forms short en-echelon fault segments that are more susceptible to later reorganization through linkage and relay ramp breaching when subsequent extension becomes orthogonal to the VD (Bonini et al., 1997; Michon and Sokoutis, 2005). In our models, the VD geometry creates a distinctive situation where extension obliquity varies both through time during successive stretching phases and in space along the VD trace.

525 Our models suggest that the amount of total VD length which is oblique to Phase 1 extension is key in determining the overall effect of Phase 2 stretching which is illustrated by comparing the results of two-phase models E13 and E8.



E13 initiates by SE directed stretching with roughly 2/3 of the total VD length (i.e. the outer segments “W” and “E”) oriented nearly orthogonally to extension direction and as a result, straight, well-defined grabens develop there during Phase 1. The Central segment acts as a large accommodation zone between two orthogonal rift branches which contains numerous smaller faults separated by relay ramps in an en-echelon configuration. The structural arrangement at the end of Phase 1 is thus reminiscent of some documented oblique rift segments such as the Reykjanes Peninsula Oblique Rift (Einarsson, 1991; Keiding et al., 2009) or the Santo Domingo Relay in the Rio Grande Rift (Minor et al., 2013). Subsequently, during Phase 2 it is the Central segment where most new faults develop, mainly as structures connecting and breaching the previously established pattern. In contrast, the peripheral segments show little new fault activity with deformation being mainly confined to already existing grabens. In the peripheral segments, the pattern of linear grabens established during nearly orthogonal Phase 1 extension appears too mature to be significantly altered by Phase 2 stretching as there are neither short fault segments to be connected nor relay ramps to be breached.

Model E8 begins with linear grabens only developed in the Central segment whereas the outer segments which constitute most of the total VD length contain shorter dispersed faults susceptible to later reorganization. Therefore, the overall effect of Phase 2 appears larger in E8 compared to E13, even though in both cases Phase 2 has the same amount of extension magnitude (35 mm). Such an interpretation confirms that when a segmented discrete basement weakness is reactivated in two non-coaxial extensional stages the final rift structure is still primarily the result of the first initial phase of stretching. However, the orientation of individual VD segments with respect to first phase stretching direction also appears important in determining how much Phase 2 will influence the final structure.

5.2 Comparison of E-series models and the Eger Graben structural pattern

The segmented basement weakness in model series E approximates a simplified trace of the northern boundary faults of upper Paleozoic basins underlying the central-eastern part of the Tertiary rift and the setup tests their reactivation under different extension directions. To assess which conditions best reproduce the natural structure, the final results of models E8 and E13 are compared with the current fault pattern in the rift (Fig. 15). The principal geometry of the Most, Ústí, and Stráž segments of the ER (Fig. 5, fig. 15) corresponds, in the model, to the Western, Central, and Eastern segment, respectively.

Based on their orientation, faults forming the tectonic framework of the Eger Graben can be grouped into four main sets: E–W, NW–SE, and NE–SW (the most abundant), with a minor set trending N to NNE (Fig. 15).

The Most Segment, hosting the largest preserved depocenter (the Most Basin), is dominated by NE–SW faults (typically around 60° N), best developed along the southern border above the upper Paleozoic basins. The northern part of the Most Basin, underlain by Saxothuringian crystalline units (significance of this rift-basement relationship is discussed in the following sections), shows a more varied pattern with numerous E–W faults. The Ústí segment is intersected by the NW–SE trending Elbe Fault System and therefore contains many faults of this orientation as well as abundant long E–W faults along the southern border (e.g., the Středohoří Fault Zone), while NE-trending faults are comparatively scarce. In the easternmost Stráž segment, NE-trending faults dominate again, but with a more northerly orientation (around 45° N) compared to the Most segment, accompanied by common E–W and NW–SE structures.

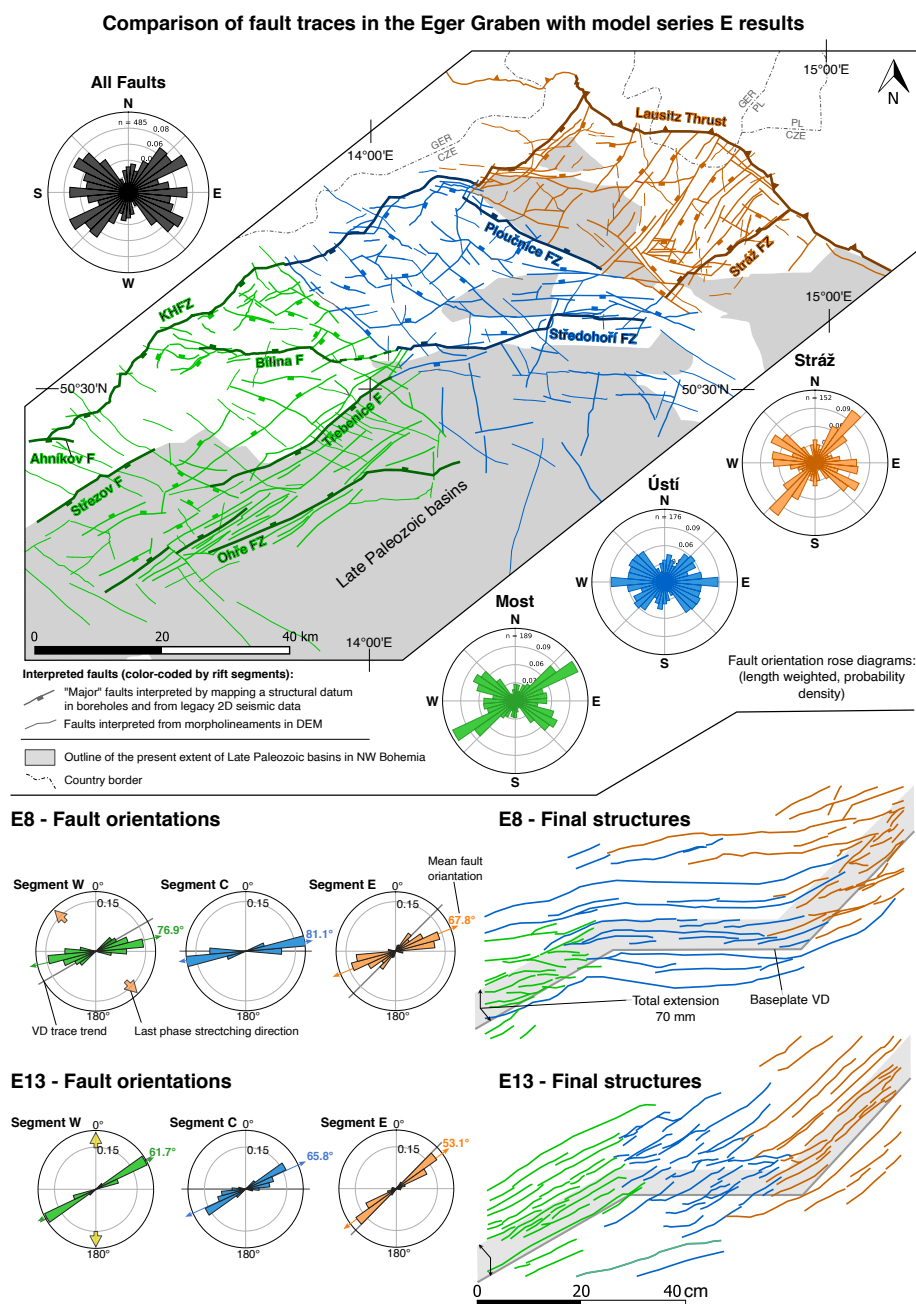


Figure 15. Comparison of interpreted fault traces and rift segmentation in the east-central Eger Graben with the results of two-phase experiments E8 and E13. KHFZ: Krušné Hory Fault Zone; VD: Velocity Discontinuity. Eger Graben fault pattern after Uličný et al. (2024)

Model E8 (and, partly, its single-phase counterpart E9), with the Phase 1 extension directed N-S, produces a fault pattern broadly comparable to the corresponding area of the Eger Graben, particularly in the Central segment. Here, long E–W faults



formed during Phase 1 bound extension-orthogonal grabens, closely matching the dominant E–W structures observed in the natural rift. The outer segments in model E8 compare less well to their natural counterparts: faults parallel to the underlying VD trend are rare and mainly develop during Phase 2. The contrast between E8 and the single-phase model E9 highlights the importance of the second stretching phase: NE–SW faults in the Eastern segment are nearly absent in E9 but do appear in E8 (Fig. 9b,10a). Locally, the Eastern segment of the model partly resembles the Stráž Fault Zone, although the stepped “staircase-like” geometry of that feature of the natural prototype is not reproduced.

Model E13 (Phase 1 extension NW–SE) reproduces the natural situation more closely in its Western and Eastern segments, as both are dominated by NE–SW trending faults, similar to the natural rift. However, the model lacks the E–W faults that still occur in corresponding areas in nature. During Phase 2, deformation largely remains confined to existing grabens, preventing the formation of new E–W structures. In the Central segment, the model diverges more strongly from the natural case: both E13 and its single-phase equivalent E14 are dominated by NE–SW faults, while E–W structures occur only as short linking segments within zig-zag fault zones.

Considering only the peripheral segments, both E8 and E13 reproduce aspects of the natural pattern, with E13 arguably closer due to its predominance of NE–SW faults. However, only E8 and E9, initiated by N–S-directed extension, generate the long E–W faults in their central part, analogous to the Ústí segment of the ER (e.g. the Středohoří Fault Zone, fig. 2, fig. 15). This suggests that an early phase of N–S extension may have indeed produced the Ústí segment fault pattern of the Eger Graben and clearly is more likely than a first phase oriented NW–SE. Before such an inference is accepted, issues that complicate a straightforward interpretation need to be considered and are discussed below.

5.3 Limitations of the modelled scenario

The first key limitation of the analogue model design is the absence of NW–SE faults associated with the Elbe Fault System (EFS) which are ubiquitous throughout the Eger Graben. Dextral shearing along structures of the EFS in the immediate post-Variscan tectonic history is believed to be responsible for the segmentation of the initially linear belt of post-collisional basins in the early Permian (Uličný et al., 2009b, 2002; Hofmann et al., 2009, fig. 4). While individual structures of the EFS are not directly incorporated into the models’ design, their prior influence is reflected in the segmented geometry of the VD which represents the underlying late Paleozoic basins.

EFS faults are thought to have remained episodically active through the Mesozoic and Cenozoic, influencing Late Cretaceous basin development and subsequent inversion (e.g., Coubal et al., 2015; Käßner et al., 2020; Scheck et al., 2002; Uličný et al., 2009a; Voigt et al., 2021). Within the Eger Graben, especially its Ústí segment, they form an important structural component, commonly acting as transfer zones delimiting segment boundaries but, in some cases, accommodating significant syn-rift vertical displacement (e.g., the Ploučnice Fault Zone; Fig. 5, Fig. 15). In the simplified model scenario with rifting driven by the reactivation of a single segmented basement fault zone, NW–SE trending faults did not appear spontaneously as no predisposed structures of such orientation were incorporated into the models. This implies that pre-existing weaknesses of this trend were likely required to form this structural element of the rift. In the future, their role could possibly be incorporated into models exploring more detailed aspects of Eger Graben evolution, both conceptual and analogue or numerical.



Another limitation concerns model scaling and rheology. The length scaling produces a realistic model size given the dimensions of the natural prototype, but the model layering was not meant to directly simulate a crustal rheological profile specific to the Eger Graben. The basal silicone layer, used to decouple the VD from the overlying crust, would, in nature, best correspond to a 500 m thick viscous evaporite layer. While such an approach has been successfully employed to model the activity of the Rhein-Bresse Transfer Zone (Ustaszewski et al., 2005), that setting does include substantial evaporite sequences, unlike the Eger Graben.

The Cretaceous succession beneath the Eger Graben lacks evaporites, but upward strain partitioning above reactivated basement faults can occur even without salt layers (e.g., Collanega et al., 2019; Frankowicz and McClay, 2010; Rodríguez-Salgado et al., 2022). When such faults are oblique to the extension direction, they often segment upward into en-echelon arrays aligned with the underlying structure (Deng et al., 2020; Phillips et al., 2022), a behaviour comparable to some models of the E-series. Determining whether similar mechanical decoupling occurred within the Bohemian Cretaceous Basin partly underlying the Eger Graben is difficult, as it would require detailed information on the 3D structure of faults propagating through the succession. Since fault traces in the central portion of the EG are mainly interpreted from boreholes by mapping a structural datum and, locally, legacy 2D seismic data, such detailed geometries are unavailable.

Even if the inference of the Cretaceous layer acting as a decoupling layer were accepted, the matter is further complicated by the highly variable thickness of the Cretaceous cover over the studied area. Previous field and experimental studies show that the surface expression of a reactivated structure strongly depends on its depth (e.g., Collanega et al., 2019; Osagiede et al., 2021; Samsu et al., 2023). Throughout the Eger Graben this depth varies significantly. In the Most segment, the Cretaceous layer is often thin or absent, so that rift-border faults likely link directly to shallow basement structures. Therefore, the rift-related faults reflect the inherited geometries, rather than stress conditions during rifting. In contrast, the Ústí and Stráž segments contain up to 1 km of Cretaceous strata, which may allow softer linkage and weaker mechanical coupling between basement faults and surface structures. Consequently, deformation styles comparable to the analogue experiments are most likely in these segments.

In summary, the model setup for experimental series E assumes a “soft-linked reactivation” scenario where the basement weakness is sufficiently mechanically decoupled from rocks near the pre-rift surface. In such a case, the model results clearly show that fault orientations and geometries are sensitive to changes in extension direction and, when compared with the structure of a natural rift, could be used to infer its extensional history, while not necessarily mimicking the specific rheology of the Eger Graben setting.

5.4 Influence of orthogonal and oblique pervasive fabrics in uniformly extending models of series T and A

Normal faults that develop in areas affected by an extension-orthogonal fabric (e.g. Fig. 12c, 14a) are generally straight, longer and relatively evenly distributed across the model surface compared to areas without an imposed fabric. An extension-orthogonal fabric also appears to promote early fault nucleation and propagation with many faults already reaching most of their final length at only 25 % of total extension in the fabric affected domains (e.g. models T2 and A1 - Fig. 11c₁, 13a₁).

Previous modelling studies with a detailed focus on fault growth show that normal faults initially develop through rapid lateral tip propagation and segment interaction, typically reaching most of their final length within the first 20 to 30 % of their

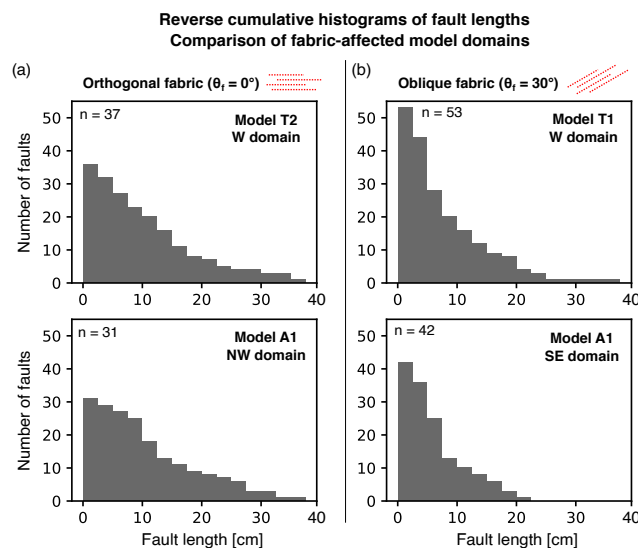


Figure 16. Reverse cumulative frequency histograms of fault lengths (i.e. showing the number of faults longer than a given value) comparing model domains with either orthogonal ($\theta_f = 0^\circ$) or oblique ($\theta_f = 30^\circ$) pattern of regular grooves in the silicone surface. (a) Model domains with an extension-orthogonal fabric: Western half of model T2 (Fig. 14c), NW half of model A1 (Fig. 16a). Note the significantly higher frequency of long (>20 cm) faults in these domains (b) Model domains with an oblique fabric: Western half of model T1 (Fig. 14b), SE half of model A1 (Fig. 16a). Note the higher total number of faults, mainly due to the prevalence of very short structures (<10 cm).

lifespan (Rotevatn et al., 2019; Schlagenhauf et al., 2008). This is followed by a phase dominated by displacement accumulation with little further lengthening, such as described by the constant-length fault growth model (Nicol et al., 2005, 2017; Walsh et al., 2002). However, this model is based on experimental and natural observations involving isotropic materials and as such does not account for the effects of structural inheritance.

Our models incorporating extension-orthogonal pervasive fabrics indicate that pervasive fabric reactivation is particularly important during the early stages of rifting, as it promotes faster development of long faults. The final fault pattern is thus characterised by a number of abnormally long faults which commonly transect the entire fabric-affected domain (Fig. 16a; cf. also Grant et al., 2024, for similar observations from the Okavango-Makgadikgadi Rift Zone). In natural rift systems, rapid early boundary fault lengthening is commonly linked to favourably oriented inherited basement structures (Heilman et al., 2019; Rotevatn et al., 2018). In such settings, multiple faults can exploit the same fabric simultaneously, producing extensional systems with faults that are unusually long relative to their displacement (Grant et al., 2024; Morley et al., 2004).

Pervasive fabric oblique to the extension direction also strongly influences the early stages of extension, as seen in model T1 where short, fabric-parallel, fault segments initially form in the Western domain (Fig. 11b). With continued extension, these segments link into longer structures with a characteristic “zig-zag” geometry, following the fabric only along parts of their trace while additional smaller faults develop across the surface (Fig. 11b_{II-IV}, 12b). Despite this linkage, long continuous faults remain relatively rare. Domains with oblique fabric are instead characterised by a large number of shorter faults (Fig. 16b).

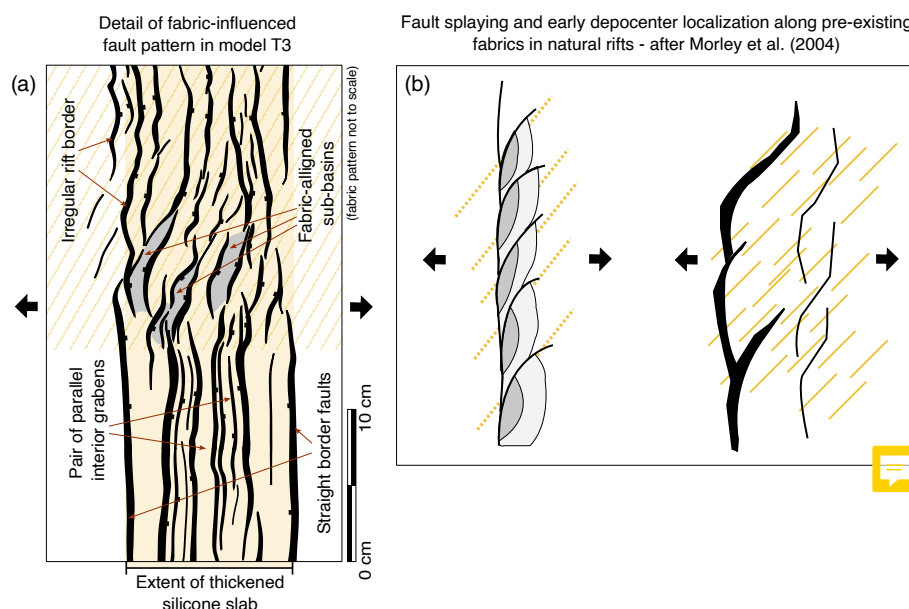


Figure 17. (a) Detail of fault structures in model T3 compared with published natural examples. (b) Sketches of fabric influence on normal fault and depocenter development based on observations from the Cenozoic rifts of Thailand – after Morley et al. (2004); Morley and Chantraprasert (2025). Note the splaying of border faults and associated depocenters into an en-echelon pattern and the development of zig-zag faults which follow the fabric trend along certain segments – features present both in the model and natural examples.

This pattern is consistent with natural observations where coexisting fault sets of different orientations (fabric-parallel and extension-orthogonal) tend to inhibit each other's lateral propagation, limiting the development of very long faults (cf. Morley et al., 2004; Morley and Chantraprasert, 2025).

650 The influence of oblique fabric becomes more pronounced when combined with a thickened silicone slab that weakens the model crust over a broader area. This is best illustrated in model T3, where a wide, orthogonal rift develops partly above a fabric-affected domain (Figs. 11d, 12d). In this area, the rift structure changes fundamentally: instead of two continuous parallel grabens, it consists of multiple small, en-echelon sub-basins aligned with the fabric and separated by relay ramps and intra-rift elevations (Fig. 17a). The nature of the rift margin also differs markedly between the Western and Eastern domains in model T3.

655 In the fabric-influenced area, border faults are shorter, irregular, and segmented, forming a wide, diffuse boundary rather than a single continuous fault (Fig. 12d, 17a). In natural systems, such structural arrangement might affect sediment pathways into the developing basins: numerous relay ramps would facilitate sediment entry, while the tectonic intra-rift relief would promote isolated depocenters and potentially limit axial sediment transport during early rift development (cf. Gawthorpe and Leeder, 2000; Morley et al., 2004, fig. 17b).



660 5.5 Model limitations and future prospects

Due to the mechanically isotropic nature of granular materials such as quartz sand, modelling the effects of pervasive fabrics in commonly used rift sandbox setups has long been considered difficult to achieve and thus only a limited number of analogue studies exists (Chattopadhyay and Chakra, 2013; Morley, 1999; Samsu et al., 2021). Although the employed method of modelling “fabrics” by sculpting grooves at the base the brittle layer appears to produce promising results it is still an imperfect approximation. It does not truly lead to a strength anisotropy inside the granular material itself (which remains essentially isotropic) that would be directly comparable to the behaviour of intensely foliated rock samples in rock deformation experiments which tend to exhibit lowered tensional strength at high angles to the planar fabric (e.g., Zang and Stephansson, 2010; Youash, 1969). Rather, it produces a pattern of alternating weak and strong zones in the brittle layer which facilitate fault nucleation. Due to the known dimensions of the grooves in relation to the thickness of the brittle layer, it can be estimated that the brittle strength contrast between a weak and strong zone in such a pattern is around 40 %. This value can be helpful for approximating qualitative properties of a suitable natural prototype, however being able to directly scale the modelled scenario to a specific block of foliated continental crust appears unfeasible.

The aim of this experimental series was to test specific scenarios relevant to the basement structure of the Most Basin. Accordingly, only two fabric orientations were considered, extension-orthogonal and 30° oblique which were combined with additional weaknesses to examine their interactions. Since this approach appears to produce fault geometries comparable to natural rift systems where the influence of inherited pervasive fabrics has been invoked, it warrants further investigation. Future studies could systematically test a wider range of fabric orientations and vary fabric intensity by modifying groove geometry (e.g., amplitude and wavelength), which may significantly affect fault development.

5.6 Model implications for the tectonic evolution of the Most Basin

A distinctive feature of the Most Basin, especially its western part on which the A series model scenarios were based, is a pronounced contrast, across the rift axis, in the character and geometry of rift-related normal faults. The SE side hosts the main depocenter bounded by long faults parallel to the 60° N trending rift axis, whereas the NE side is dominated by the segmented Krušné Hory Fault Zone (KHFZ) consisting of E–W faults linked by NE-trending segments. A similar contrast is reflected in the structure of the basement, separated by the Teplá Suture, as described above (Fig. 3). It should be noted, however, that the arrangement of fabric-affected domains in the experiments, even in model series A, is a highly simplified representation of the complex basement architecture in NW Bohemia. While along the KHFZ the structural trends in the crystalline basement are well constrained due to exposures, in the Teplá-Barrandian Unit at the southern rift flank there is greater uncertainty as it is not exposed at the surface. Therefore, the linear upper Paleozoic basin-bounding faults are assumed as the main source of inheritance in that area, rather than anisotropy in the crystalline basement itself.

Despite the difference in orientation of the basement features, it is plausible that they were reactivated contemporaneously under uniform extension, as best shown in model A3 (Fig. 13d, 14c). Its results indicate that a bimodal distribution of fault orientations can arise in the presence of suitable inherited weaknesses with fault sets of both orientations being active since



early stages of the experiment (Fig. 13d_{I-II}). If the degree of weakening is high enough, as is the case above linear viscous seeds, the seed will produce faults in the sand pack which run parallel to it even at angles oblique to the stretching direction (possibly up to around 45°, cf. Osagiede et al., 2021). In the southern flank of the Most Basin, inherited upper Paleozoic normal faults likely represent such high-contrast weaknesses. Therefore, the roughly 60° N trending, southeastern border faults of the Most Basin and vicinity could have been active since the onset of rifting since the late Eocene, even under the presumed N-S extension, coevally with E-W trending fault segments at the opposite rift flank. This contrasts with the earlier interpretation of Rajchl et al. (2009) or Špičáková et al. (2000) that linked NE-trending faults in the Eger Graben mainly to a presumed later, NW–SE extensional phase. More recent dating of faults in the Most Basin region activity, also appears to support a broadly contemporaneous activity of the E-W and NE-SW fault sets.

With respect to the effect of Variscan fabric on the geometry of the northern rift flanks, models featuring a larger oblique weak zone in the form of a thickened silicone slab (A2 and T4) are considered the most illustrative. In such models, the silicone slab is incorporated to align the rift axis obliquely to the N-S extension direction as well as to the E-W pervasive fabric. In the natural prototype, the deep seated Teplá Suture is often cited as the “principal weakness” which localised the rift in its western and central portion (Babuška et al., 2010; Babuška and Plomerová, 2012). During the extensive volcanic phase preceding and partly coeval with the onset of extension, the Teplá Suture is assumed to have acted as a pathway for melts ascending from the sub-lithospheric mantle (Plomerová et al., 2016). Our models were confined to the crustal scale and thus did not simulate weaknesses in the lithospheric mantle directly; instead the thickened silicone slab was added to represent a hypothetical region of thermally weakened crust located above the suture trace. The final structural pattern of these models illustrates that the rift border tends to be diffuse in areas affected by an extension-orthogonal fabric, where a series of en-echelon, fabric-aligned faults delimits relay ramps. In model A2 (Fig. 14b) it is apparent that some of these relay ramps tend to eventually breach, even under constant N-S extension, confirming that their breaching does not necessarily require a change in the stress field such as invoked by Rajchl et al. (2009) as long as the rift axis is oblique to extension (Fig. 18b).

As the oblique rift zone crosses both the model domains with and without pervasive orthogonal fabrics, illustrated in model T4 (Fig. 12e), the character and orientation of the border faults reflect the fabric (or its absence) in the surrounding area. The fabric-affected domain contains E-W trending en-echelon faults along the rift border whereas the “isotropic” domain will develop faults that are more likely to parallel the rift zone’s NE trend. In part, this effect might explain the observed segmented geometry of the Krušné Hory Fault Zone even if developed under constant N-S extension. In areas where the basement is formed by the southern limb of the Catherine Dome (CD) with pronounced E-W fabrics and lithological contacts, rift-related faults and fault segments of corresponding orientation tend to dominate (such as the Ahníkov Fault exposed in an active open pit mine, cf. Mach et al., 2017; Rajchl et al., 2009). However, further northeast into the core of the CD, a NE-aligned trend of the KHFZ coincides with the absence of a strong E-W anisotropy (Fig. 18, cf. also fig. 4 and Mlčoch and Schulmann, 1992).

A common feature of models A2 and A3, which is also potentially relevant for the Most Basin, is the activity of NW-SE oriented faults. A few of these transverse faults occur above the diagonal weakness zone present in these models (i.e. the thickened silicone slab and viscous seeds in model A2 and A3, respectively) and show sinistral oblique slip kinematics. Unlike in the models, analogous faults the Most Basin are likely predisposed by inherited faults and fracture zones of corresponding ori-

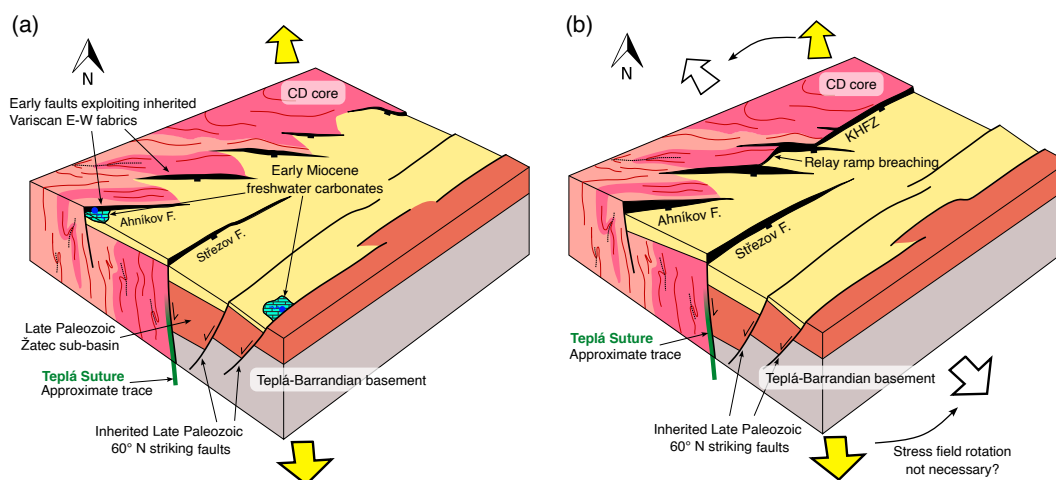


Figure 18. Conceptual block-diagram illustrating the different inherited structures contributing to the tectonic framework of the western Most Basin. Approximate extent of the displayed area is highlighted in fig. 1. Not to scale. (a) Initially, E-W trending faults will tend to concentrate in areas with predisposed fabrics. The deep-seated “principal weakness” (likely the Teplá Suture) together with the inherited upper Paleozoic faults are believed to be responsible for the 60° N trend of the rift axis. (b) With continued extension, some relay ramps separating E-W faults will breach and NE striking segments of the KHFZ will develop in domains where the inherited anisotropy is weak or absent – such as the CD core. These features are hypothesised to have been able to develop coevally under uniform approximately N-S extension.

entation. Nevertheless, their “spontaneous” appearance in the models further enhances their similarity to the natural prototype and contributes to the credibility of the experimental setup.

730 In summary, the main implication of the foam-block-base models is that contrasting fault populations of the western Most Basin can result solely from the effects of several types of inherited structures in genetically different basement regions and may not require a temporal change in extension direction to explain their observed geometries. That still does not mean that a NW-SE extensional phase did not occur at all; for example the dataset from the Lužice Fault Zone crossing the eastern part of the EG (Coubal et al., 2015) seems to support the stress reorientation during the Miocene, similar to Rajchl et al. (2009).
735 Nevertheless, some structures in the western Most Basin previously assigned to a later stage of rift development may in fact have been active earlier than previously assumed.

6 Conclusions

Two-phase experiments using a setup with a discrete velocity discontinuity (VD) at the model base (E series) confirmed the key role of the initial stretching phase in defining the final fault pattern when the two phases have the same magnitude. When the basal VD is segmented, as is the case in our models, the degree of obliqueness of individual segments to the initial stretching direction affects how much second-phase faulting will occur. An initially oblique VD segment will be more prone to later
740



reorganisation of the structural pattern whereas an initially orthogonal VD segment will mostly accommodate strain on already existing faults with limited growth of new structures.

Only the E series models starting with South-directed extension produced long E-W faults present in the Ústí (“Central”) segment of the Eger Graben; models that also included a second SE-directed phase showed arguably the closest similarity to key features of the natural prototype. This appears in accordance with the existing interpretation of changing paleostress directions; however, such an inference is potentially limited by simplifications in the model setup, especially regarding the rheology of the model crust and the degree of mechanical coupling between the model base and the surface.

In the pure-shear style models with a foam base (series T and A) the pervasive fabric appears to have the most prominent effect in the initial stages of extension where it promotes rapid fault nucleation and lateral tip propagation while fabric orientation to the extension vector affects the length and total number of resulting faults. When fabrics were combined with a wider weakened region to localise the rift, they significantly altered the geometry of the rift border as well as the segmentation of the intra-rift tectonic relief when compared to cases where fabrics were absent. Combining pervasive fabrics with linear viscous seeds revealed that complex fault geometries with a bimodal distribution of orientations can arise in a uniform N-S stress field when suitable inherited structures are present.

Therefore, it is suggested that certain structural features of the Most Basin in the Eger Graben, mainly the across-axis contrast in dominant fault trends, can be attributed to coeval reactivation of several types of inherited structures in the basement under constant approximately N-S stretching without requiring the change to a NW-SE extension proposed in earlier studies to explain their geometries. On a more local scale, variations in fabric intensity and orientation along the Krušné Hory Fault Zone, the principal northern rift boundary fault, may help explain the segmented geometry of certain portions of this fault zone.

Overall, the fault geometries developed in these models share a great degree of similarity to those observed in natural rifts where the effect of structural inheritance has been invoked. Since the incorporation of pervasive fabrics into rift sandbox models has been considered challenging with a limited number of published works, we consider our approach, albeit not without limitations, a potentially valuable methodical contribution with prospects for application in future studies.

Appendix A

The results of surface strain analysis of a “blind” experiment that tested the deformation of the basal foam block used for experimental series T and A are shown below. In the blind experiment, extension proceeded at the same velocity (25 mm h^{-1}) as in all other experiments which used this setup. Apart from a small amount of white sand, which was sprinkled on top of the foam block to provide a contrasting surface required for Digital Image Correlation, no analogue materials were used.



"Blind" experiment results illustrating foam block surface deformation

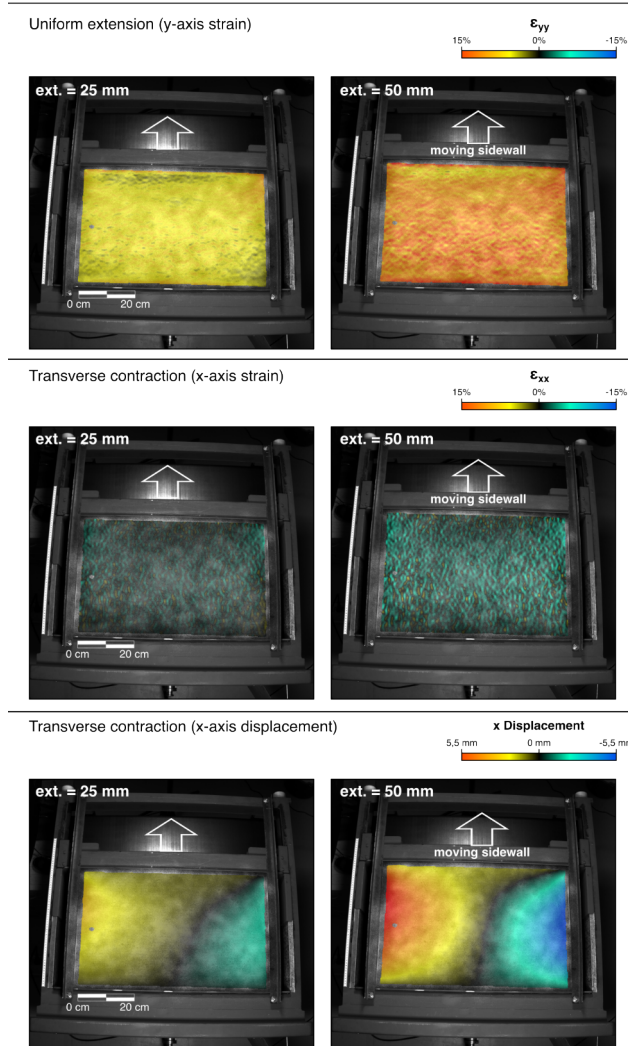


Figure A1. "Blind" experiment results

770 **Data availability.** Data regarding DIC analysis results and the surface fault pattern of finished experiments were uploaded to a Zenodo repository and are available at 10.5281/zenodo.21397623

Author contributions. FH and DU conceptualised the study and the experimental procedure. FH carried out the experiments, analysed the experimental results and composed the original draft of the manuscript. DU supervised the project, secured funding and substantially contributed to sections the manuscript concerning the structural framework of the Eger Graben and related figures. DU critically reviewed and



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